TRUST RELATIONSHIPS, NAMING, AND SECURE COMMUNICATION IN LARGE DISTRIBUTED COMPUTER SYSTEMS

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by

P. Venkata Rangan

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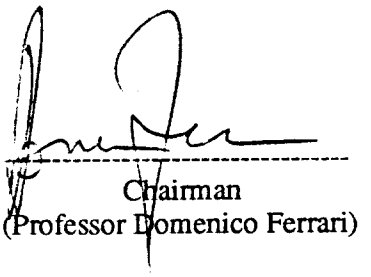
ABSTRACT

Computing systems are evolving into distributed systems that interconnect competing organizations and individuals, and even countries, using high-speed global networks. The relationships among these entities are characterized by the need for competition and cooperation without a common *trusted* agent. To build such distributed systems that incorporate lack of global trust in them, it is necessary first to understand precisely what *trust* consists of and then to categorize it. This thesis develops an axiomatic theory of trust in distributed systems. The theory is based on modal logics of belief. We present systematic methods for synthesizing protocols that implement a given trust specification.

Trust is primarily required to establish channels for secure communication. We present methods for reasoning about trusts required by various channel establishment mechanisms. Channel establishment mechanisms are commonly based on either public key encryption (PKE) or single key encryption (SKE). PKE-based mechanisms require ternary trust relationships known as *authenticity trusts*. SKE-based mechanisms have much larger trust requirements. Starting from the differences in trust requirements of PKE and SKE, we derive several advantages of the former over the latter. Our analyses provide insight into the trust structure and limitations of various mechanisms.

We show that a distributed system must provide a tree of channels at system configuration time, and that this tree also represents the system's global name space. We develop polynomial-time algorithms for synthesizing name spaces so as to satisfy an *a priori* given set of trust specifications. We present some interesting duality results and NP-completeness results with regard to some variations of the synthesis problems. Sample runs of the polynomial-time algorithms show that small differences in trust relationships can cause substantial differences in the structure of the name spaces.

Trust requirements and the performance of channel establishment can be traded for each other. If channels are PKE-based, slightly increasing the trust requirements can greatly increase the performance of channel establishment. However, if channel composition is SKE-based, global trusts, which may not be satisfied in the system's name space, are required for significant improvements in performance.



Chairman
(Professor Domenico Ferrari)

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Invocation

The inspiration for my pursuit of doctoral research comes from the challenge of discovering an answer to the following question posed in the ancient Indian philosophical texts of the Mundaka Upanyshadh and the Bhagavadh Geetha.

Shaunako hy vai mahäshätho angyrasam vydhyvad upäsannah prapaccha:
"Kasmynnu bhagavo vygnäthe, sarvamydam vygnätham bhavathythy ?"

In ancient times, Shaunaka approäched Angyras and asked:
"What is That, by knowing Which, everything else becomes known ?"

To my parents: Amma and Anna

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CHAPTER 1

INTRODUCTION

1.1. Motivation

A moment's reflection is sufficient to realize that computing systems are evolving into very large distributed systems that interconnect competing organizations and individuals, and even countries, using global networks (see Figure 1.1). The relationships among these entities are characterized by the need for competition and cooperation, and by inherent conflicts of interests. There are few policies that are agreeable to all of the entities, and, even in the case of policies on which all the entities agree, there are no globally acceptable administrative authorities to enforce the policies. Consequently, a very large distributed system (VLDS) spanning all these entities will be characterized by the absence of globally *trusted* agents. The interconnecting networks, owing to their ultra-high bandwidths [SlP86], will be capable of supporting secure and integrated, but extremely fast access to non-local resources. A scenario in which workstations and high-speed fibers replace telephones and telephone wires, and a VLDS interconnecting these workstations replaces the functions of most media (telephone, physical mail, printed media, audio and video media) is not far from the real possibilities of the medium-term future. The use of a VLDS for carrying out commercial operations such as bank transactions, monetary transactions, and airline flight reservations is being seriously explored. Consequently, the issues of security and trust become critical in a VLDS. A VLDS must maintain the security and autonomy of its components without restricting the sharing of resources and without requiring its components to place global trust in any entity.

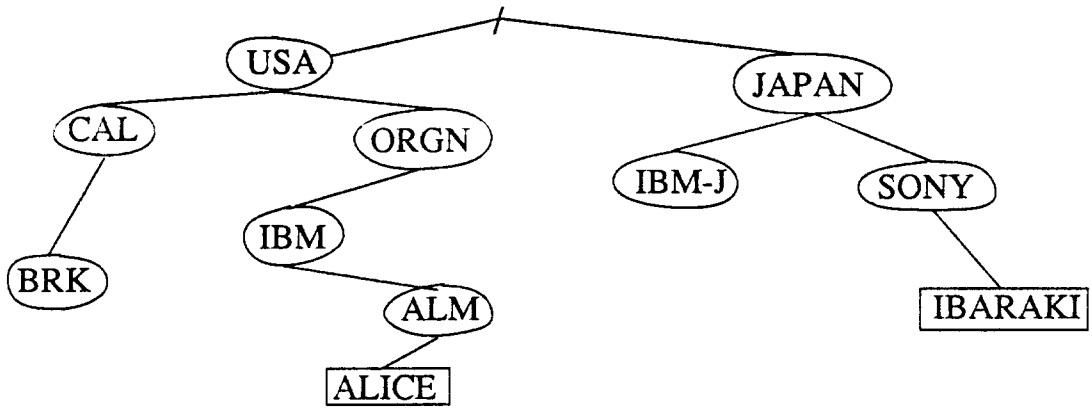

Figure 1.1: A sample space of entities that might be spanned by a future distributed system

To build such distributed systems that allow partial trust, it is necessary first to understand precisely what trust consists of, and then to characterize it. In literature, the term "trust" is used frequently but rarely defined [CGH81, EKW74, Sal74, Wei69] [Dif82, KlP79, Lan81]. The kind of trust that underlies expressions such as "Alice trusts Bob" has never been adequately characterized. Unless we make an effort to investigate trust and security, their inadequate understanding will be a major obstacle to the commercial realization of very large distributed systems.

1.2. Trust Relationships, Naming and Secure Communication in Distributed Systems

To see how trust is needed in a distributed system, consider the case of secure communication between two users, *Alice* and *Ibaraki*. Alice (actually, a process belonging to Alice) on a host H_A needs to communicate securely with Ibaraki on another host H_B (see Figure 1.2(a)).

In distributed systems, secure communication between two agents is based on the notion of a *logical secure channel* (or just a *channel*) between the two agents. A secure channel has associated with it algorithms for securely sending and receiving messages on it. To communicate securely, Alice must establish a secure channel to Ibaraki. Secure channels are based on encryption, and hence, to establish a secure channel to Ibaraki, Alice must obtain the encryption key of Ibaraki [Den82, FNS75]. In a large distributed system, the database of encryption keys cannot be replicated at each host, and hence encryption keys are stored and managed by *authentication servers* [Lu86, NeS78, Ter]. Thus Alice must obtain Ibaraki's encryption key from an authentication server (Figure 1.2(b)). Since the security of communication between Alice and Ibaraki depends on the validity of the encryption key that Alice obtains from the authentication server, informally we can say that Alice is placing *trust* in the authentication server with respect to Ibaraki.

Figure 1.2(c) shows a more general scenario in which the nodes labeled *IBM*, *IBM–J*, *USA*, *SONY–US*, *JAPAN* and *SONY* are authenticaton servers managed by the respective organizations. In the sequel, we will use the term *agent* to abstractly denote either a user or an authentication server. We can draw some generalizations regarding secure channel establishment between agents, such as that between Alice and Ibaraki. In any system, given a set of existing secure channels (denoted by solid lines in Figure 1.2(c)), the only way to establish a new secure channel is by composing adjacent secure channels. Intuitively, considering the example shown in Figure 1.2(c), to establish a new channel to Ibaraki, Alice must receive Ibaraki's encryption key on one of Alice's existing channels, which in this case is Alice's channel to *IBM*. If we go back a step in the itinerary of Ibaraki's key, Ibaraki's key must have arrived at *IBM* on one of the channels incident on *IBM*, and so on. Thus for Alice to establish a channel to Ibaraki, a sequence of adjacent channels must exist forming a path between Alice and Ibaraki. In fact, we will formally show in Chapter 3 that any secure channel establishment consists of a sequence of channel compositions, with each composition involving two adjacent channels.

There are two distinct problems in channel composition: (1) which are the channels to be composed, and (2) in what order should these channels be composed. These two aspects of channel composition give rise to different trust requirements in a distributed system. These aspects are related to naming because of a reciprocal association between naming and channel establishment: (1) resolving a name (i.e., translating human-readable names of agents to attributes such as their location) requires the establishment of channels to name servers, and (2) channel establishment requires translating names of agents to their encryption keys, for which a name resolution procedure must be used. Thus, even though naming and channel establishment can be realized separately, combining them into a single mechanism can result in higher

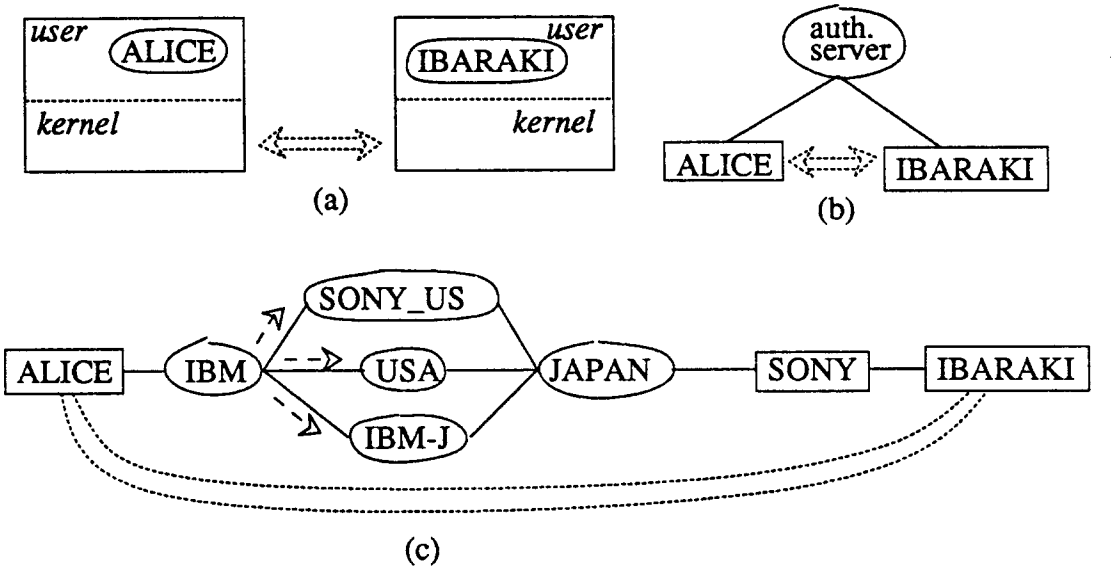

Figure 1.2: Problem of trust in a VLDS. (a) Logical secure channel. (b) Adjacent channel composition. (c) Channel establishment as a sequence of adjacent channel compositions.

performance. In the sequel, we will use the term name server synonymously with the term authentication server.

It should be noted that the problems of trust in a distributed system are interesting in their own right, irrespective of whether the distributed system is large or not. However, efforts to solve those problems are justified by their crucial importance to very large distributed systems. Small distributed systems, such as those that do not span more than one organization, do not have significant trust problems. In distributed systems that span more than one organization but with a small number of organizations, trust problems are sufficiently simple that they can be solved using informal methods. Only when a distributed system spans a large number of autonomous organizations does the need for systematically characterizing the trust relationships in the system arise. In fact, only in large distributed systems is there a need for storing encryption keys at name servers. In small distributed systems, the database containing the encryption keys of all agents can be replicated at each host, and the problem of trust in secure communication disappears.

1.3. Relation to Previous Work

Most existing and proposed distributed systems make trust-related assumptions, though often implicitly. A sample of these assumptions is as follows:

- All system-level components trust one another. Hosts trust each other, and agents trust all name servers [Che84, MuT84, STB86]. Systems such as Amoeba [MuT84] further assume that both the network and the network interfaces are secure.

- Hosts may not trust each other, but name servers are globally trusted [BLN82, SJR86].

Clearly these trust-related assumptions are incompatible with one or more of the characteristics of very large distributed systems we projected in Section 1. Many of the trust-related assumptions made in current systems are based on the supposition that each distributed system has a logically centralized administrative authority that can enforce policies and punish violators. The absence of such a single administrative authority in a VLDS has significant trust-related consequences. The agents in a VLDS have to cope with the inherent existence of lack of trust and the associated possibilities for losses. A recent case involving a foreign company over which the United States was unable to enforce its laws is an appropriate example. Thus, a VLDS must not only allow lack of global trust but also incorporate explicit patterns of lack of trust.

The Arpanet [81a, 81b] is similar to a VLDS in that it spans a large number of organizations and individuals, and has a global name server [TPR84]. However, the Arpanet does not have global authentication mechanisms, and hence it does not provide secure integrated access to non-local resources. An agent must have independent accounts and passwords on each host that it uses. The total lack of integration of services in the Arpanet prevents it from being a true VLDS.

Birrell *et al.* [BLN86] consider naming and authentication in large distributed systems without global trust. They suggest that an agent must be able to specify the sequence of name servers to be trusted for establishing a channel. However, they neither give a precise meaning to the notion of trust nor provide a precise analysis of the trust properties of various secure channel establishment mechanisms. We give a precise notion of trust in Chapter 2, in Chapter 3 we analyze the trust properties of the various channel establishment mechanisms, and in Chapter 5 we investigate trust properties of various network protocols for channel establishment. These analyses reveal surprising differences among, and limitations of, the various mechanisms and protocols with regard to their trust properties. For instance, we show that, if secure channels are based on single key encryption (rather than public key encryption), handling channel establishment at the host-to-host level of the network protocol hierarchy requires global trust.

Birrell *et al.* [BLN86] also suggest that, in order to choose the name servers trusted in establishing a new channel, the channels to be composed must be chosen appropriately, and the burden of choosing these channels is left to the users. In Chapter 4, we will develop algorithms for synthesizing name servers so as to satisfy an *a priori* given set of trust specifications of agents. Thus, the user is no longer burdened with choosing channels based on whom he or she trusts; the design of the name server automatically takes care of the user's trust relationships.

Popek and Kline [KlP79, PoK79] compare trust properties in secure communication using single key encryption and public key encryption, and conclude that the two have the same trust properties. In Chapter 3, we will show that this conclusion, which they arrived at using an informal notion of trust, is incorrect.

1.4. Outline of the Thesis

The goal of this thesis is to develop techniques by which distributed systems can be synthesized so as to satisfy a given set of trust specifications. Such a synthesis will have to employ some basic channel composition mechanisms. Before we can employ a channel composition mechanism in a synthesis, we must know the trust relationships inherent in (and hence required by) the mechanism. Thus, we must analyze the various channel composition mechanisms and investigate the trust relationships they require. But before we can analyze a mechanism from

the viewpoint of the trust relationships it requires, we must precisely define what we mean by *trust*. Thus, the dissertation will consist of the following sequence of steps.

Theory of Trust: To capture and incorporate lack of trust into a distributed system, it is necessary first to understand precisely what trust consists of, and then to characterize it. Basic foundations are necessary to clarify our understanding and to reason adequately about lack of trust in distributed systems. A clear definition of trust in a distributed system can reveal subtle distinctions that may not be otherwise apparent. Formal descriptions of security have traditionally avoided any explicit treatment of trust. It is desirable to unify security and trust into a single theory. To satisfy all these requirements, we develop an axiomatic theory of trust in Chapter 2.

Analysis: Formal analysis of trust can offer insights into the basic structure and the limitations of mechanisms with regard to their trust requirements. Zero-trust mechanisms may be possible. Chapter 3 analyzes trust relationships in various channel composition mechanisms. We develop methods for reasoning about trust requirements in various mechanisms, and discuss methods for arriving at the minimal trust requirements in a given distributed system. While doing so, we will encounter some surprising differences among various mechanisms with regard to their trust requirements.

Synthesis: The eventual goal of the thesis is to provide algorithms for synthesizing distributed systems so as to satisfy a priori trust specifications of agents. As was shown in Section 2, trust requirements arise in naming. Chapter 4 develops algorithms for synthesizing name servers from trust specifications. A sample set of trust specifications may be as follows: "Alice never sends false information to Bob about Fred, and Bob never sends false information to Riccardo about Alice. Fred and Riccardo cannot be trusted to secretly store information about Bob or Alice. Fred cannot be trusted for any information about any agent that Alice or Bob trust for information about Riccardo." Or it may involve organizations as in, "IBM trusts DEC for Hitachi but not for AT&T".

No synthesis methodology is complete without performance considerations. Under some conditions, trust requirements and performance of channel establishment mechanisms can be traded for each other. Chapter 5 shows that, if channel composition is based on public key encryption, slightly increasing the number of trust relationships that are satisfied can greatly increase the performance of channel establishment mechanisms, and that the additional trust relationships still form a subset of the set of trust specifications from which the distributed system name space has been synthesized. We also show that, if channel composition is based on single key encryption, global trust, which may not be satisfied in the system name space, is required for significant improvements in performance.

Clearly the goals of the thesis are pragmatic, but the approach is partly formal. This work was carried out as part of the DASH project at Berkeley [AFV87c], which is investigating issues in the design and implementation of very large distributed systems.

CHAPTER 2

AXIOMATIZATION OF TRUST

This chapter develops an axiomatic theory of trust in distributed systems. The chapter discusses what it means to develop a logic or a theory, and shows that modal logics of belief with their semantic interpretation based on the *possible worlds semantics* of Kripke, are appropriate as a starting point for a theory of trust. We review a modal logic of belief that is an enhancement of propositional logic with a belief operator, and construct a model of a distributed system so that the logic is sound and complete with respect to the model. Any sentences in the logic may then be added to the logic as axioms, and these axiomatic sentences are considered as trust specifications. The logic and the trust specifications, together with the model, constitute a formal theory of trust for the target distributed system. However, a theory of trust is of practical significance only if abstract trust specifications can be implemented in a real distributed system. We present formal techniques for synthesizing protocols that are necessary and sufficient for implementing a given trust specification in a distributed system.

2.1. Introduction

To build distributed systems that capture and account for lack of global trust, it is first necessary to understand precisely what trust consists of, and then to characterize it. Basic foundations are needed to clarify our understanding and to reason adequately about lack of trust in distributed systems. This chapter develops an axiomatic theory of trust for such systems. In Section 2.2, we discuss basic notions of what it means to develop a logic or a theory, and show that modal logics of belief are appropriate as bases for a theory of trust. Section 2.3 reviews modal logics of belief, and Section 2.4 presents a distributed system model. Section 2.5 presents a modal logic of belief that is sound and complete with respect to this model. In Section 2.6, we develop a formal theory of trust, and, in Section 2.7, we present methods for synthesizing protocols that implement a given abstract trust specification. Finally, Section 2.8 concludes the chapter.

2.2. An Approach to Axiomatization

2.2.1. Theories

Our first step, as we saw, is to capture the highly informal notion of trust into a formal theory. The term *theory* is used here in the sense of Mendelson [Men87]. A theory is based on a *logic*. Briefly, a *logic* consists of a *language*, which defines the set of *well formed formulas* (WFFs) or valid sentences, a set of *axioms*, and a set of *rules of inference*. An *axiom* is a WFF and a *rule of inference* is a transformation from one WFF to another. (We will shortly define the roles played by axioms and rules of inference in a logic.) The logic provides a framework for reasoning and abstracts some fundamental notions. A *theory* consists of a logic enhanced with a set of assumptions that are particular to the real-world problem being modeled by the theory. These assumptions are called *proper axioms*. To develop a theory of trust, we must first start with a logic on which to base the theory.

A *proof* starts out from the axioms and the proper axioms, and repeatedly uses rules of inference to arrive at a WFF. A WFF that is the result of a proof is called a *theorem*. The

theory is said to be *consistent* if for no WFF are both the WFF and its negation theorems in the logic.

Each logic (theory) has a set of *models* which provide the *semantic interpretation* for the logic (theory). The semantic interpretation is outside the logic and corresponds to the real-world situation being modeled by the logic (theory). Assuming two-valued logics, a semantic interpretation of a WFF under any assignment to variables in the WFF yields one of the two values: *true* or *false*. A WFF whose semantic interpretation is true in a model under any assignment to the variables in the WFF is said to be *valid* in the model. A WFF whose semantic interpretation is true in a model under at least one assignment to the variables is said to be *satisfiable* in the model.

A logic (theory) is said to be *sound* with respect to a model if and only if the theorems in the logic (theory) are valid in the model. A logic can also be shown to be sound with respect to a model if and only if the axioms of the logic are valid in the model and the rules of inference are validity preserving. It can be shown that a theory is sound with respect to a model if and only if the logic on which the theory is based is sound with respect to the model and the proper axioms of the theory are valid in the model. Thus, the set of models with respect to which a theory is sound is a subset of the set of models with respect to which the logic the theory is based on is sound. A logic (theory) is said to be *complete* with respect to a model if and only if all WFF that are valid in the model are theorems in the logic (theory).

To develop a formal theory of trust, we must first start with a logic on which to base the theory.

2.2.2. A Logic for Trust

What kind of a logic is suitable for modeling trusts in distributed systems ? To answer this question, consider the simplest case of secure communication.

To communicate securely, agents encrypt messages using keys belonging to other agents. We may say that each agent must make assertions of propositions of the form *owner* (*key of the other agent*, *the other agent*), where the semantic interpretation of *owner* (*key*, *agent*) is that it returns true if and only if *key* belongs to *agent*. Thus, it seems appropriate to consider propositions of this type as forming the atomic propositions of a logic of trust. (An *atomic proposition* is a proposition representing a basic notion in the model at a given level of abstraction.)

In a system in which the complete database of keys is securely replicated at every agent using mechanisms external to the system (such as telephone conversations between agents, or couriers), two agents can communicate securely without placing trust in a third agent. In a distributed system with distributed name servers, an agent has to obtain the keys of other agents from name servers.

Figure 2.1 represents a distributed system in which there are agents A_i, A_j and A_k, and where A_j is a name server. There are two channels in the initial state, A_i-A_j, and A_j-A_k. A_k sends a message msg_{kj} containing its key key_k to A_j. When A_i sends a request to A_j asking for A_k's key, A_j sends a message msg_{ji} to A_i containing key_k. If the proposition *owner* (key_k, A_k) cannot be proved false (i.e., if it is satisfiable and hence *possible*) at A_i, A_i may now consider accepting key_k. However, A_i is not prepared to use key_k for secure communication to A_k unless it is able to prove that *owner* (key_k, A_k).

Suppose, to start with, that we make no assumptions whatsoever about security or about the validity of the messages sent by one agent to another, and that the *belief* in a proposition is used to represent an attitude by which the believer may not be able to prove the proposition

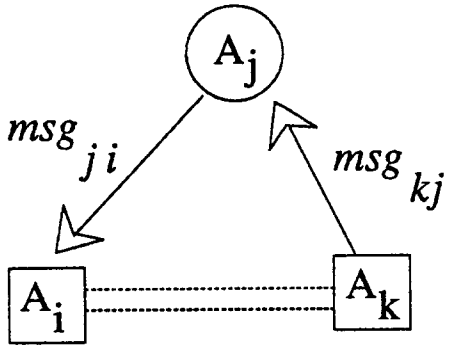

Figure 2.1: Messages and beliefs in secure communication. Secure communication channel A_i-A_k is to be established using name server A_j.

valid but thinks the proposition might be valid. Thus, the belief of an agent corresponds to the notion of having in the agent's database a proposition that is satisfiable so that, even though there may be a measure of uncertainty about the validity of the proposition, the agent has strong reasons to conjecture that the proposition might be valid in the real world. Specifically, let the *belief* in a proposition p, denoted by $B_i p$, indicate a relationship between an agent A_i and a proposition p such that (a) A_i may not be able to assert the truth of p, (b) A_i cannot prove p's falsity, and (c) A_i expects and desires p to be true. Thus, there may be a measure of uncertainty about p's validity, but there is a high likelihood that p might be valid.

Using this notion of belief, we might say that the message from A_k to A_j creates a belief $B_j$owner(key_k, A_k). The message from A_j to A_i creates a belief $B_i B_j$owner(key_k, A_k). Thus, A_i *believes that* A_j *believes owner* (key_k, A_k). This can be extended to a scenario in which the key successively passes through several name servers during name resolution.

However, A_i is not prepared to use key_k for secure communication to A_k unless it is able to prove that *owner* (key_k, A_k) is valid. To infer *owner* (key_k, A_k) from its belief, A_i has to use some assumptions such as that A_k does not usually send a false key, the key-parts of messages msg_{kj} and msg_{ji} are identical, and so on. Such assumptions are encapsulated into the notion of trust, and are precisely abstracted by proper axioms. In this example, one possible proper axiom may be "$B_i B_j$owner(key_k, A_k) => owner(key_k, A_k)". While a belief is an operator, a trust is a proper axiom, i.e., a WFF that is assumed to be true in the system. Thus for instance, a belief such as $B_i p$ denotes that A_i believes that proposition p is true, while a WFF such as $B_i p$ => p is a trust denoting the assumption that, A_i believes in p only when p is true. Agents use trusts to make inferences about the validity of their beliefs.

It is easy to see that reasoning about trusts involves reasoning about the notion of belief, and that a theory of trust may be based on a logic of belief. After all, one of the most desirable properties of a formal theory is its ability to capture what people intend to say, and we have arrived at the suitability of a logic of beliefs in the course of making natural statements about secure communication. At this point it is useful to pause, and review the kinds of logics available to us for reasoning about beliefs in general.

2.2.3. Logics of Belief

Belief represents an attitude of an agent towards a proposition. A logic for expressing propositional attitudes must be able to express the appropriate relations between believers and attitudes [Hin62]. Classical first order logic does not handle these attitudes properly [FaH85, HaM85]. *Modal logics* [HuC68], which enhance propositional and first-order predicate logics with modal operators such as belief, have been found suitable for modeling belief.[1]

2.3. Modal Logic of Belief: A Review

2.3.1. Syntax

In the language of the modal logic of belief, agents are named $A_1, \ldots, A_m$, and the atomic propositions are denoted by $p, q, \ldots$ Let "Λ", "V" and "$\sim$" denote conjunction, disjunction and complementation, respectively. For $i = 1, ..., m$, let B_i be an operator, read as "agent A_i believes". The set of WFFs is the smallest set that contains atomic propositions, is closed under boolean connectives, and contains B_iF $(i = 1, ..., m)$ if it contains F. Since quantified modal logics are not well understood, we restrict ourselves to using the propositional modal logic for belief. However, when a variable x varies over a finite set $X = \{x_1, ..., x_n\}$, "$\forall x\ F(x)$" is used as a short-hand notation for $F(x_1)\Lambda \cdots \Lambda F(x_n)$. Thus, if F is a WFF, and x varies over a finite set, $\forall x\ F(x)$ is a WFF.

2.3.2. Semantics

Unlike classical logic operators, modal operators such as belief do not allow a truth-functional semantic interpretation. (An operator is truth-functional if and only if, given any WFF that is a result of applying the operator to some arguments, the truth value of the WFF can be deduced solely from the truth values of the arguments. Belief is not a truth-functional operator because, belief in a proposition may be true or false irrespective of the truth value of the proposition.) Thus, modal logics use a *possible-worlds semantics* [HaM85, Kri63] in which the notions of possibility and necessity are used, and the notion of a possible world is used in the semantic interpretation. [2] A set of possible worlds is postulated, and a belief is true if it is true in a set of possible worlds. The real world may be one of the possible worlds.

An agent's belief arises primarily because of the agent's ignorance about the global state of the distributed system. An agent's state of belief relates to the level to which the agent can determine the system's global state based on its local state. In each global state of the system, one can associate with each agent a set of *possible global states* that are determined as follows: if the agent's beliefs are true, any of them could *possibly* be the real global state. In other words, based on its local state, an agent cannot determine the real global state that it is in; it can only conclude that some global states are possible. An agent believes p, denoted by B_ip, if and only if p is true in all the global states that the agent considers possible. An agent does not believe p if and only if, in at least one of the global states that the agent considers possible, p is not true. Since this semantic interpretation of belief uses the notion of possible global states, it is called the *possible worlds semantics* [Kri63].

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[1] As we will see later, modal logics use the notions of possibility and necessity. In medieval logic, possibility, necessity, and so on, were thought of as *modes* in which a proposition could be true or false.

[2] Halpern and Moses wrote an excellent paper on modal logics of belief and knowledge [HaM85]. The review of modal logics presented in Section 2.3 of this chapter is based heavily on this paper.

In a future section we show that the addition of any proper axiom to a logic (giving rise to a theory) requires the construction of a new set of models from the old set of models for which the logic was sound and complete. This is to ensure that the theory is sound and complete for the new set of models. If this cannot be ensured, then the theory may be ill suited for the new set of models of the system, i.e., some statements that are provable as being true in the theory may be actually false in the system, and some that are true in the system may be provable as being false in the theory. Thus, it is necessary to ensure that the theory is sound and complete for the new set of models. In the modal logic approach, by making minor changes to the possible worlds semantics, we can capture different problem situations. By imposing various constraints on what global states are considered possible by an agent in a given real global state, one can capture a number of interesting notions of belief. For example, if the relation between the global state and the set of possible global states is restricted to be transitive, then an agent believes that it believes p, if it believes p. Since it lends itself to easy translation between a proper axiom of a theory and its semantic interpretation in the model, the possible worlds approach is a powerful tool for developing theories. Thus, we say that this approach is *customizable*, i.e., with little effort a theory can be derived from a logic for a given security environment. We have chosen this approach for our theory of trust.

2.3.3. The Kripke Structure: A Formal Semantic Interpretation of Belief

Kripke [Kri63] introduced what is known as a *Kripke structure* as a formal model for possible worlds semantics. Let S be the set of all global states, and Φ be the set of all atomic propositions. A Kripke structure K is a tuple $(S, \pi, \rho_1, ..., \rho_m)$, where π is a truth assignment to the atomic propositions of Φ for each global state s in S (i.e., $\forall p, s$ such that $p \in \Phi$ and $s \in S$, $\pi(s, p) \in \{\textbf{true}, \textbf{false}\}$), m is the number of agents, and ρ_i, $i = 1, ..., m$, is a relation on the global states in S. ρ_i is A_i's *possibility relation*; $(s, t) \in \rho_i$ if and only if in global state [3] s A_i considers the global state t as possible.

We will now review a formal definition of the truth of a WFF given using the relation $\models$, a relation between states and WFFs [HaM85]. "$s \models p$" stands for "p is true in s" (which is equivalent to, "w satisfies s").

$\forall p \in \Phi, s \models p$ if and only if $\pi(s, p) = \textbf{true}$

$s \models p \wedge q$ if and only if $s \models p$ and $s \models q$

$s \models \neg p$ if and only if $s \not\models p$

$s \models B_i p$ if and only if $\forall t$ such that $(s, t) \in \rho_i, t \models p$

The last definition above formalizes the idea that an agent A_i believes p in global state s if and only if p is true in all the states that A_i considers possible when the system is in state s. A WFF p is *valid* (or *satisfiable*) if and only if $s \models p$ for all states s (or for some state s, respectively). It may be observed that p is satisfiable if and only if $\neg p$ is not valid.

In order to use this logic for reasoning about communication security, we have first to relate distributed systems to Kripke structures.

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[3] In the sequel, we use the term *state* synonymously with the term *global state* except when explicitly mentioned that it is *local state*. There is a distinction between a *world* and a *global state*, but, in the sequel, this distinction is unimportant, and we use them synonymously.

2.4. A Distributed System Model

2.4.1. States

A distributed system can be modeled as a set of agents communicating with each other via messages. The *state* of the distributed system consists of the states of all its agents. The *state* of an agent consists of its message history, which is the sequence of messages received or sent by the agent. A message in the message history consists of a WFF, a sender, and a receiver. At least one of either the sender or the receiver is the agent itself. Messages that are not of this format are not of interest to the agent and are not interpreted by the agent. To start with, we make no assumptions about the security in the system: i.e., an agent may send or receive any message, may masquerade as any other agent, and so on. An agent may impose any conditions for accepting a message, such as a test for message authenticity. A non-accepted message does not become a part of the agent's message history. The state of an agent uniquely determines the agent's beliefs.

Having defined states, we now define the possibility relations in a Kripke structure.

2.4.2. Possibility Relations

Consider a global state s in which the state of agent A_i is s_i. The following definitions will be used:

$MS(s_i, A_j)$ = the sequence of messages in the message history of A_i in state s_i that were sent to A_j.

$MR(s_i, A_j)$ = the sequence of messages in the message history of A_i in state s_i that were received from A_j.

$BR(s_i, A_j)$ = the set of WFFs sent in the message sequence $\mathrm{MR}(s_i, A_j)$.

$Bel(s_i)$ = the set of beliefs of A_i in state s_i.

Let the symbol $\leq$ denote the subsequence relationship between sequences or the subset relationship between sets. The possibility relation ρ_i consists of all pairs of states s and t such that $\forall j, j \neq i$:

(PC1) $s_i = t_i$, i.e., the i_{th} components of state s and state t are the same,

(PC2) $\mathrm{MR}(s_i, A_j) \leq \mathrm{MS}(t_j, A_i)$ (i.e., there is an authenticated channel from A_j to A_i), and

(PC3) $\mathrm{BR}(s_i, A_j) \leq \mathrm{Bel}(t_j)$ (i.e., A_j has not lied about its beliefs to A_i).

We will refer to these three conditions as the *possibility conditions* with respect to s_i. Note that each possibility relation is specific to an agent.

In effect, the possible states from the viewpoint of A_i are those states of the distributed system in which all the messages in A_i's message history are authentic and the senders of those messages have not sent false messages to A_i (see Figure 2.2). Thus, A_i holds a limited optimistic view of the possible distributed system states: the possible states are secure as far as A_i is concerned. In the real state, agents might have sent false messages to, or masqueraded to A_j. Note that states in which A_j has masqueraded to A_k, $k \neq i$, or sent false beliefs to A_k are possible from the viewpoint of A_i. As we will see, we will make use of trusts to turn a possible secure state into the real state.

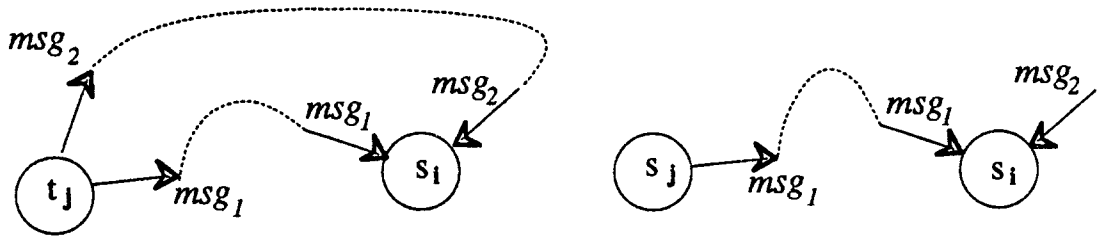

Figure 2.2: A possible state from the viewpoint of A_i and the real global state. (a) A possible global state from agent A_i's viewpoint: the possible global state consists of the real local state s_i of A_i and a possible local state t_j of A_j. In this possible global state, A_j has sent messages msg_1 and msg_2 to A_i and the WFFs that msg_1 or msg_2 contain are true. (b) The real global state consists of the real local states s_i and s_j. In s_j, A_j has sent message msg_1, the WFF contained in msg_1 is not true (A_j has *lied* to A_i), and A_j did not send msg_2. Masquerading as A_j, some other agent has sent msg_2 to A_i.

2.4.3. Belief Acquisition

What should agent A_i's beliefs be ? The semantic interpretation of a belief in a state s_i is that the believed proposition is true in all the states in the possibility relation ρ_i corresponding to s_i, i.e., in all the possible states. The system is not necessarily in one of the states considered possible by A_i, and hence the believed proposition need not be true in the real world. Any event in the system may trigger a belief acquisition or a belief revision. The events of interest depend on the particular application. For simplicity, we only consider the reception of a message as resulting in a belief acquisition. When A_i receives a WFF f from an agent A_j, A_i adds the belief B_iB_jf to its belief database if and only if B_jf is consistent with the beliefs that A_i has previously acquired as a consequence of a message from A_j (i.e., if $B_j\tilde{}f$ cannot be proved from A_i's current beliefs). Thus, incoming messages may cause an agent to add to its beliefs.

In the logic, WFFs received by A_i from two different agents will not be inconsistent with each other. For example, let A_j send a WFF f to A_i, let A_j send $\tilde{}f$ to A_k, and let A_k send $B_j\tilde{}f$ to A_i. B_iB_jf, and $B_iB_k\,B_j\tilde{}f$ are consistent with each other, and A_i will add both the beliefs. The possible states from the viewpoint of A_i in this example include those in which B_jf is true at A_j and A_j has sent a WFF $\tilde{}f$ to A_k (thus, $B_j\tilde{}f$ is true at A_k), as well as those in which A_j has sent a WFF f to A_i. To see why agents may need to send beliefs in a real system, in the example of Section 2.2.2 in which A_i establishes a channel to A_k using a name server A_j, A_k sends its key key_k to A_j, and the reception of key_k creates a belief $B_j\,owner(key_k, A_k)$ in A_j. A_j sends this belief to A_i, and this creates a belief $B_iB_j\,owner(key_k, A_k)$ in A_i. Notice that A_j must send its belief, and not $owner(key_k, A_k)$ to A_i, because, that key_k belongs to A_k is only a belief of A_j, and it is not certain if the key really belongs to A_k. Thus for instance, since we are not making any assumptions about the security behavior of various agents at this point, some other agent may have sent key_k masquerading as A_k.

2.4.4. Sending Beliefs

What beliefs can an agent A_i send to another agent A_j ? A_i can send any WFF, whether or not the WFF is a belief of A_i. However, A_j accepts a belief sent by A_i only if the belief is consistent with the beliefs that A_j has previously received from A_i. Thus, A_i is not allowed to change its mind. It is not necessary that a WFF sent by A_i to A_j (1) be one of A_i's beliefs, (2) be consistent with A_i's beliefs, or (3) be consistent with the beliefs that A_i sends to other agents.

2.5. A Logic of Belief for the Distributed System Model

The axioms and the inference rules for a logic of belief depend on the properties of the possibility relations. The properties of interest are *transitivity*, *euclidean property*, *serial property*, and *reflexivity*. A relation ρ is transitive if and only if $\forall s, t, u, ((s, t) \in \rho$ and $(t, u) \in \rho) \Rightarrow (s, u) \in \rho$. A relation ρ is euclidean if and only if $\forall s, t, u, ((s, t) \in \rho$ and $(s, u) \in \rho) \Rightarrow (t, u) \in \rho$. A relation ρ is serial if and only if $\forall s, \exists t$ such that $(s, t) \in \rho$. A relation ρ is reflexive if and only if $\forall s, (s, s) \in \rho$. We now show that the possibility relations for our distributed system model satisfy exactly the first three of these properties.

$\forall i, i = 1, ..., m$:

(1) *Transitivity*: for any states s, t, and u, suppose (s, t) and (t, u) are in ρ_i. By the possibility conditions, $s_i = t_i$ and $u_i = t_i$. Thus, $u_i = s_i$. For all $j, j \neq i$, t_j satisfies the last two possibility conditions with respect to s_i, and u_j satisfies the last two possibility conditions with respect to t_i. However $s_i = t_i$, and hence u_j satisfies the last two possibility conditions with respect to s_i. Thus (s, u) belongs to the possibility relation, and ρ_i is transitive.

(2) *Euclidean property*: consider any two pairs (s, t) and (s, u) in ρ_i. We have $s_i = t_i$ and $s_i = u_i$. Thus, $t_i = u_i$. For all $j, j \neq i$, u_j satisfies the last two possibility conditions w.r.t. s_i. Since $s_i = t_i$, u_j satisfies the last two possibility conditions w.r.t. t_i. Thus, all the three possibility conditions are satisfied for the pair (t, u). Hence (t, u) belongs to ρ_i, and consequently ρ_i is euclidean.

(3) *Serial property*: the possibility conditions are constructive. Thus, for every state s_i of A_i, for every j, $j \neq i$, t_j can be constructed directly from the possibility conditions and independently of any k, $k \neq j$, $k \neq i$. This is because the possibility conditions impose constraints only on the messages between A_i and other agents, and on the beliefs of other agents. There are no constraints on the messages between agents A_j and A_k, if $j \neq i$ and $k \neq i$. Thus, for every state of $s, \exists t$ such that $(s, t) \in \rho_i$. Hence ρ_i is serial.

The actual state may not be one of the possible states. Thus, the possibility relation is *not reflexive*, and a believed WFF may not be true in the real world.

Given these properties of the possibility relations, an axiom schema must be chosen for the modal logic of belief. Several axiom schemas are possible. An axiom schema not only provides a sound and complete formal system but also determines whether the satisfiability of WFFs is decidable or not in the logic, and hence must be chosen carefully. The following axiom schema is known to provide a sound and complete characterization of our notion of belief, and a decidable satisfiability of WFFs [HaM85]. The axiom schema consists of the following axioms:

for all $i, i = 1, ..., m$:

A1. All substitution instances of propositional tautologies.
A2. $B_i p \wedge B_i(p \Rightarrow q) \Rightarrow B_i q$.
A3. $B_i p \Rightarrow B_i B_i p$ (*introspection of positive belief*).
A4. $\neg B_i p \Rightarrow B_i \neg B_i p$ (*introspection of negative belief*).
A5. $\neg B_i$(**false**) (*agent i does not believe a contradiction*).

and the following inference rules:

for all $i, i = 1, ..., m$:

R1. From p and $p \Rightarrow q$ infer q (*modus ponens*).
R2. From p infer $B_i p$ (*generalization*).

Some of these axioms directly correspond to the properties of the possibility relations $\rho_1,...\rho_m$: **A3** corresponds to transitivity, **A4** to the euclidean property and **A5** to the serial property.

2.6. A Theory of Trust

The beliefs that an agent has may not be true in the real world. Trusts, encoded as proper axioms, are used to derive the truth (or falsity) of beliefs. A *trust* is any proper axiom added to the modal logic of belief presented in Section 2.3, i.e., any WFF that is assumed to be valid in addition to the axioms in the logic. In the logic, we started with no assumptions about the security behavior of agents. In the theory, we explicitly add the necessary assumptions in a precisely codified manner, and these assumptions are regarded as trusts. The simplest trusts are implications of the form, $B_i F \Rightarrow F$, where F is a WFF. Since any WFF can be regarded as a trust specification, this approach gives a lot of power and generality to expressing trust relationships [Ven88]. Security theories [Lan81], which are first-order, can be incorporated into our theory of trust.

As was observed in Section 2.2, adding proper axioms to a logic results in a theory. Let us assume that we have a theory consisting of the modal logic of belief and some trusts (which are the proper axioms). What are the effects of adding a new trust to an existing theory ? If the theory is decidable [4] and the new trust can be proved as a theorem in the theory, there is no need to add the new trust. If the new trust is not a theorem, adding it gives rise to a new theory. If the new trust does not invalidate the old theory [5], the monotonicity of the logic is retained and the new theory will continue to be complete with respect to the old model. However, the new theory is no longer sound with respect to the old semantic model (i.e., the semantic model corresponding to the old theory). Thus, a new model has to be constructed so that the new theory is sound and complete with respect to the new model. Proving soundness of the new theory w.r.t. the new model is usually easy, but proving completeness is more often than not cumbersome, non-intuitive, and difficult. However, the possible worlds semantic model is highly amenable to *incremental* modification such that the new theory is sound and complete with respect to the modified model. The modification consists of adding new constraints to possibility relations ρ_1, ..., ρ_m in the Kripke structure (this will be illustrated in the next section). This is exactly the reason why the possible worlds model was chosen: it provides a powerful

[4] A theory is *decidable* if, for any WFF in the theory, it can be determined whether the WFF is satisfiable or not.

[5] The following three statements are equivalent to each other: (1) a WFF does not invalidate a theory, (2) the negation of a WFF cannot be proved as a theorem, (3) a WFF is satisfiable in the theory.

and flexible framework for *customizing* a logic.

A trust specification can be thought of as an abstract representation of a policy in the distributed system. The next step is pragmatic: Given a trust policy, what are the protocols necessary to ensure that the policy holds in the system ? The following section illustrates the method for synthesizing protocols from a given abstract trust specification.

2.7. Synthesizing Protocols from Abstract Trust Specifications

Consider a distributed system in which there are three agents A_i, A_j and A_k. Let Q be any WFF. Let "$\forall Q, B_j B_i B_k Q \Rightarrow B_i B_j B_k Q$" be the given trust specification that is to be implemented in the distributed system. Informally, this trust specification says that, for all well-formed formulas Q, if A_j believes that A_i believes that A_k believes Q, it is necessary that A_i believes that A_j believes that A_k believes Q. This particular trust specification may not correspond to any particularly useful notion of trust in a real system. However, it serves as a good example for illustrating how an abstract trust specification can be translated into concrete distributed system protocols.

To see clearly the advantages of the formal theory of trust, let us first look at the solution that an informal analysis might yield. For the trust to hold, A_i has to believe $B_j B_k Q$ before A_j believes $B_i B_k Q$. A_i's belief can be created by a message from A_j containing $B_j B_k Q$. A_j's belief can be created by a message from A_i containing $B_i B_k Q$. Thus, for the trust to hold, A_j sends a message containing $B_j B_k Q$ to A_i before A_i sends a message containing $B_i B_k Q$ to A_j.

Let us now see what the formal techniques yield. The outline of the formal method is as follows: Given a WFF such as "$B_j B_i B_k Q \Rightarrow B_i B_j B_k Q$" as the trust specification, we semantically interpret it. For this WFF, interpreting the beliefs in the antecedent and the consequent yields possibility relations, which contain pairs of states. For the consequent to be true whenever the antecedent is true, the possibility relations of the consequent must be subsets of those of the antecedent. Possibility relations are nothing but sets of pairs of states, and hence we obtain relationships between the set of states of the antecedent and the set of states of the consequent. States are nothing but message histories, and thus we obtain relationships between message histories of agents, which with some more manipulation are reduced to such conditions as, for instance, that an agent must send/receive a particular message before or after sending/receiving some other message, and so on.

The given trust specification is required to be true in all system states. Let the state of the system be s, and the states of A_i, A_j and A_k be s_i, s_j and s_k respectively (see Figure 2.3). If the antecedent $B_j B_i B_k Q$ of the trust specification is not true in s, the trust specification "$B_j B_i B_k Q \Rightarrow B_i B_j B_k Q$" is trivially true in s. Suppose the antecedent is true in s. The antecedent is created by a message received by A_j such that the message sender field is A_i and the message contains $B_i B_k Q$. Thus, the message exchanges specified by condition M_s below must have taken place in s:

Message Condition M_s: A_j receives $B_i B_k Q$ from A_i.

Since s is the real state (as opposed to a possible state) of the system, we say:

State Condition C_s: s is the real system state.

The antecedent $B_j B_i B_k Q$ is a belief. Its semantic interpretation is that there is a possible state t such that $(s, t) \in \rho_j$, and the message exchanges specified by condition M_t below must have taken place in t:

Message Condition M_t: A_i sends $B_i B_k Q$ to A_j.

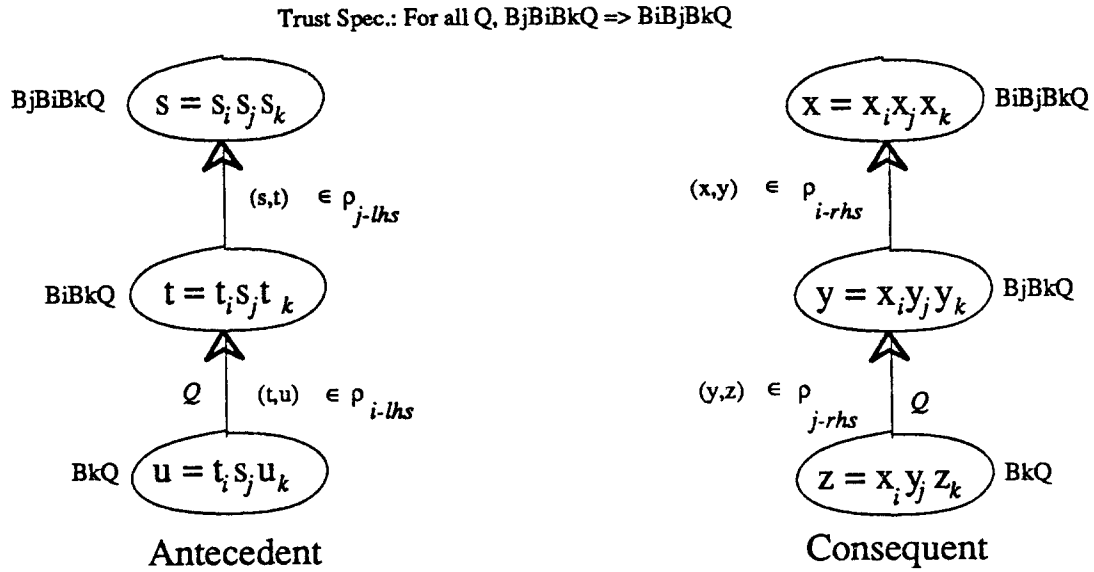

Figure 2.3: The Kripke structure semantic interpretation of the trust $B_jB_iB_kQ$ => $B_iB_jB_kQ$. The local states of A_i, A_j, and A_k in the various global states have been derived using the possibility conditions PC1, PC2 and PC3. For example, in global state t, the local state of A_i is t_i, the local state of A_j is s_j, and the local state of A_k is t_k. States s and x are real states. All other states are possible states.

Since t is a possible state, the possibility conditions PC1, PC2 and PC3 must be satisfied in t:

State Conditions C_t:

(a) $t_j = s_j$.

(b) There is an authenticated channel from A_i to A_j,

(c) A_i sends a message B_iB_kQ only if it believes B_kQ, i.e., only if A_i has received B_kQ from A_k. In other words, A_i does not lie about its beliefs to A_j.

Now consider state t. By M_t and C_t, A_i believes B_kQ, i.e., B_iB_kQ is true. If we further interpret B_iB_kQ, we obtain that in state t there is a possible state u such that $(t, u) \in \rho_i$, and the message exchanges specified by condition M_u must have taken place in u:

Message Condition M_u: A_k sends B_kQ to A_i.

Since u is a possible state, the possibility conditions PC1, PC2 and PC3 must be satisfied in u:

State Conditions C_u:

(a) $u_k = t_k$.

(b) There is an authenticated channel from A_k to A_i.

(c) A_k believes Q, i.e., A_k has not lied about its beliefs to A_i.

This concludes the interpretation of the antecedent. Let us now interpret the consequent, $B_iB_jB_kQ$. For $B_iB_jB_kQ$ to be true in a real system state x, A_i must have received B_jB_kQ from A_j in x:

Message Condition M_x: A_i has receives B_jB_kQ from A_j.

Since x is a real state of the system, we say:

State Condition C_x: x is the real state of the system.

The belief $B_iB_jB_kQ$ of the consequent is interpreted in exactly the same way as that of the antecedent, and we obtain that there must be a possible state y such that $(x, y) \in \rho_i$, and the message exchanges specified by M_y below must have taken place in y:

Message Condition M_y: A_j sends B_jB_kQ to A_i.

Since y is a possible state, the possibility conditions must be satisfied in y:

State Conditions C_y:

(a) $y_i = x_i$.

(b) There is an authenticated channel from A_j to A_i.

(c) A_j believes in B_kQ, i.e., A_j has received B_kQ from A_k. In other words, A_j has not lied about its beliefs to A_i.

Interpreting B_jB_kQ in y yields that there must be a possible state z such that $(y, z) \in \rho_j$, and the following message exchange must have taken place in z:

Message Condition M_z: A_k sends B_kQ to A_j.

Since z is a possible state, the possibility conditions must be satisfied in z:

State Conditions C_z:

(a) $z_k = y_k$.

(b) There is an authenticated channel from A_k to A_j.

(c) A_k believes Q is true, i.e., A_k has not lied about its beliefs to A_j.

This concludes the interpretation of the consequent.

Let ρ_{i-lhs}, ρ_{j-lhs}, and ρ_{k-lhs} denote the possibility relations of A_i, A_j, and A_k, respectively, on the antecedent side, and ρ_{i-rhs}, ρ_{j-rhs}, and ρ_{k-rhs} denote the possibility relations of A_i, A_j, and A_k, respectively, on the consequent side. The trust specification requires that the consequent be true whenever the antecedent is true. Since the beliefs of the antecedent and consequent are determined by their respective possibility relations [6], the possibility relations required for the consequent must be subsets of the possibility relations required for the antecedent. This yields two constraints, R1 and R2:

Constraint R1: ρ_{i-rhs} must be a subset of ρ_{i-lhs}. ρ_{i-rhs} contains (x, y), and ρ_{i-lhs} contains (t, u). Thus, the set of pairs of states, $\{(x, y)\}$ must be a subset of $\{(t, u)\}$. Thus set of states, $\{x\}$ must be a subset of $\{t\}$, and $\{y\}$ must be a subset of $\{u\}$ [7]. If a set of states $\{r_1\}$ is to be a

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[6] See Section 2.3.3.

[7] Sets of states are used in place of single states because, the various state and message conditions do not uniquely specify the states, rather they define sets of states.

subset of a set of states $\{r_2\}$, the state conditions of r_1 must be satisfied in r_2 and the message exchange conditions of r_1 must be satisfied prior to the message exchange conditions of r_2 (i.e., the message history of r_1 must be a subset of the message history of r_2). Thus "$\{x\}$ must be a subset of $\{t\}$" yields:

R1.1: C_x must be satisfied in C_t. Thus, in the system's real state, A_i must have an authenticated channel to A_j, and A_i must send B_iB_kQ to A_j only after receiving a message containing B_kQ from A_k.

R1.2: M_x must be satisfied prior to M_t. Thus, A_i must receive B_jB_kQ from A_j before sending B_iB_kQ to A_j.

Since we are only interested in constraints that affect real system states (rather than possible states), and since both y and u are possible states, we will not elaborate on the result that $\{y\}$ must be a subset of $\{u\}$.

Constraint R2: ρ_{j-rhs} must be a subset of ρ_{j-lhs}. Thus, $\{(y, z)\}$ must be a subset of $\{(s, t)\}$. Therefore, $\{y\}$ must be a subset of $\{s\}$, and $\{z\}$ must be a subset of $\{t\}$. "$\{y\}$ must be a subset of $\{s\}$" yields:

R2.1: C_y must be satisfied in C_s. In A_j's real state, A_j must have an authenticated channel to A_i, and A_j must send B_jB_kQ to A_i only after receiving a message B_kQ from A_k.

R2.2: M_y must be satisfied prior to M_s. Thus, A_j must send B_jB_kQ to A_i before receiving B_iB_kQ from A_i.

Notice that from R1 we have "$\{y\}$ must be a subset of $\{u\}$", and from R2 we have "$\{y\}$ must be a subset of $\{s\}$". Thus, the state conditions of u and s must be identical:

R2.3: u must be a real state, and hence, in A_k's real state, A_k must have an authentic message channel to A_i, and A_k must send Q to A_i only if it believes Q.

R2 also yields that $\{z\}$ must be a subset of $\{t\}$. Thus:

R2.4: C_z must be satisfied in C_t. In the system's real state, by R 1.1, C_t is satisfied, and hence C_z must be satisfied. Hence in the system's real state, A_k must have an authentic message channel to A_j, and A_k must send B_kQ to A_j only if it believes Q.

R2.5: M_z must be satisfied prior to M_t. But M_t may become satisfied at any instant after M_u. Hence, M_z must be satisfied prior to M_u. Thus, A_k must send B_kQ to A_j before sending it to A_i.

This concludes the derivation of the constraints that are necessary and sufficient for $B_jB_iB_kQ \Rightarrow B_iB_jB_kQ$ to hold in the distributed system. Notice that the constraints we have derived are in fact the protocols that agents A_i, A_j and A_k must follow if the trust is to be satisfied in the system. Since in this procedure we map a trust to its semantic interpretation, we obtain the protocols that are necessary and sufficient for the trust to hold. Any WFF can be mapped to its semantic interpretation, and hence semantic interpretation can be carried out for any trust resulting in the protocols necessary and sufficient for the trust to hold. Since we have not made any particular assumptions with respect to the nature of the system, its models, or the trusts, this methodology of obtaining protocols necessary and sufficient for a given trust to hold is general in its applicability to trusts, systems, and their models. Even for such a simple trust specification which involves just three agents, the constraints that we obtained earlier using a casual interpretation form a small subset of those we have obtained using a formal interpretation. Thus, formalism is essential, and mere intuition is not dependable.

It can be shown that, if any of the constraints R1.1, R1.2, R2.1, R2.2, R2.3, R2.4 and R2.5 are not satisfied, this may result in a violation of the trust. Let us illustrate this by an example. Suppose part of constraint R2.1, namely,

"A_j sends $B_jB_k\tilde{Q}$ to A_i only after receiving a message containing B_jQ from A_k",

is not satisfied in a system. The trust specification "$\forall\ Q, B_jB_iB_kQ \Rightarrow B_iB_jB_kQ$" is falsified at the end of the following sequence of steps (see Figure 2.4):

Step 1 (Figure 2.4(a)): B_kQ is true. A_j sends "$B_jB_k\tilde{Q}$" to A_i, and this creates a belief "$B_iB_jB_k\tilde{Q}$" in A_i.

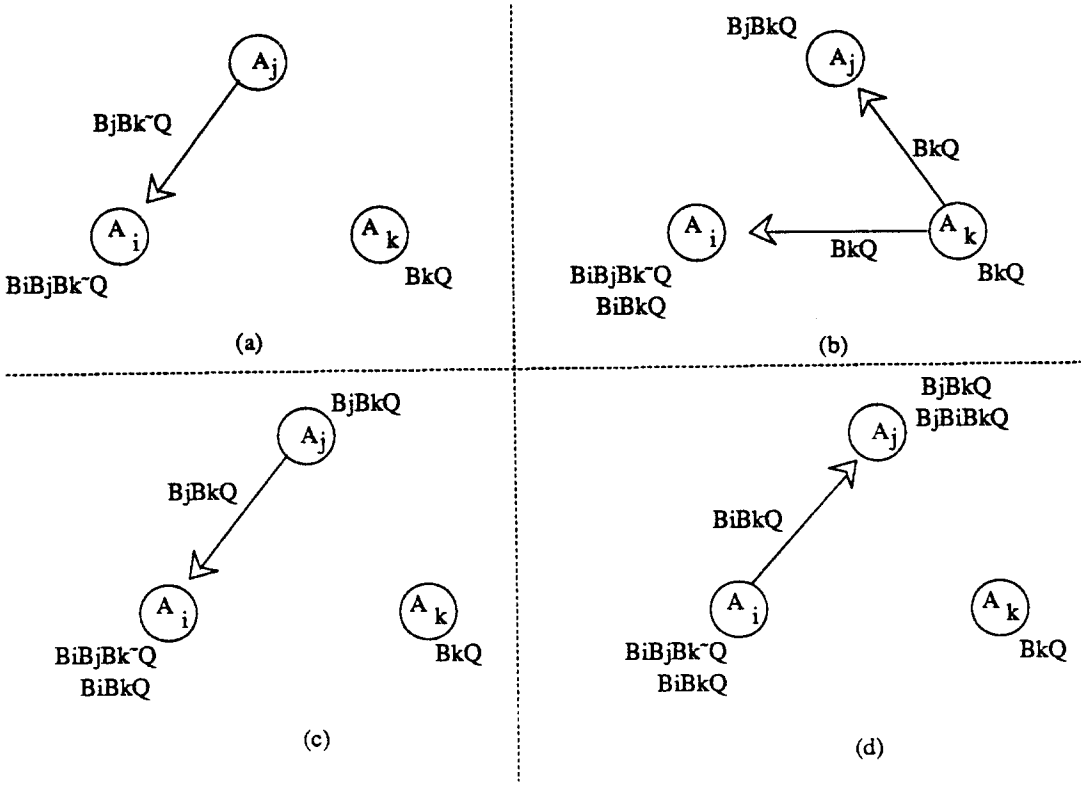

Figure 2.4: A scenario which shows that the trust can be falsified if constraint R2.1 is not satisfied. (a) The sending of $B_jB_k\tilde{Q}$ by A_j to A_i creates a belief $B_iB_jB_k\tilde{Q}$ in A_i. (b) The sending of B_kQ by A_k to A_i and A_j creates beliefs B_iB_kQ and B_jB_kQ. (c) The sending of B_jB_kQ by A_j to A_i is rejected by A_i as it is inconsistent with the message A_i received from A_j in (a). (d) The sending of B_iB_kQ by A_i to A_j creates a belief $B_jB_iB_kQ$. Since $B_iB_jB_kQ$ is not true, the trust is falsified at this juncture.

Step 2 (Figure 2.4(b)): A_k sends its belief "B_kQ" first to A_j and then to A_i. At this point, both A_j and A_i have belief "B_kQ".

Step 3 (Figure 2.4(c)): A_j sends "B_jB_kQ" to A_i. Since A_i has earlier received "$B_jB_k\tilde{}Q$" from A_j in step 1, and since "B_kQ" is inconsistent with "$B_k\tilde{}Q$", A_i rejects the message from A_j containing "B_jB_kQ". Notice that the trust $B_jB_iB_kQ \Rightarrow B_iB_jB_kQ$ is *not* violated. This is because the trust is violated only when the antecedent of the trust $B_jB_iB_kQ$ is true but the consequent $B_iB_jB_kQ$ is not true. However, at the end of this step the antecedent is not true.

Step 4 (Figure 2.4(d)): A_i sends its belief "B_iB_kQ" to A_j. This creates a belief "$B_jB_iB_kQ$" in A_j. Thus the antecedent of the trust $\forall\ Q, B_jB_iB_kQ \Rightarrow B_iB_jB_kQ$ *is* true. But the consequent $B_iB_jB_kQ$ is *not* true (recall that $B_iB_jB_k\tilde{}Q$ is true at the end of step 1), and hence the trust "$B_jB_iB_kQ \Rightarrow B_iB_jB_kQ$" becomes false.

2.8. Conclusion

We have developed an axiomatic theory of trust in distributed systems. The theory of trust is based on modal logics of belief. Any well formed formula assumed to be valid in addition to the axioms of the logic is considered as a trust specification. This gives us much power and generality in expressing trust relationships. We have given a formal method for synthesizing protocols which are necessary and sufficient for implementing a given trust specification in a distributed system. In comparison, even for some simple trust specifications, informal methods do not yield all the required protocols. In Kripke's theory, any well formed formula can be given a semantic interpretation, and since our method of synthesizing protocols that are necessary and sufficient for a trust to hold is based on giving a semantic interpretation to the trust, our method is general in its applicability to trusts, systems, and their models.

CHAPTER 3

ANALYSIS

Trust arises primarily in establishing channels for secure communication. This chapter analyzes the trust properties of various channel establishment mechanisms. We define a channel precisely and show that the only way to establish a new channel is by composing a sequence of existing adjacent channels. Channel composition mechanisms are commonly based on either public key encryption (PKE) or single key encryption (SKE). We present methods for reasoning about the trust characteristics of PKE- and SKE-based channel composition mechanisms. PKE-based channel composition requires 3-agent trust predicates called *authenticity trusts*. The trust requirements of SKE-based channel composition are much more extensive than those of PKE-based channel composition. The differences in trust properties of PKE and SKE-based channel compositions are used to compare these two methods, and derive several advantageous properties of the former over the latter.

3.1. Introduction

It was observed in Chapter 1 that in any system, given a set of existing channels, the only way to establish new channels is by *composing* a sequence of adjacent existing channels. Channel composition mechanisms may require the satisfaction of some trust relationships. Having given a precise meaning to the notion of trust in the previous chapter, we analyze the trusts inherent in various channel composition mechanisms in this chapter. The next chapter discusses the synthesis of distributed systems so as to satisfy a given set of trust relationships. The analyses presented in this chapter must precede the design methodology of the next chapter because, to be able to make use of a mechanism in a distributed system that is designed to satisfy a given set of trusts, one has to know the trust properties of the mechanism. These analyses provide insight into the basic structure and the limitations of mechanisms with regard to their trust requirements.

In Section 3.2 we define a channel precisely, and prove that the only way to establish new channels is by composing existing channels. In order to analyze trusts formally in various channel composition mechanisms, the fundamental actions in the mechanisms must be encoded in the language of the logic of trust. Section 3.3 introduces the atomic propositions that encode these fundamental actions. Channels are based on encryption, and there are two commonly used encryption techniques, namely, public key encryption (PKE) and single key encryption (SKE). Sections 3.4-3.7 analyze the trust relationships required in PKE- and SKE-based channel composition mechanisms, with Sections 3.4 and 3.5 considering the composition of two channels, and Sections 3.6 and 3.7 considering the composition of more than two channels. Making use of the results of these formal analyses, Section 3.8 discusses the advantages of PKE-based mechanisms over SKE-based mechanisms for channel composition. Finally, Section 3.9 concludes the chapter.

3.2. Channels

In order to analyze trusts in channel composition mechanisms, we first have to define a *channel* precisely.

3.2.1. Definition of Channel

A *channel*(A_i, A_k) is said to exist between two agents A_i and A_k if and only if the following two conditions are satisfied (see Figure 3.1):

(1) **Authenticity Condition:** A_i can authenticate messages coming from A_k, i.e., A_i can determine whether a message it received has been really sent by A_k, and

(2) **Privacy Condition:** A_i can send a secret message to A_k, A_i knows the identities of agents other than A_k that can decrypt the secret message (because these agents might possess the key with which the secret message is encrypted), and the decryption of the secret message by those agents is acceptable to A_i.

Algorithms for ensuring both these conditions are executed at A_i using information such as encryption keys associated with A_k. The privacy condition is motivated by the observation that agents other than A_i and A_k may have been involved in establishing channel(A_i, A_k), in which case those agents may possess the channel encryption key and hence have the capability to decrypt secret messages on the channel. The privacy condition requires that A_i precisely know the identities of those agents. As we shall see in later sections, the agents that may possess the channel encryption key are those that are in the path between A_i and A_k in the system's name space, and with each such agent, A_i has to have a trust relationship that guarantees that the agent will not compromise the security of channel(A_i, A_k). In Chapter 4, we shall see how A_i can control the set of such agents. Notice that channel(A_i, A_k) involves messages in either direction and does not imply that messages can only flow from A_i to A_k. Channel(A_i, A_k) and channel(A_k, A_i) together form a *bidirectional channel* between A_i and A_k.

3.2.2. Channel Establishment

We now show that in any system, given a set of existing channels, the only way to establish a new channel is by composing a sequence of adjacent existing channels. Even though this result seems very intuitive, it is a very powerful result. As we shall see in Sections 3.4-3.7, this result greatly simplifies the analysis of trust properties of channel establishment mechanisms. A channel established by composing other channels is called a *dependent channel*. On the

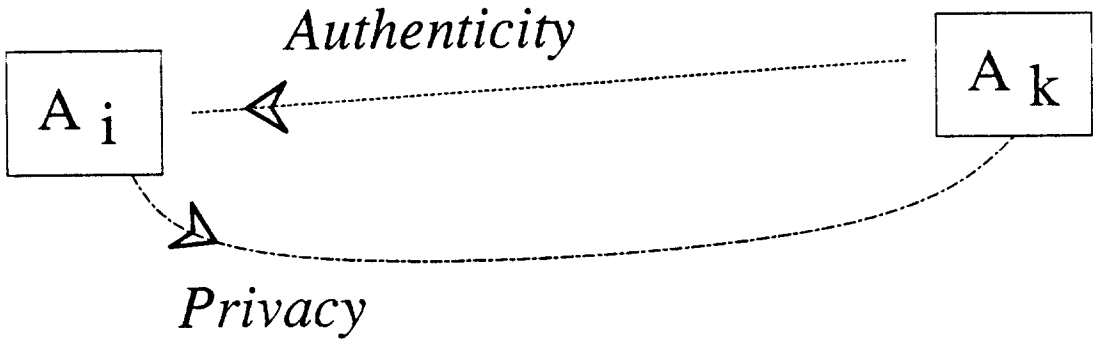

Figure 3.1: Channel(A_i, A_k)

other hand, an *independent channel* does not use any other channels for its establishment. The system provides independent channels at the time of system configuration. Independent channels are established using mechanisms external to the system, such as courier-exchanges between agents.

Theorem 3.1 (Channel Composition Theorem): Suppose that, in a system consisting of agents A_i, A_j^1, A_j^2, ..., A_j^n, A_k, the only existing channels are channel(A_i, A_j^1), channel(A_j^1, A_j^2), ..., channel(A_j^n, A_k), which form a path between A_i and A_k. Any mechanism that establishes channel(A_i, A_k) necessarily involves messages on all the existing channels, and the mechanism must necessarily consist of a succession of compositions of two adjacent channels.

Proof: The proof is by induction on the number of agents A_j^1, A_j^2, ..., A_j^n in the path between A_i and A_k.

Base Case: Suppose $n = 0$. The result is trivially true.

Induction Step: Assuming that the theorem holds for $n < m$, we show that it holds for $n = m$. Let the sequence of channels form the only path between A_i and A_k (see Figure 3.2). The establishment of channel(A_i, A_k) requires that A_k's encryption key be received by A_i. Since A_i can receive messages only on its existing channels, and since its only existing channel is channel(A_i, A_j^1), for channel(A_i, A_k) to be established, A_i must receive A_k's key in a message from A_j^1 on channel(A_i, A_j^1). Thus, a message on channel(A_i, A_j^1) is necessary, and A_j^1 must have possessed A_k's key prior to sending it to A_i. But A_j^1 possessing A_k's key implies that channel(A_j^1, A_k) exists. Consequently, channel(A_j^1, A_k) must have been established prior to A_j^1's sending of A_k's key to A_i. Hence, channel(A_i, A_k) was composed from two adjacent channels, channel(A_i, A_j^1) and channel(A_j^1, A_k), and the composition involved a message on channel(A_i, A_j^1). However, from the induction hypothesis, channel(A_j^1, A_k) involved messages

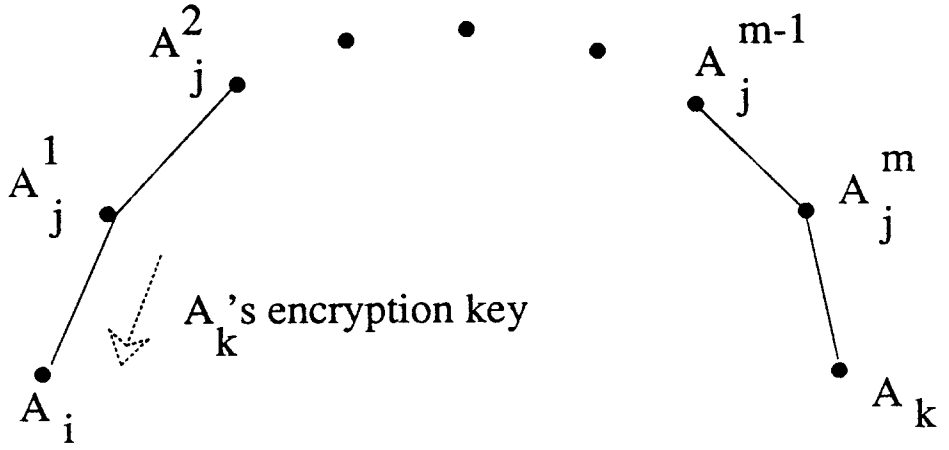

Figure 3.2: The Channel Composition Theorem

on all the channels in the path between A_j^1 and A_k, and hence channel(A_j^1, A_k) was the result of a succession of adjacent two-channel compositions between A_j^1 and A_k. Thus, any mechanism that establishes channel(A_i, A_k) must necessarily involve messages on all the existing channels, and must necessarily consist of a succession of adjacent two-channel compositions. This completes the proof of the Channel Composition Theorem.

□

Channel establishment, which is a sequence of adjacent channel compositions, requires trust relationships. The trust relationships required are such that, when they hold in the system, the authenticity and privacy conditions of the newly established channel are satisfied, and, when they do not hold, these conditions are not satisfied.

In the next few sections, we analyze the trust requirements of various channel composition mechanisms. The trust requirements depend on the algorithms used for ensuring the two channel conditions. We will consider the two commonly used kinds of these algorithms, namely, *public key encryption algorithms (PKE)* [DiH76,RSA78] and *single key encryption algorithms (SKE)* [NBS77].

In order to do a formal analysis of the various mechanisms, we have to encode the fundamental actions of the mechanisms into the language of the logic of trust. This is accomplished in the next section.

3.3. Atomic Propositions

Fundamental actions at a given level of abstraction are encoded in the language of the logic of trust by atomic propositions. Atomic propositions are so called because they are the most basic well formed formulas in the language of the logic, and an atomic proposition cannot be described in terms of any other atomic propositions. Thus, the set of atomic propositions is not unique to a system, but depends on the level of abstraction at which we are analyzing the system. For our analysis of trust relationships in PKE- and SKE-based channel composition mechanisms, the fundamental actions are key-generation, message-sending and message-reception. These are abstracted by the following atomic propositions:

(1) **owner($\mathbf{key_x}$, $\mathbf{A_i}$) (Ownership Proposition)**: PKE and SKE algorithms make use of encryption keys belonging to agents. Let a *key* denote an encryption key from a finite key space *KEY*. An ownership proposition encodes the generation of a key. **Owner($\mathbf{key_x}$, $\mathbf{A_i}$)** returns *true* if and only if *agent* A_i generated the encryption key key_x. Given a notion of feasible computation, it is assumed that an agent can generate keys (perhaps using random number generators) that cannot be generated using a feasible computation by any other agent [Den82]. Note that the generator of the key is always its owner. Thus, if a key server generates a key and hands it over to an agent, the key server retains the ownership of the key. In Section 3.4, we shall describe using beliefs the relationship between an agent and a key that the agent receives from a key server.

(2) **send($\mathbf{A_i}$, $\mathbf{msg_x}$)**: This atomic proposition abstracts the sending of a message msg_x by an agent A_i. Suppose msg_x can be derived using a feasible computation from another message msg_y. From the viewpoint of security, sending msg_y on a channel has also the effect of sending msg_x on the channel. Thus **send($\mathbf{A_i}$, $\mathbf{msg_x}$)** returns true if and only if A_i sends a message msg_y such that at the time of sending, A_i can derive msg_x from msg_y using a feasible computation. Msg_x can be identical to msg_y. Notice that a second agent A_j may be able to derive msg_z from msg_y; if A_i cannot derive msg_z from msg_y, then the

proposition is not true. In practice, msg_x is a message that can be obtained by decrypting msg_y using a key that A_i possesses.

(3) **receive(A_i, msg_x)**: This atomic proposition abstracts the receiving of a message msg_x by an agent A_i. Suppose msg_x can be derived from another message msg_y using a feasible computation. From the viewpoint of security, receiving msg_y on a channel has also the effect of receiving msg_x on the channel. Thus **receive(A_i, msg_x)** returns true if and only if A_i receives a message msg_y such that, at the time of receiving, A_i can derive msg_x from msg_y using a feasible computation.

We are now fully equipped to proceed with the analysis of trust relationships in channel composition mechanisms. For ease of understanding, the analysis considers the following cases separately (in the order of increasing complexity):

(1) Composition of two independent channels using PKE,

(2) Composition of two independent channels using SKE,

(3) Composition of two dependent channels using PKE or SKE, and

(4) Composition of more than two independent/dependent channels using PKE or SKE.

In the sequel, the composition of two independent channels will be termed *independent channel composition* and that of two dependent channels will be termed *dependent channel composition.*

3.4. Composition of Two PKE-based Independent Channels

Suppose channel(A_i, A_k) is to be obtained from channel(A_i, A_j) and channel(A_j, A_k). In the PKE scheme [DiH76, RSA78], each agent has a two keys, namely, a *public key* and a *private key* that form a pair. A message sent encrypted with a public key can only be received by decrypting it with the corresponding private key, and vice versa. To compose channel(A_i, A_k) from channel(A_i, A_j) and channel(A_j, A_k), A_k selects a (public key, private key) pair and sends the public key to A_j on channel(A_j, A_k) (see Figure 3.3). In practice, A_j may be a name server that stores A_k's public key. When A_i sends a request for A_k's public key to A_j, A_j forwards A_k's public key to A_i on channel(A_i, A_j). For channel(A_i, A_k) to be established, it is necessary and sufficient for A_i to know A_k's public key.

3.4.1. Trusts in PKE-based Channel Composition

Let us look at the PKE-based channel composition mechanism more formally. When A_k selects a public-key private-key pair (key_x^{pub}, key_x^{priv}), it adds a belief "$B_k owner(key_x^{pub}, A_k)$". Since the public key uniquely determines the private key, a second belief claiming ownership of the private key is redundant. Note that it is not necessary for A_k to be the owner of the key pair, it suffices if A_k believes to be the owner. Thus, an agent that does not have the ability to generate keys can obtain a key pair from some other agent and at its risk, use that key pair as its own.

A_k then sends its belief, $B_k owner(key_x^{pub}, A_k)$ to A_j, and this creates a belief, $B_j B_k owner(key_x^{pub}, A_k)$ in A_j. When A_j receives a request for A_k's public key from A_i, A_j replies with its belief, $B_j B_k$owner(key_x^{pub}, A_k). This reply from A_j to A_i creates a belief, $B_i B_j B_k owner(key_x^{pub}, A_k)$ in A_i.

However, the belief $B_i B_j B_k owner(key_x^{pub}\ A_k)$ is not sufficient for channel(A_i, A_k) to be established at A_i. For channel(A_i, A_k) to be established at A_i, A_i must prove that A_k believes key_x^{pub} to be its public key, i.e., A_i must prove that $B_k owner(key_x^{pub}, A_k)$ is true. A_i is not

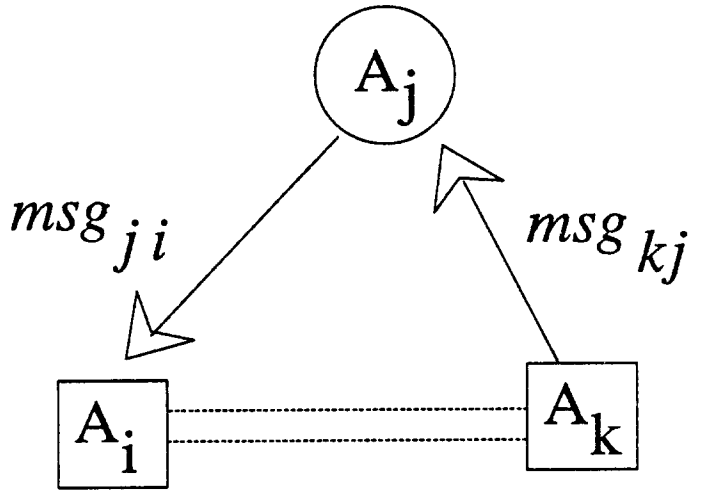

Figure 3.3: PKE-based channel composition mechanism

required to prove *owner* (key_x^{pub}, A_k) because it is permissible for A_i to obtain a key pair from a key server and to use the key pair as its own. In such a case the key server retains the ownership of the key pair, whereas A_i adds a belief B_k*owner* (key_x^{pub}, A_k). The required trust relationship must be such that A_i can infer $B_k$owner(key_x^{pub}, A_k) from its belief $B_iB_jB_k$*owner* (key_x^{pub}, A_k). Rewriting this requirement as a formula, we obtain the following trust for PKE-based channel composition:

$T_A(A_i, A_j, A_k)$ (Authenticity Trust): $\forall$ key_x^{pub} in the public-key space *PKEY*, $B_iB_jB_k$owner(key_x^{pub}, A_k) => $B_k$owner(key_x^{pub}, A_k).

The trust is called *authenticity trust* because its validity requires A_j to forward correctly to A_i the public key that A_j received from A_k. In other words, A_j has to forward *authentic* information about A_k to A_i.

Interpreting $T_A(A_i, A_j, A_k)$ as "A_i trusts A_j for A_k" gives a connotation that A_i is inevitably the only loser if $T_A(A_i, A_j, A_k)$ is not true. We will now show that falsity of $T_A(A_i, A_j, A_k)$ may be disadvantageous to either A_i or A_k, and hence $T_A(A_i, A_j, A_k)$ should be interpreted as an agreement involving A_i, A_j and A_k in which A_j has agreed to correctly forward A_k's key to A_i.

If we use a client-server model of a distributed system, there are two cases of interest with respect to the interaction between A_i and A_k (see Figure 3.4):

(1) A_i is a client and A_k is a server. As an example, let A_k be a time server. Suppose A_i sends a time-of-day request to A_k, and A_i receives a reply purporting to be from A_k. Falsity of $T_A(A_i, A_j, A_k)$ can result in A_i accepting a reply from another agent A_m which in collusion with A_j is masquerading as A_k. Thus, A_i accepts an incorrect time-of-day reply, and A_i is the loser for the falsity of $T_A(A_i, A_j, A_k)$.

(2) A_i is a server and A_k is a client. As an example, let A_i be a file server. Falsity of $T_A(A_i, A_j, A_k)$ can result in an agent A_m colluding with A_j to masquerade as A_k in sending a file-write request to the file server A_i. A_i accepts an incorrect write to A_k's file, and thus A_k is the loser for the falsity of $T_A(A_i, A_j, A_k)$. (A_i might be a loser too if it has to pay damages.)

In summary, falsity of $T_A(A_i, A_j, A_k)$ can be disadvantageous to either A_i or A_k or both, and hence $T_A(A_i, A_j, A_k)$ should be interpreted as an accord involving A_i, A_j and A_k, in which A_j has agreed to forward correctly A_k's key to A_i.

3.4.2. Necessity and Sufficiency of Authenticity Trust

Trust requirements depend on the channel composition mechanism under consideration. A set of trust relationships is sufficient w.r.t. a channel composition mechanism if, by using the trusts as assumptions, the two channel conditions presented in Section 3.2 can be shown to be satisfied for the newly composed channel. A set of trusts is necessary w.r.t. a channel composition mechanism if, for each assignment to the variables in the trusts that makes at least one of the trusts false, the same assignment also makes at least one of the two channel conditions not satisfied. If a set of trusts is necessary and sufficient w.r.t. a channel composition mechanism, the trusts in the set exactly encode the assumptions inherent in the channel composition mechanism. The following theorem proves that the authenticity trust is necessary and sufficient in PKE-based channel composition mechanism.

Theorem 3.2: The authenticity trust is necessary and sufficient w.r.t. PKE-based channel composition mechanism.

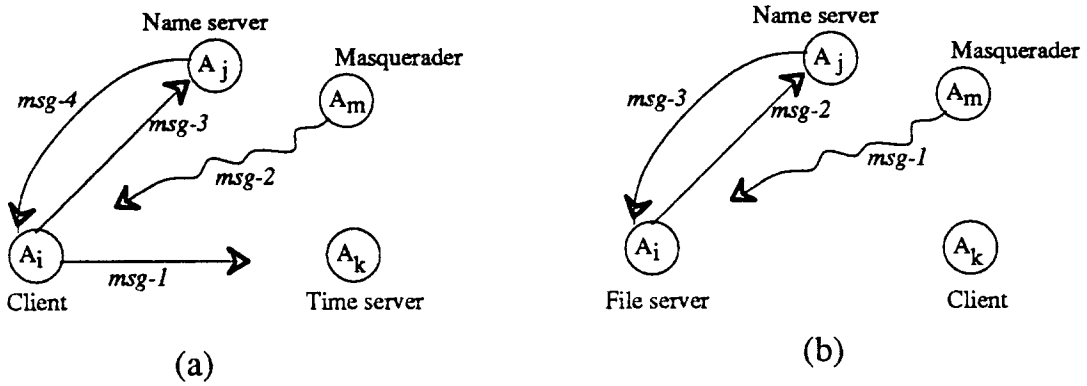

Figure 3.4: Interpreting authenticity trust: Illustration of how either A_i or A_k may lose owing to falsity of $T_A(A_i, A_j, A_k)$. A_m in collaboration with A_j, masquerades as A_k to A_i (a) $msg-1$ is a time request, $msg-2$ is a time reply from A_m $msg-3$ is a request for A_k's public key, and $msg-4$ is a reply containing A_m's public key. (b) $msg-1$ is a write-request to A_k's file, $msg-2$ is a request for A_k's public key, and $msg-3$ is a reply containing A_m's public key.

Proof: Suppose channel(A_i, A_j) and channel(A_j, A_k) are composed to form channel(A_i, A_k) using the PKE-based channel composition mechanism. We first show that the authenticity trust is sufficient, and then show that it is necessary.

The proof that authenticity trust is sufficient is straight-forward. For channel(A_i, A_k) to have been established, A_i must have received key_x^{pub} on its existing channel(A_i, A_j), hence $B_iB_jB_k$owner(key_x^{pub}, A_k) is true. By the authenticity trust, $B_k$owner(key_x^{pub}, A_k) must be true. Thus, A_k alone uses key_k^{priv} and the properties of public key encryption ensure the satisfaction of both the channel conditions. Thus, the authenticity trust is sufficient for channel(A_i, A_k) to be established.

Let "V", "Λ", and "$\neg$" denote inclusive OR, AND, and complementation respectively. To show that the authenticity trust is necessary, notice that this trust can be written as:

$$B_k owner(key_x^{pub}, A_k)\ V\ \neg B_iB_jB_k owner(key_x^{pub}, A_k). \tag{3.1}$$

The negation of formula (3.1) is:

$$\neg B_k owner(key_x^{pub}, A_k)\ \Lambda\ B_iB_jB_k owner(key_x^{pub}, A_k). \tag{3.2}$$

The only variable in the above formula is key_x^{pub}. Suppose that, for some assignment to key_x^{pub}, formula (3.2) is satisfied, i.e., both $\neg B_k$owner(key_x^{pub}, A_k) and $B_iB_jB_k$owner(key_x^{pub}, A_k) are true. Since $B_iB_jB_k$owner(key_x^{pub}, A_k) is true, A_i has received key_x^{pub} during the creation by composition of channel(A_i, A_k), and hence A_i uses key_x^{pub} as the key of channel(A_i, A_k). Thus, when A_i receives a message purporting to be from A_k, A_i uses key_x^{pub} for authenticating the received message. If the received message has been encrypted with key_x^{priv}, A_i determines that the message sender is A_k. However, since $\neg B_k$owner(key_x^{pub}, A_k) is true, A_k does not use key_x^{priv} to encrypt messages, and hence the message was not sent by A_k. Thus, the authenticity condition of channel(A_i, A_k) becomes false. Thus, if any assignment to the only variable in the authenticity trust makes the trust false, the same assignment can make the authenticity condition of channel(A_i, A_k) false. This completes the proof that authenticity trust is necessary w.r.t. the PKE-based channel composition mechanism.

□

There is another method by which we can show that the authenticity trust exactly encodes the assumptions inherent in PKE-based channel composition mechanism, and that is by viewing the trust as a well-formed formula in the logic of belief and carrying out its formal semantic interpretation. Techniques developed in Section 2.7 are used to carry out the formal semantic interpretation. The following section illustrates the method.

3.4.3. Semantic Interpretation of the Authenticity Trust

Let the state of the system be s. Consider the antecedent of the authenticity trust, $B_iB_jB_k$owner(key_x^{pub}, A_k). The semantic interpretation of this belief is that there is a possible state t such that $(s, t) \in \rho_i$ [1], and the following conditions are satisfied in t (see Figure 3.5):

(A1): The state of A_i is the same as that in s,

[1] ρ_i is A_i's possibility relation. The method of semantically interpreting a belief was described in Section 2.7.

(A2): there is an authenticated channel from A_j to A_i,

(A3): A_j has sent $B_jB_k$owner(key_x^{pub}, A_k) to A_i, and

(A4): $B_jB_k$owner(key_x^{pub}, A_k) is true, i.e., A_j has received "$B_k$owner(key_x^{pub}, A_k)" from A_k.

Now consider state t. By condition A4, $B_jB_k$owner(key_x^{pub}, A_k) is true in t, and interpreting this belief yields that there is a possible state u such that $(t, u) \in \rho_j$, and the following conditions are satisfied in u:

(A5): The state of A_j is same as that in t, hence conditions A2, A3 and A4 are satisfied in u,

(A6): there is an authenticated channel from A_k to A_j,

(A7): A_k has sent $B_k$owner(key_x^{pub}, A_k) to A_j, and

(A8): $B_k$owner(key_x^{pub}, A_k) is true.

Now consider the consequent of the authenticity trust, $B_k$owner(key_x^{pub}, A_k). The trust requires that in any state in which the antecedent is true, the consequent also be true. Since the antecedent is true in state s, we need also the consequent to be true in state s. Comparing condition A8 and the consequent, we obtain that the consequent is true in u. Thus, for the consequent to be true in s, it must be the case that $s = u$. However, in u, conditions A5, A6, A7 and A8 are satisfied. Thus, in the real state s, conditions A5, A6, A7 and A8 must be satisfied. But A5 requires that A2, A3 and A4 be satisfied. Thus, in real state s, A2, A3, A4, A6, A7 and A8 must be satisfied. Notice that these conditions are exactly the assumptions on which the PKE-based channel composition mechanism is founded:

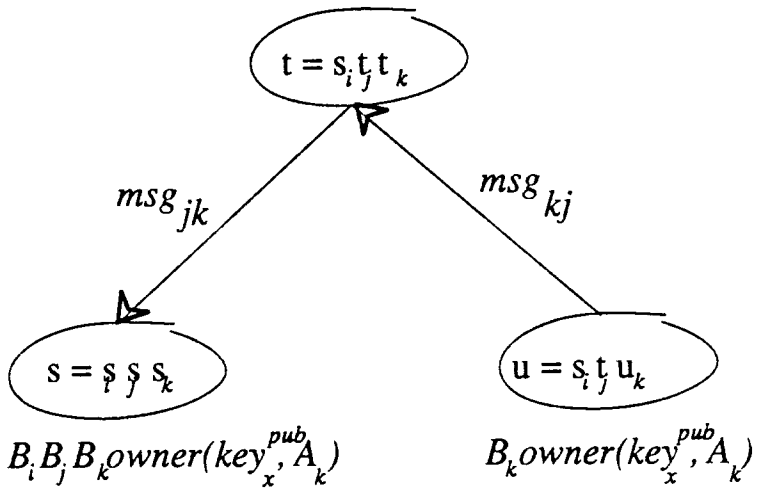

Figure 3.5: Semantic interpretation of authenticity trust

A2: Existence of channel(A_i, A_j),

A3 and A4: A_j correctly forwards A_k's key,

A6: Existence of channel(A_j, A_k), and

A7 and A8: A_k selects a public-key private-key pair and sends the public key to A_j.

This concludes the verification that the authenticity trust exactly encodes the assumptions inherent in the PKE-based channel composition mechanism, and hence the authenticity trust is necessary and sufficient w.r.t. the PKE-based channel composition mechanism.

3.5. Composition of Two SKE-based Independent Channels

Suppose that channel(A_i, A_k) is to be composed from channel(A_i, A_j) and channel(A_j, A_k). In the SKE scheme [NBS77], there is one key belonging to each agent, and the key is referred to as the agent's *single key*. A message sent encrypted with a single key can only be received by decrypting it with the very same single key, and vice versa. To obtain channel(A_i, A_k) from the composition of channel(A_i, A_j) and channel(A_j, A_k), A_k selects a single key and sends the single key to A_j in a message msg_{kj} on channel(A_j, A_k) (see Figure 3.6). When A_i sends a request for A_k's key to A_j, A_j forwards A_k's single key to A_i in a message msg_{ji} on channel(A_i, A_j). It is necessary for A_i to know A_k's single key for channel(A_i, A_k) to be established. Thus, the authenticity trust is necessary as in the PKE scheme.

There is a major difference between the PKE and SKE schemes with regard to trust requirements. In the PKE scheme, an agent such as A_j, even though it has obtained A_k's public key during channel composition, cannot masquerade as A_k or decrypt secret messages on channel(A_i, A_k). But in the SKE scheme, knowing A_k's single key enables A_j to masquerade as

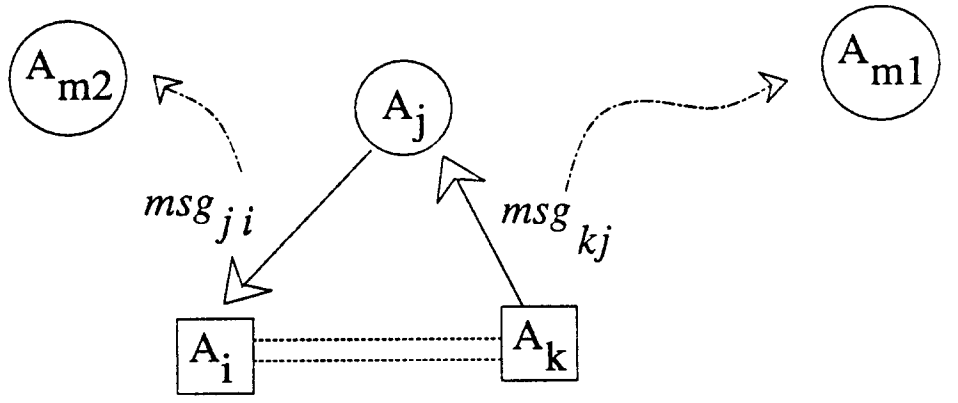

Figure 3.6: SKE-based channel composition mechanism

A_k and to decrypt secret messages by eavesdropping on channel(A_i, A_k).[2] Thus, authenticity and privacy conditions of channel(A_i, A_k) are not satisfied. Hence, the authenticity trust is not sufficient w.r.t. the SKE-based channel composition mechanism.

To determine the remaining trust requirements of the SKE scheme, notice that the definition of channel(A_i, A_k) requires A_i to know the set of agents other than A_i and A_k that can receive secret messages sent on channel(A_i, A_k). The set of agents that can decrypt secret messages on channel(A_i, A_k) are those that have obtained A_k's single key. During the channel establishment process, an agent may have obtained A_k's single key either when the key traversed the path from A_k to A_j in message msg_{kj} or when the key traversed the path from A_j to A_i in message msg_{ji}.

Consider an agent A_{m1} that may have obtained the key by receiving msg_{kj} [3]. Notice that, by definition, channel(A_k, A_j) allows A_k to send a secret message to A_j so that A_k knows the identity of agents who can decrypt the secret message. Thus the identity of agent A_{m1} is known to A_k if A_k sends msg_{kj} as a secret message on channel(A_k, A_j).

Now consider an agent A_{m2} that may have obtained the key by receiving msg_{ji}. By definition, channel(A_j, A_i) allows A_j to send a secret message to A_i so that A_j knows the identity of agents who can decrypt the secret message. Thus, the identity of agent A_{m2} is known to A_j if A_j sends msg_{ji} as a secret message on channel(A_j, A_i).

To ensure that A_i knows the identity of A_{m1} and A_{m2}, the following mechanism can be used: A_k sends the string "A_{m1}, $B_k$owner(key_x, A_k)" to A_j in a secret message msg_{kj} on channel(A_k, A_j). When A_j receives msg_{kj}, it decrypts msg_{kj} using the key of channel(A_k, A_j) and authenticates msg_{kj} using the key of channel(A_j, A_k) [4]. At this juncture, A_j knows the identities of both A_{m1} and A_{m2}. A_j sends the string "A_{m1}, A_{m2}, $B_jB_k$owner(key_x, A_k)" to A_i in a secret message msg_{ji} on channel(A_j, A_i). When A_i receives msg_{ji}, it decrypts msg_{kj} using the key of channel(A_j, A_i) and authenticates msg_{kj} using the key of channel(A_i, A_j).

The assumptions in the above mechanism are formally captured in the following trust definition:

$T_F(A_i, A_j, A_k)$ (Forwarding Trust): $\forall$ key_x, A_{m1}, A_{m2},

$B_iB_jB_k$*owner* (key_x, A_k) => (((send(A_j, key_x) Λ receive(A_{m2}, key_x)) => $B_iB_j$receive(A_{m2}, key_x)) Λ ((send(A_k, key_x) Λ receive(A_{m1}, key_x)) => $B_jB_k$receive(A_{m1}, key_x)) Λ ($B_jB_k$receive(A_{m1}, key_x) => $B_iB_jB_k$receive(A_{m1}, key_x))).

The antecedent in the above definition of forwarding trust encodes that A_i has received A_k's key through A_j.

The first term of the consequent, "(send(A_j, key_x) Λ receive(A_{m2}, key_x)) => $B_iB_j$receive(A_{m2}, key_x)" encodes that, if A_{m2} is able to obtain A_k's key by decrypting msg_{ji}, A_j informs A_i of A_{m2}'s identity.

The first factor in the second term of the consequent, "(send(A_k, key_x) Λ receive(A_{m1}, key_x)) => $B_jB_k$receive(A_{m1}, key_x)" encodes that, if A_{m1} is able to obtain A_k's key by

---

[2] Notice that, even if channel(A_i, A_k) does not physically go through A_j, A_j can still decrypt secret messages by eavesdropping on the channel.

[3] The set of agents {A_{m1}} may be empty, but that is only a special case.

[4] Notice that channel(A_k, A_j) is necessary for A_k to send a secret message to A_j, whereas channel(A_j, A_k) is necessary for A_j to authenticate a message sent by A_k.

decrypting msg_{kj}, A_k informs A_j of A_{m1}'s identity. The second factor, "$B_jB_k$receive(A_{m1}, key_x) => $B_iB_jB_k$receive(A_{m1}, key_x)" encodes that A_j correctly forwards the identity of A_{m1} to A_i.

To recapitulate, the forwarding trust allows A_i to determine the identities of all agents A_m that may have obtained key_x by decrypting msg_{kj} or msg_{ji}. Three more assumptions are necessary for the conditions of channel(A_i, A_k) to be satisfied. Firstly, A_m must not reveal key_x to any other agent A_l. This assumption is captured by the *Key Privacy Trust* below. Secondly, for the authenticity condition of channel(A_i, A_k) to be satisfied, A_m must not use key_x to masquerade on channel(A_i, A_k). This assumption is captured by the *Trust against Masquerading* defined below. Lastly, for the privacy condition of channel(A_i, A_k) to be satisfied, A_m must not decrypt and reveal a secret message sent on channel(A_i, A_k). This final assumption is captured by the *Message Privacy Trust* defined below.

$\mathbf{T_{KP}(A_l, A_m, A_k)}$ **(Key Privacy Trust):** $\forall\ key_x, B_iB_k owner(key_x, A_k) \Rightarrow \neg send(A_m, key_x)$.

$\mathbf{T_{AMasq}(A_l, A_m, A_k)}$ **(Trust against Masquerading):** $\forall\ msg_x$, (receive(A_i, msg_x) $\wedge$ $B_i$send(A_k, msg_x)) => ¬send(A_m, msg_x).

$\mathbf{T_{MP}(A_l, A_m, A_k)}$ **(Message Privacy Trust):** $\forall\ msg_x$, (send(A_i, msg_x) $\wedge$ $B_i$receive(A_k, msg_x) $\wedge$ receive(A_m, msg_x)) => ¬send(A_m, msg_x).

These three trusts are required of any agent that possesses A_k's key. The three trusts together form the **Key User-Possessor Trust**, denoted by $\mathbf{T_{KUP}}$.

The following theorem summarizes all the above results about SKE-based channel composition.

Theorem 3.3: Suppose that in a system there are agents A_i and A_k, and channel(A_i, A_k) is to be established using SKE-based composition. There must exist an agent A_j such that there are four channels, channel(A_i, A_j), channel(A_j, A_i), channel(A_j, A_k) and channel(A_k, A_j). The authenticity trust, the forwarding trust and the key user-possessor trust are necessary and sufficient w.r.t. SKE-based channel composition.

Proof: By the Channel Composition Theorem, there must exist an agent A_j such that there are channels (A_i, A_j) and (A_j, A_k). By the definition of forwarding trust, the forwarding trust requires privacy of messages from A_k to A_j, and from A_j to A_i. Thus, channel(A_k, A_j) and channel(A_j, A_i) are required for forwarding trust. We show below that the forwarding trust is necessary, and hence channel(A_k, A_j) and channel(A_j, A_i) are necessary.

We first show that the authenticity trust, the forwarding trust and the key user-possessor trust are sufficient, and then that they are necessary.

In SKE-based composition of channel(A_i, A_k) from channels (A_i, A_j) and (A_j, A_k), when A_i uses key_x for channel(A_i, A_k), it must have received key_x on its existing channel with A_j, and hence $B_iB_jB_k$owner(key_x, A_k) is true. Applying the authenticity trust, $B_k$owner(key_x, A_k) is true. Thus, A_k uses key_x to send messages to A_i and to receive secret messages from A_i. We have to show that no other agent possessing key_x compromises the two conditions of channel(A_i, A_k).

Consider a fourth agent that possesses key_x. The agent must have obtained key_x either (1) directly from A_j or A_k, or (2) indirectly from A_j or A_k, i.e., through a sequence of agents, starting with some agent that received directly from A_j or A_k. Since the forwarding trust $T_F(A_i, A_j, A_k)$ is true, A_i knows the identities of all agents A_m that have obtained key_x directly from A_j or A_k. Since the key privacy trust $T_{KP}(A_i, A_m, A_k)$ is true, no such agent A_m can obtain key_x indirectly. For each A_m, the trust against masquerading is true, hence no other agent except A_k

sends messages using key_x and the authenticity condition of channel(A_i, A_k) is satisfied. For each A_m, the message privacy trust is true, and hence no other agent except A_k, A_j and A_m obtain a secret message sent by A_i using key_x. But A_i knows the identities of A_k, A_j and A_m, and hence the privacy condition of channel(A_i, A_k) is satisfied. Thus, the trusts are sufficient for channel(A_i, A_k) to be established.

The proof that the authenticity trust is necessary is the same as that in Theorem 3.2.

We now show that each assignment to the variables key_x, msg_x, A_{m1}, A_{m2} and A_m that falsifies either the forwarding trust or the key privacy trust or the trust against masquerading or the message privacy trust can also falsify one of the two conditions of channel(A_i, A_k).

Consider the forwarding trust. Its negation can be written as:

$$(B_iB_jB_k owner(key_x, A_k) \Lambda send(A_j, key_x) \Lambda receive(A_{m2}, key_x) \Lambda$$

$$\bar{B}_iB_j receive(A_{m2}, key_x)) V (B_iB_jB_k owner(key_x, A_k) \Lambda send(A_k, key_x) \Lambda$$

$$receive(A_{m1}, key_x) \Lambda \bar{B}_jB_k receive(A_{m1}, key_x) V (B_iB_jB_k owner(key_x, A_k) \Lambda$$

$$B_jB_k receive(A_{m1}, key_x) \Lambda \bar{B}_iB_jB_k receive(A_{m1}, key_x)) \quad (3.3)$$

In the above expression, if the first disjunct is satisfied, A_i uses key_x as the key of channel(A_i, A_k), A_{m2} receives key_x, but A_i does not receive the identity of A_{m2}. Thus, the second channel condition is not satisfied. If either the second or the third disjunct is satisfied, A_i uses key_x as the key of channel(A_i, A_k), A_{m1} receives key_x, but A_i does not receive the identity of A_{m1}. Thus, again, the second channel condition is not satisfied. Hence the forwarding trust is necessary.

The negation of the message privacy trust can be written as follows:

$$send(A_i, msg_x) \Lambda B_i receive(A_k, msg_x) \Lambda receive(A_m, msg_x) \Lambda$$

$$send(A_m, msg_x) \quad (3.4)$$

If expression (3.4) is satisfied, A_i sends a secret message msg_x to A_k, A_m is able to decrypt msg_x, and A_m sends msg_x to some other agent. In this instance, the privacy condition of channel(A_i, A_k) is not satisfied.

The negation of the key privacy trust can be written as follows:

$$B_iB_k owner(key_x, A_k) \Lambda send(A_m, key_x) \quad (3.5)$$

If expression (3.5) is satisfied, A_i uses key_x as the key of channel(A_i, A_k), and A_m sends key_x to some other agent whose identity A_i may not know. Thus, the privacy condition of channel(A_i, A_k) is not satisfied.

The negation of the trust against masquerading can be expressed as:

$$receive(A_i, msg_x) \Lambda B_i send(A_k, msg_x) \Lambda send(A_m, msg_x) \quad (3.6)$$

If expression (3.6) is satisfied, A_i receives a message msg_x, A_i determines that the sender of msg_x is A_k, but the true sender of msg_x is A_m. Thus, the authenticity condition of channel(A_i, A_k) is not satisfied.

All of the above trusts, i.e., the authenticity trust, the forwarding trust, the key privacy trust, the trust against masquerading and the message privacy trust are necessary.

This concludes the proof of Theorem 3.3.

□

The key and message privacy trusts exhibit an interesting property. In SKE-based composition of channel(A_i, A_k) from channels (A_i, A_j) and (A_j, A_k), let the key of channel(A_j, A_i) be key_y. For channel(A_j, A_i) to exist, for each agent A_n that possesses key_y, message privacy trust $T_{MP}(A_j, A_n, A_i)$ must be true. When A_j sends A_k's key, key_x on channel(A_j, A_i), agent A_n can receive key_x. However, $T_{MP}(A_j, A_n, A_i)$ requires that A_n not reveal a message sent on channel(A_j, A_i) and hence not reveal key_x. The condition that A_n not reveal key_x is exactly the requirement of the key privacy trust, $T_{KP}(A_i, A_n, A_k)$. Thus, the validity of the key privacy trust, $T_{KP}(A_j, A_n, A_i)$, follows from the validity of the message privacy trust, $T_{MP}(A_j, A_n, A_i)$. This is summarized by the following theorem.

Theorem 3.4 (Privacy Trust Theorem): $\forall\ A_i, A_j, A_k, A_n, key_x$,

$(B_i B_j B_k \text{owner}(A_k, key_x) \wedge T_{MP}(A_j, A_n, A_i)) \Rightarrow T_{KP}(A_i, A_n, A_k)$.

□

3.6. Composition of Two Dependent Channels

Suppose that channel(A_i, A_k) is to be composed from channels (A_i, A_j) and (A_j, A_k). Let channels (A_i, A_j) and (A_j, A_k) be dependent channels with channel(A_i, A_j) having been composed earlier from channels (A_i, A_1^1), (A_1^1, A_2^1), ..., (A_n^1, A_j), and with channel(A_j, A_k) having been composed earlier from channels (A_k, A_1^2), (A_1^2, A_2^2), ..., (A_m^2, A_k) (see Figure 3.7). Being dependent channels, channels (A_i, A_j) and (A_j, A_k) have some trust requirements, and these trust requirements get carried over to channel(A_i, A_k). In contrast, component channels in independent channel composition have no trust requirements.

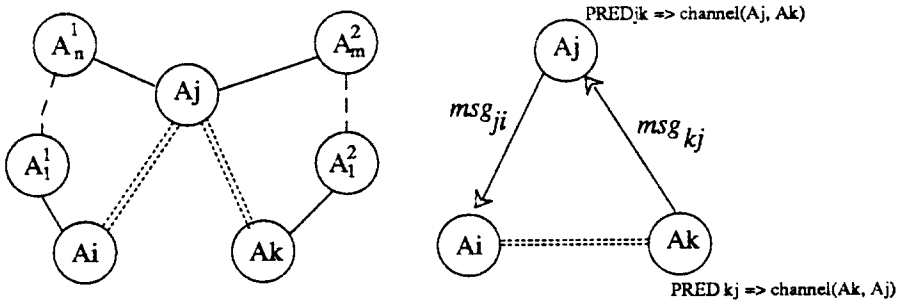

Figure 3.7: Dependent channel composition

The channel composition mechanism is identical in independent and dependent channel composition, but the trust requirements are different. To see why, let A_k send its key, key_x, to A_j in a message msg_{kj}, and let A_j forward key_x to A_i in a message msg_{ji} to A_i. Key_x is a public key in the PKE scheme and a single key in the SKE scheme. In the SKE scheme msg_{kj} and msg_{ji} are both secret messages encrypted using the algorithms of channels (A_k, A_j) and (A_j, A_i) respectively. In both SKE and PKE schemes, when A_j receives msg_{kj}, A_j authenticates msg_{kj} using the algorithm of channel(A_j, A_k), and when A_i receives msg_{ji}, A_i authenticates msg_{ji} using the algorithm of channel(A_i, A_j). However, the validities of these algorithms are contingent upon the satisfaction of the trust requirements of the respective channels with which the algorithms are associated. Thus the validities of messages msg_{kj} and msg_{ji}, and the validity of key_x transmitted in these messages, are dependent upon the trust requirements of the component channels.

Let us compute exactly the effects of the trust requirements of the component channels on the validity of key_x. The trust requirements of the component channels can in general be expressed as *trust predicates*, which are boolean combinations of the trusts such as the authenticity trust, the forwarding trust, etc. Given the truth or falsity of the various trusts in these boolean combinations, trust predicates can be evaluated to true or false. The satisfaction of a trust predicate associated with a channel is necessary and sufficient for the satisfaction of the authenticity and privacy conditions (given in Section 3.2) of the channel. Let $pred_{kj}$, $pred_{jk}$, $pred_{ji}$ and $pred_{ij}$ denote the trust requirements of channels (A_k, A_j), (A_j, A_k), (A_j, A_i) and (A_i, A_j) respectively [5]. The effects of these trust predicates on channel(A_i, A_k) are computed in four steps:

(1) A_k sends its key, key_x to A_j in msg_{kj}: In the PKE scheme, there are no trust-related computations [6] at this step of the mechanism. In the SKE scheme, msg_{kj} is sent as a secret message, and A_k has to compute the set set_{m1} of all agents A_{m1} that can decrypt msg_{kj}. For each A_{m1}, a key user-possessor trust involving A_i, A_{m1} and A_k is required. Let $T_{KUP}(A_i, set_{m1}, A_k) = \{T_{KUP}(A_i, A_{m1}, A_k) \mid A_{m1} \in set_{m1}\}$. The key user-possessor trust requirement is expressed as follows:

$$T_{KUP}(A_i, set_{m1}, A_k) => channel(A_i, A_k) \tag{3.7}$$

However, the set of agents that can decrypt msg_{kj} depends on the encryption algorithm of channel(A_k, A_j), which depends on $pred_{kj}$. This dependency is expressed by modifying formula (3.7) to:

$$pred_{kj} => (T_{KUP}(A_i, A_m, A_k) => channel(A_i, A_k)) \tag{3.8}$$

(2) A_j receives msg_{kj}: In both PKE and SKE schemes, A_j authenticates msg_{kj} using the algorithm of channel(A_j, A_k), which is dependent on $pred_{jk}$. This dependency in the PKE scheme is expressed as:

---

[5] If channel(A_k, A_j), channel(A_j, A_k), channel(A_j, A_i) and channel(A_i, A_j) had been independent channels, none of the trust predicates $pred_{kj}$, $pred_{jk}$, $pred_{ji}$ and $pred_{ij}$ would have been necessary, which is equivalent to saying that the trust predicates would have been equal to the boolean constant "TRUE".

[6] By *trust-related computation* at an agent we mean an encryption or decryption operation involving the key of another agent.

$$pred_{jk} => channel(A_i, A_k) \tag{3.9}$$

In the SKE scheme, this dependency is expressed by modifying formula (3.8) to:

$$pred_{jk} => (pred_{kj} => (T_{KUP}(A_i, set_{m1}, A_k) => channel(A_i, A_k))) \tag{3.10}$$

(3) A_j forwards key_x in msg_{ji} to A_i: In the PKE scheme there are no trust-related computations at this step of the mechanism. In the SKE scheme, the key user-possessor trust is required in all agents A_{m2} that can decrypt the secret message msg_{ji}. This requirement is expressed by modifying formula (3.10) to:

$$T_{KUP}(A_i, set_{m2}, A_k) => (pred_{jk} => (pred_{kj} => (T_{KUP}(A_i, set_{m1}, A_k) =>$$

$$channel(A_i, A_k)))) \tag{3.11}$$

However, the set of agents that can decrypt msg_{ji} depends on the encryption algorithm of channel(A_j, A_i), which depends on $pred_{ji}$. Thus, formula (3.11) gets modified to:

$$pred_{ji} => (T_{KUP}(A_i, set_{m2}, A_k) => (pred_{jk} => (pred_{kj} => (T_{KUP}(A_i, set_{m1}, A_k)$$

$$=> channel(A_i, A_k))))) \tag{3.12}$$

(4) A_i receives msg_{ji}: In the PKE scheme, the authenticity trust is required of A_j. This requirement is expressed by modifying formula (3.9) to:

$$T_A(A_i, A_j, A_k) => (pred_{jk} => channel(A_i, A_k)) \tag{3.13}$$

However, the validity of the determination of A_j as the sender of msg_{ji} is contingent upon the validity of the algorithm of channel(A_i, A_j) that A_i uses to authenticate msg_{ji}. This final dependency in the PKE scheme is expressed by modifying formula (3.13) to:

$$pred_{ij} => (T_A(A_i, A_j, A_k) => (pred_{jk} => channel(A_i, A_k))) \tag{3.14}$$

In the SKE scheme, three trusts involving A_i, A_j and A_k are required, namely, the authenticity trust, the forwarding trust and the key user-possessor trust. These trust requirements are expressed by modifying formula (3.12) to:

$$(T_A(A_i, A_j, A_k) \wedge T_F(A_i, A_j, A_k) \wedge T_{KUP}(A_i, A_j, A_k)) =>(pred_{ji} =>$$

$$(T_{KUP}(A_i, set_{m2}, A_k) =>(pred_{jk} => (pred_{kj} => (T_{KUP}(A_i, set_{m1}, A_k) =>$$

$$channel(A_i, A_k)))))) \tag{3.15}$$

However, the identity of A_j used in the above expression is authentic only if the algorithm of channel(A_i, A_j) used by A_i to authenticate the received message msg_{ji}, is valid. Thus, we obtain the following final expression for the SKE scheme:

$$pred_{ij} => ((T_A(A_i, A_j, A_k) \wedge T_F(A_i, A_j, A_k) \wedge T_{KUP}(A_i, A_j, A_k)) => (pred_{ji} =>$$

$$(T_{KUP}(A_i, set_{m2}, A_k) => (pred_{jk} => (pred_{kj} => (T_{KUP}(A_i, set_{m1}, A_k) =>$$

$$channel(A_i, A_k))))))) \tag{3.16}$$

The following two theorems summarize all the above results regarding trust requirements in PKE- and SKE-based dependent channel composition.

Theorem 3.5: Let dependent channels (A_i, A_j) and (A_j, A_k) be composed to form channel(A_i, A_k) using the PKE scheme. Let the trust predicates associated with the two component channels be $pred_{ij}$ and $pred_{jk}$, respectively. The trust requirements of channel(A_i, A_k) are expressed as follows:

$$pred_{ij} \Rightarrow (T_A(A_i, A_j, A_k) \Rightarrow (pred_{jk} \Rightarrow \text{channel}(A_i, A_k)))$$

□

Theorem 3.6: Let dependent channels (A_i, A_j), (A_j, A_k), (A_j, A_k) and (A_k, A_j) be composed to form (A_i, A_k) using the SKE scheme. Let the trust predicates associated with the four component channels be $pred_{ij}$, $pred_{ji}$, $pred_{jk}$ and $pred_{kj}$, respectively. Further, let the sets of agents that can decrypt secret messages on channel(A_k, A_j) and channel(A_j, A_i) be set_{m1} and set_{m2}, respectively. The trust requirements of channel(A_i, A_k) are expressed as follows:

$$pred_{ij} \Rightarrow ((TA(A_i, A_j, A_k) \wedge T_F(A_i, A_j, A_k) \wedge T_{KUP}(A_i, A_j, A_k)) \Rightarrow (pred_{ji} \Rightarrow (T_{KUP}(A_i, set_{m2}, A_k) \Rightarrow (pred_{jk} \Rightarrow (pred_{kj} \Rightarrow (T_{KUP}(A_i, set_{m1}, A_k) \Rightarrow \text{channel}(A_i, A_k)))))))$$

□

Notice that, since an independent channel is a special case of a dependent channel, in which the trust predicate associated with the channel is the constant "TRUE", a composition involving an independent channel and a dependent channel is a special case of dependent channel composition, and hence does not require a separate analysis.

We conclude this section with the observation that, as channels are composed to form newer channels, the trust requirements propagate. With each channel composition, the number of trusts required for the composed channel increases by a factor of two for the PKE scheme and by a factor of four for the SKE scheme.

3.7. Composition of More Than Two Channels

A distributed system provides independent channels at the time of system configuration. By Theorem 3.1, any other channel in the system must be composed from independent or dependent channels using a sequence of two-channel compositions. Some of these two-channel compositions will involve only independent channels, and some will involve dependent channels that are results of earlier two-channel compositions in the sequence. We now illustrate the analysis of trust requirements in a sequence of two-channel compositions. Notice that, after a channel has been established by composing a sequence of existing channels, the messages on the channel do not have to follow the same route as the channel establishment messages. However, any agent that has the channel key can obtain a message on the channel by eavesdropping on whatever route the message takes. Thus, the route taken by the messages does not affect the trust requirements of the channel.

Figure 3.8 shows a sample distributed system, in which there are agents A_i, A_{j1}, A_{j2}, A_{j3} and A_k, and there are existing independent channels (A_i, A_{j1}), (A_{j1}, A_{j2}), (A_{j2}, A_{j3}) and (A_{j3}, A_k). Figure 3.8 can be thought of as part of the system's hierarchical name space [Lu86, TPR84], in which A_{j1}, A_{j2} and A_{j3} are name servers and there are independent channels between each node and its parent.

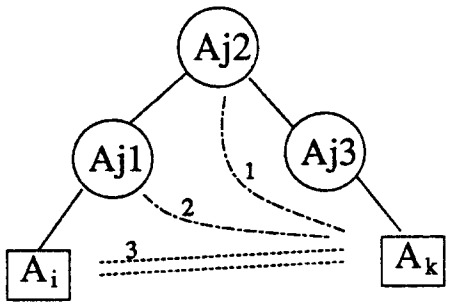

Figure 3.8: Composition of more than two channels

Suppose a new channel, (A_i, A_k), is to be established. Several sequences of two-channel compositions can be used. One such sequence is:

(1) channels (A_{j2}, A_{j3}) and (A_{j3}, A_k) are composed to form channel(A_{j2}, A_k),

(2) channels (A_{j1}, A_{j2}) and (A_{j2}, A_k) are composed to form channel(A_{j1}, A_k), and

(3) channels (A_i, A_{j1}) and (A_{j1}, A_k) are composed to form channel(A_i, A_k).

The intermediate channels, channel(A_{j2}, A_k) and channel(A_{j1}, A_k), are both dependent channels. In the following two sub-sections, we analyze the trust requirements in the above sequence of channel compositions using PKE and SKE schemes.

3.7.1. Sequence of PKE-based Channel Compositions

In the PKE scheme, each of the three compositions in the sequence requires an authenticity trust, and hence channel(A_i, A_k) requires a conjunction of all the three authenticity trusts:

$$T_A(A_{j2}, A_{j3}, A_k) \Lambda T_A(A_{j1}, A_{j2}, A_k) \Lambda T_A(A_i, A_{j1}, A_k) \tag{3.17}$$

3.7.2. Sequence of SKE-based Channel Compositions

SKE-based two-channel composition requires bidirectional component channels, hence, all the independent channels must be bidirectional, and all the intermediate dependent channels must be established in both directions. Thus, establishing channel(A_i, A_k) in the system of Figure 3.8 consists of a sequence of five compositions. Thus, five authenticity trusts are required:

$$T_A(A_{j2}, A_{j3}, A_k) \Lambda T_A(A_k, A_{j3}, A_{j2}) \Lambda T_A(A_{j1}, A_{j2}, A_k) \Lambda T_A(A_k, A_{j2}, A_{j1}) \Lambda$$

$$T_A(A_i, A_{j1}, A_k) \tag{3.18}$$

Each of the five channel compositions also gives rise to a forwarding trust, resulting in the following predicate of forwarding trusts:

$$T_F(A_{j2}, A_{j3}, A_k) \Lambda T_F(A_k, A_{j3}, A_{j2}) \Lambda T_F(A_{j1}, A_{j2}, A_k) \Lambda T_F(A_k, A_{j2}, A_{j1}) \Lambda$$

$$T_F(A_i, A_{j1}, A_k) \tag{3.19}$$

Evaluating the key user-possessor trust requirements consists of evaluating the identities of agents other than A_i and A_k who may have obtained the keys of the five newly established channels when they participated in the sequence of channel compositions leading to the establishment of the new channels. Let us assume that the key of each independent channel is known only to the two ends of the independent channel. In the first two compositions, the keys of newly established channels (A_{j2}, A_k) and (A_k, A_{j2}) are known only to A_{j3} in addition to A_{j2} and A_k. Thus, the first two compositions require two key user-possessor trusts, one for each composition:

$$T_{KUP}(A_{j2}, A_{j3}, A_k) \Lambda T_{KUP}(A_k, A_{j3}, A_{j2}) \tag{3.20}$$

In the next two compositions, channels (A_{j1}, A_k) and (A_k, A_{j1}) are established from channels (A_{j1}, A_{j2}) and (A_{j2}, A_k). In these compositions, not only A_{j2}, but also A_{j3} can obtain the keys of channel(A_{j1}, A_k) and channel(A_k, A_{j1}). Thus, the key user-possessor trust requirements proliferate, and the key user-possessor trust requirements for the third and the fourth compositions are:

$$T_{KUP}(A_{j1}, A_{j2}, A_k) \Lambda T_{KUP}(A_{j1}, A_{j3}, A_k) \Lambda T_{KUP}(A_k, A_{j2}, A_{j1}) \Lambda$$

$$T_{KUP}(A_k, A_{j3}, A_{j1}) \tag{3.21}$$

In the final composition, channel(A_i, A_k) is established from channels (A_i, A_{j1}) and (A_{j1}, A_k). Agents A_{j1}, A_{j2} and A_{j3} can all obtain the key of channel(A_i, A_k). Thus the key user-possessor trust requirements for the final composition are:

$$T_{KUP}(A_i, A_{j1}, A_k) \Lambda T_{KUP}(A_i, A_{j2}, A_k) \Lambda T_{KUP}(A_i, A_{j3}, A_k) \tag{3.22}$$

The key user-possessor trust requirement for the entire sequence of compositions is a conjunction of the three formulae (3.20), (3.21), and (3.22).

It is interesting to observe that the trust expressions are not symmetric in A_{j1}, A_{j2} and A_{j3}. Hence, different channel composition sequences, even when they use the same set of independent channels and establish the same final channel, may require different trust relationships.

3.8. Differences between PKE and SKE Schemes

It is clear from the previous sections that channel compositions using PKE and SKE schemes require different trust relationships. In fact, the PKE scheme requires only a small subset of the trusts required by the SKE scheme.

Using informal arguments, Popek and Kline [KIP79] claim that PKE and SKE schemes have identical trust requirements. Because of their informal approach to trust, Popek and Kline were not able to see differences in trust requirements between the PKE and SKE schemes, and hence a number of advantages of the PKE scheme were not identified. To compare their approach with ours, we briefly describe Popek and Kline's approach to determining trust requirements in PKE and SKE-based channel composition mechanisms.

Consider the composition of channels (A_i, A_j) and (A_j, A_k) to form channel(A_i, A_k). In the PKE scheme, each channel requires a (public-key, private-key) pair. In particular, A_j must possess its private key and A_k's public key. A_j must keep its private key secret. For channel(A_i, A_k) to be established, A_j forwards A_k's public key to A_i. In the SKE scheme, each channel requires a single key. Channels (A_i, A_j) and (A_j, A_k) require A_j to possess their single

keys. During the establishment of channel(A_i, A_k), A_j may come to know the single key of that channel (since A_j is involved in forwarding it). A_j has to keep all the single keys in its possession secret. However, notice that A_j can encrypt all the single keys in its possession with another key $key_{overall}$ and keep $key_{overall}$ secret. Since in the PKE scheme A_j had to keep its own private key secret anyway, one can conclude that in both PKE and SKE schemes A_j is trusted to keep one key secret. Thus, the trust requirements in both the PKE and SKE schemes are the same.

In the approach described above, Popek and Kline are using the notion of trust to represent the secret-keeping behavior of an agent, and ignore all other aspects of agent behavior. This lack of consideration of all the inherent assumptions in PKE and SKE-based channel composition mechanisms is a major drawback of their approach, and is a consequence of its informality. Assumptions about keeping secrets are just one kind of assumptions necessary in channel composition mechanisms. For instance, in the SKE-based channel composition scenario, A_j is assumed not only to keep the single key of channel(A_i, A_k) secret, but also not to use that single key either for masquerading as A_k or for decrypting a secret message on channel(A_i, A_k). It should be noted that, in our formal approach to trust, we capture all these assumptions.

Even with regard to assumptions about keeping secrets, there are three major differences between the two approaches. The differences are best explained with reference to the composition of channels (A_i, A_j) and (A_j, A_k).

(1) In our approach (unlike Popek and Kline's), there is no trust requirement involving an agent A_j if A_j has to keep its own private key secret. Trust requirements involving A_j arise only when A_j has to keep the key of some other agent or channel secret. To illustrate this difference, notice that, in the PKE scheme, if A_j's private key gets compromised after channel(A_i, A_k) has been established, only A_j needs to change its private key, and A_i and A_k are unaffected. In the SKE scheme, A_j has to keep the key of channel (A_i, A_k) secret, and if this key gets compromised, A_i and A_k have to re-establish channel (A_i, A_k) whereas A_j is unaffected. Popek and Kline's approach does not yield these distinctions.

(2) Unlike Popek and Kline's approach, in our approach two trusts are different if the security losses due to their being ill posed are different. To see this point, notice that, in the PKE scheme, if A_j's private key gets compromised after channel(A_i, A_k) has been established, security losses may involve resources owned by A_j. In the SKE scheme, suppose A_j encrypts all the single keys in its possession with a key $key_{overall}$, and keeps $key_{overall}$ secret. Security losses resulting from a leak of $key_{overall}$ may involve resources owned by A_i, A_j, and A_k. Thus, the security losses due to a leak of A_j's private storage are different in the PKE and SKE schemes, and hence, in our approach, their trust requirements are vastly different. Popek and Kline's approach does not make these distinctions, as is clear from the fact that their approach equates the trust concerned with keeping A_j's private key secret with that with keeping $key_{overall}$ secret.

(3) Popek and Kline's approach, unlike ours, captures only the steady state assumptions with regard to keeping secrets. Thus, in SKE-based channel composition, even though A_j can store all the single keys encrypted with another key $key_{overall}$, there is a finite time period preceding the encryption by $key_{overall}$ during which more than one single key has to be kept secret.

To further see how our formal approach yields differences between PKE and SKE schemes, notice that, in our approach, the SKE scheme requires four more trusts than the PKE scheme, namely, the forwarding trust, the message privacy trust, the trust against masquerading, and the key privacy trust. As we will now show, each of these additional trusts gives rise to important

differences between PKE and SKE schemes. The usual channel composition scenario involving A_i, A_j and A_k is used throughout.

3.8.1. Differences Arising from the Forwarding Trust

Consider the SKE channel composition scenario depicted in Figure 3.6. Suppose that A_{m1} obtained A_k's key by decrypting msg_{kj}. A security attack on A_{m1} can make the key available to the attacker, who can then compromise the security of channel(A_i, A_k). Thus, A_i must constantly monitor the security situation at A_{m1}, and A_i must invalidate channel(A_i, A_k) the moment it detects a security attack on A_{m1}. For A_i to take these actions, A_i must know the identity of A_{m1}, which is what is exactly abstracted by the forwarding trust. In contrast, in the PKE scheme, A_{m1} can only obtain the public key of A_k, and an attack on A_{m1} may reveal A_k's public key, but that does not pose any security danger to channel(A_i, A_k).

3.8.2. Differences Arising from the Message Privacy Trust

In the SKE scheme, A_j can decrypt secret messages sent by A_i on channel(A_i, A_k). Suppose there is a security attack on A_j after channel(A_i, A_k) has been established. Any secret message on channel(A_i, A_k) that A_j might possess becomes available to the attacker. In the event of a similar attack in the PKE scheme, A_j, since it does not possess A_k's private key, cannot decrypt secret messages on channel(A_i, A_k), and hence secret messages on channel(A_i, A_k) remain unavailable to A_j's attacker.

3.8.3. Differences Arising from the Trust Against Masquerading

In the SKE scheme, A_j may have the key of channel(A_i, A_k) in its possession. Thus, A_j can send messages masquerading as A_k on channel(A_i, A_k). In the PKE scheme, A_j, since it does not possess A_k's private key, cannot masquerade as A_k on channel(A_i, A_k).

3.8.4. Differences Due to the Key Privacy Trust

In the SKE, A_j has the single key of channel(A_i, A_k). Suppose there is a security attack on A_j after channel(A_i, A_k) has been established. Furthermore, suppose the attacker has kept track of all encrypted messages exchanged on channel(A_i, A_k). Once the attacker obtains the key from A_j, all past, present and future secret messages on channel(A_i, A_k) may become available to the attacker. In the event of a similar attack in the PKE case, since A_j does not possess the private key of A_k, past, present and future secret messages on the channel remain unavailable to the attacker. This difference has a significant impact on key caching and can be illustrated as follows. Consider A_k's key which is used as the key of channel(A_i, A_k). When key caching is used, at different moments different agents may cache A_k's key. Some of these agents may not have obtained A_k's key for the purpose of encrypting messages to A_k, but may have obtained it together with some other keys from the name server for the sole purpose of caching them. In the SKE scheme, since any agent that may have cached A_k's key can decrypt all past, present, and future messages on channel(A_i, A_k), A_i must place key user-possessor trust in every agent at which A_k's key may have been cached at some instant in time, even when channel(A_i, A_k) is no longer in use. Such enormous trust requirements make caching highly unattractive. In contrast, in the PKE scheme, caching of public keys can be used without limitations. Note that, in distributed systems, caching in general is highly desirable from the viewpoint of performance [Ter].

3.8.5. Differences with Regard to Replication

We will now illustrate that replication makes trusts easier to satisfy in the PKE scheme, but makes trusts harder to satisfy in the SKE scheme.

Consider the scenario shown in Figure 3.9, in which there are independent channels (*ibm*, *ibm−j*), (*ibm−j*, *jap*), (*ibm*, *sony−us*), and (*sony−us*, *jap*). Suppose a new channel called $channel_A$ is established between *ibm* and *jap* by composing (*ibm*, *ibm−j*) and (*ibm−j*, *jap*). In PKE-based composition, *ibm* obtains a key, key_A, which is guaranteed to be the public key of *jap* if the trust requirement (obtained using Theorem 3.3) $T_A(ibm, ibm{-}j, jap)$ for $channel_A$ is satisfied. In SKE-based composition, *ibm* obtains a key, key_A, which is guaranteed to be the single key of *jap* if the trust requirement (obtained using Theorem 3.4) $T_A(ibm, ibm{-}j, jap) \wedge T_F(ibm, ibm{-}j, jap) \wedge T_{KUP}(ibm, ibm{-}j, jap)$ for $channel_A$ is satisfied.

Suppose a second channel, $channel_B$, is established between *ibm* and *jap* by composing (*ibm*, *sony−us*) and (*sony−us*, *jap*). In PKE-based composition, *ibm* obtains a key, key_B, which is guaranteed to be the public key of *jap* if the trust requirement $T_A(ibm, sony{-}us, jap)$ for $channel_B$ is satisfied. In SKE-based composition, *ibm* obtains a key, key_B, which is guaranteed to be the single key of *jap* if the trust requirement $T_A(ibm, sony{-}us, jap) \wedge T_F(ibm, sony{-}us, jap) \wedge T_{KUP}(ibm, sony{-}us, jap)$ for $channel_B$ is satisfied.

Suppose *ibm* compares the keys, key_A and key_B, and uses either one of them for channel(*ibm*, *jap*) only if both are identical. In the PKE scheme, if at least one of *ibm−j* or *sony−us* returns the valid public key of *jap*, the security of channel(*ibm*, *jap*) is guaranteed. Thus, the trust relationship required for channel(*ibm*, *jap*) is a disjunction of the trust relationships for $channel_A$ and $channel_B$ (also see [VeA87]):

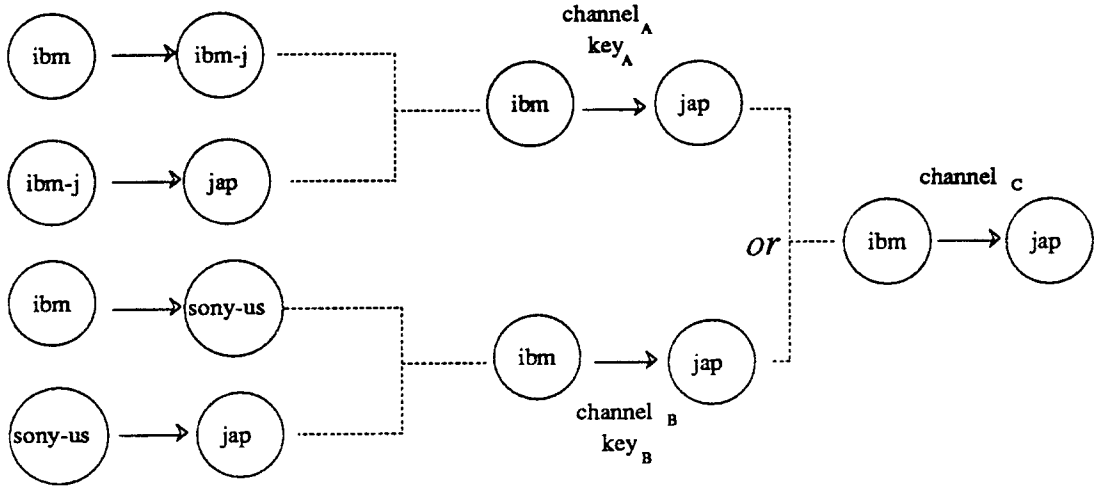

Figure 3.9: Replication of channels

$$T_A(ibm, ibm\_j, jap) \; V \; T_A(ibm, sony\_us, jap) \tag{3.23}$$

Thus, the trust requirements decrease with replication in the PKE scheme.

In the SKE scheme, even though it is necessary that at least one of *ibm_j* or *sony_us* return the valid single key of *jap*, both *ibm_j* and *sony_us* may possess the single key of *jap*, and the forwarding and key user-possessor trusts are required of both agents. The forwarding and key user-possessor trusts requirements are:

$$T_F(ibm, ibm\_j, jap) \; \Lambda \; T_{KUP}(ibm, ibm\_j, jap) \; \Lambda \; T_F(ibm, sony\_us, jap) \; \Lambda$$

$$T_{KUP}(ibm, sony\_us, jap) \tag{3.24}$$

This shows that the forwarding and key user-possessor trusts increase with replication in SKE scheme. Thus, from the viewpoint of security, replication is advantageous in PKE systems but disadvantageous in SKE systems.

In conclusion, our formal analysis has revealed several differences between PKE and SKE schemes, and these differences make PKE schemes much more attractive than SKE schemes in large distributed systems.

3.9. Conclusion

Trust arises primarily in establishing channels for secure communication. The only way to establish a new channel is by composing a sequence of existing adjacent channels. There are two kinds of channels: independent channels, which have no trust requirements and are provided by the system at configuration time, and dependent channels, which are composed from independent channels and have trust requirements. Channel composition mechanisms are commonly based on either public key encryption (PKE) or single key encryption (SKE). PKE-based channel composition requires what we have called *authenticity trusts*, which are functions of three agents. SKE-based channel composition has much larger trust requirements than PKE-based channel composition. The differences in trust requirements of PKE and SKE-based channel compositions translate to significant advantages of PKE over SKE-based channel composition with respect to replication, caching, permanence of trust requirements, and so on. Different sequences of compositions, even though they use the same set of independent channels and establish the same final channel, have different trust requirements. Thus, our analyses provide insight into the basic structure and limitations of mechanisms with regard to their trust requirements.

CHAPTER 4

SYNTHESIS

We show that it is desirable to have a tree of independent channels in a distributed system, and that this tree represents the global name space of the system. To establish a channel between two agents in a name space, there are two alternatives for the order in which the independent channels in the path between the two agents can be composed, and they are called *iterative* and *recursive*. These two channel composition orders have different trust requirements and exhibit interesting duality properties. We develop algorithms for synthesizing name spaces so that, given a channel composition order and the actual trusts of all agents, channel composition between any two agents requires only a subset of the given set of trusts. The given trusts are in general functions of three agents, but they can also be functions of two agents, in which case the algorithms are simpler. We derive some NP-completeness results with respect to putting bounds on the size of the database of encryption keys stored at each node in a name space. Sample runs of the algorithms show that small differences in trust relationships can cause substantial differences in the resulting name spaces.

4.1. Introduction

Agents sharing a distributed system have trust relationships among themselves. One of the most important applications of a formal theory of trust consists of synthesizing a distributed system that satisfies the trust relationships of the agents in the system. The synthesis of a system from trust specifications was in fact the eventual goal with which we began our formal study of trust.

In this chapter, we show how a distributed system's name space determines the trust requirements needed for channel composition between every pair of agents, and we develop algorithms for synthesizing a name space so as to satisfy a given set of trust specifications of agents. Section 4.2 shows the association between a name space and a tree of independent channels. In Section 4.3, we show that there are two alternatives for the order in which the channels between two agents in a name space can be composed, which are called *iterative* and *recursive*, and examine their trust properties. In Sections 4.4-4.9, we develop polynomial-time algorithms for synthesizing name spaces given actual trusts of all agents. Each node in the name space stores a database with the encryption keys of all its children, and it is desirable to put bounds on the size of this database. We derive some NP-completeness results in this regard. The polynomial-time name space synthesis algorithms to be described in Sections 4.4-4.9 have been implemented and experimented with. Section 4.10 presents some interesting sample runs of these algorithms, and finally, Section 4.11 concludes the chapter.

4.2. Necessity of Fast Channel Establishment Procedures in a VLDS

Any two agents in a distributed system must be able to communicate securely (see Figure 4.1). One way to achieve this is to have an independent channel between each pair of agents in the system (see Figure 4.2). In such a system, no new channels need be established, and hence there are no trust requirements for communication. However, there are several disadvantages in having independent channels between all pairs of agents. Since independent channels have to be established using external mechanisms, there would be $O(n^2)$ channels that need to be

established using such mechanisms. External mechanisms, e.g., trusted couriers, are expensive, extremely slow and cumbersome. Since having an independent channel to an agent requires storing the agent's encryption keys, each agent would have to store the entire database of encryption keys of all other agents.

Such a scheme has numerous performance disadvantages in a large distributed system. For example, when an agent changes its keys, the agent has to inform every other agent of the change through external mechanisms. When a new agent joins a distributed system, the new agent has to choose n different channel keys and exchange its keys with every other agent in the system through external mechanisms. In summary, in a large distributed system, it is not desirable to have a independent channel between each pair of agents. The number of independent channels must be minimized.

Given an initial set of independent channels in a distributed system, any two agents must be able to establish a channel by composing the independent channels and any existing dependent channels between them. Therefore, if we represent the agents as nodes and independent channels as edges in a graph, the initial graph of independent channels must be connected.

Let us suppose that we have a connected graph of independent channels. It was shown in the previous chapter that the trust relationships required in establishing a channel between two agents is determined by both the independent channels between the two agents and the order of compositions of these independent channels. Thus, to establish a channel to an agent *Ibaraki*, an agent such as *Alice* would have to keep a database of its trust relationships, and find a path to *Ibaraki* in the graph of independent channels such that the trust relationships in composing the independent channels in the path in some order are present in the database. The channel establishment procedure would involve trying out a sequence of independent channels, backtracking if either no path is found beyond a node in the graph or a path is found but the path requires

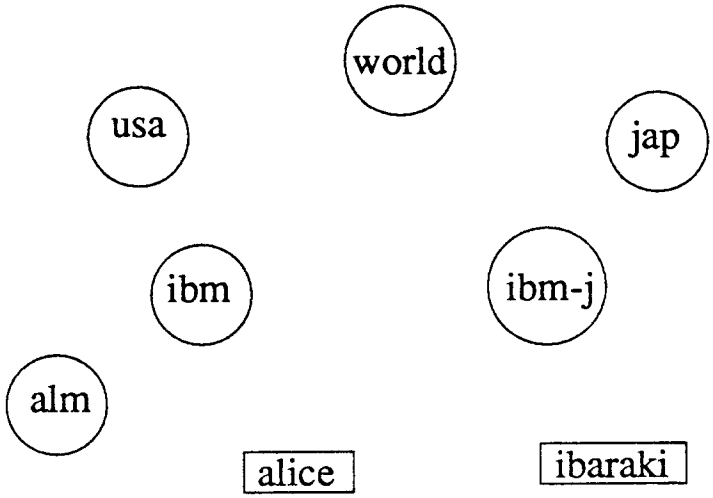

Figure 4.1: Agents in a sample VLDS

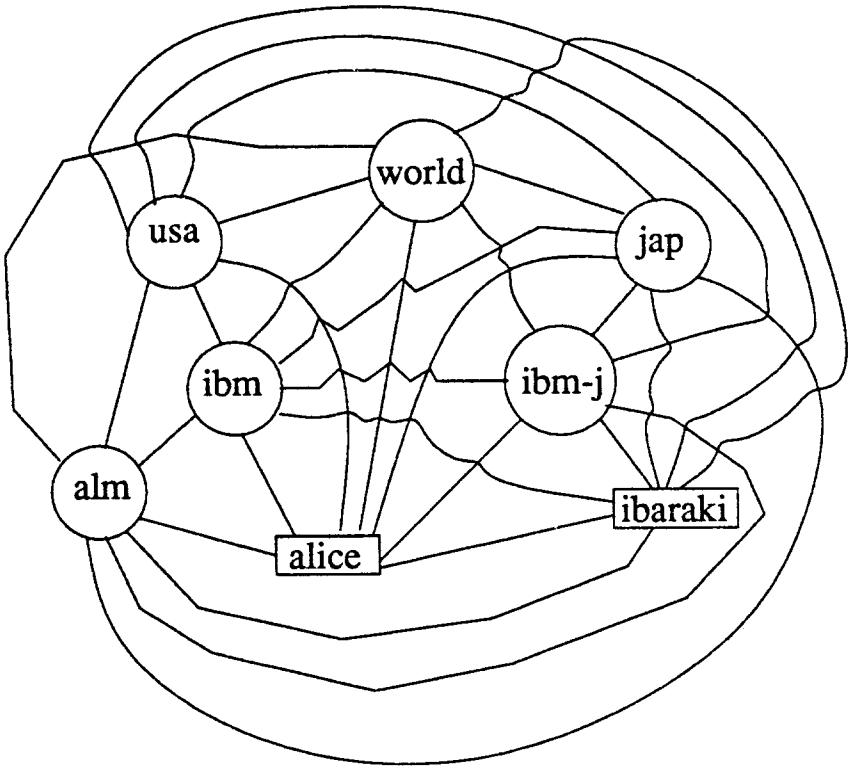

Figure 4.2: Independent channels between every pair of agents

trust relationships not present in its database, and so on (see Figure 4.3). The worst-case performance of such a channel establishment procedure would be intolerable.

The goal of this chapter is to investigate whether, given the trust relationships of all agents at system configuration time, we can synthesize a graph of independent channels so that, between any two agents there is a path in the graph, and composition of the independent channels in the path in a pre-specified order requires only a subset of the given set of trust relationships. Thus, an agent would not have to keep a database of its trust relationships, and at channel establishment time the agent would not have to check either the existence of a path or the satisfiability of a path's trust requirements. Consequently, the channel establishment procedure would be much faster.

What kind of a graph of independent channels should we synthesize ? It is desirable to minimize the number of independent channels. A connected graph with a minimum number of edges is a tree. Thus, our goal is to synthesize a tree of independent channels. We will later examine the kinds of trees that are more preferable than others.

In a tree of independent channels connecting n nodes, there are exactly $n-1$ independent channels yielding an average of one independent channel per agent, and there is a unique path between each pair of agents. An agent in the tree must be able to determine the unique path

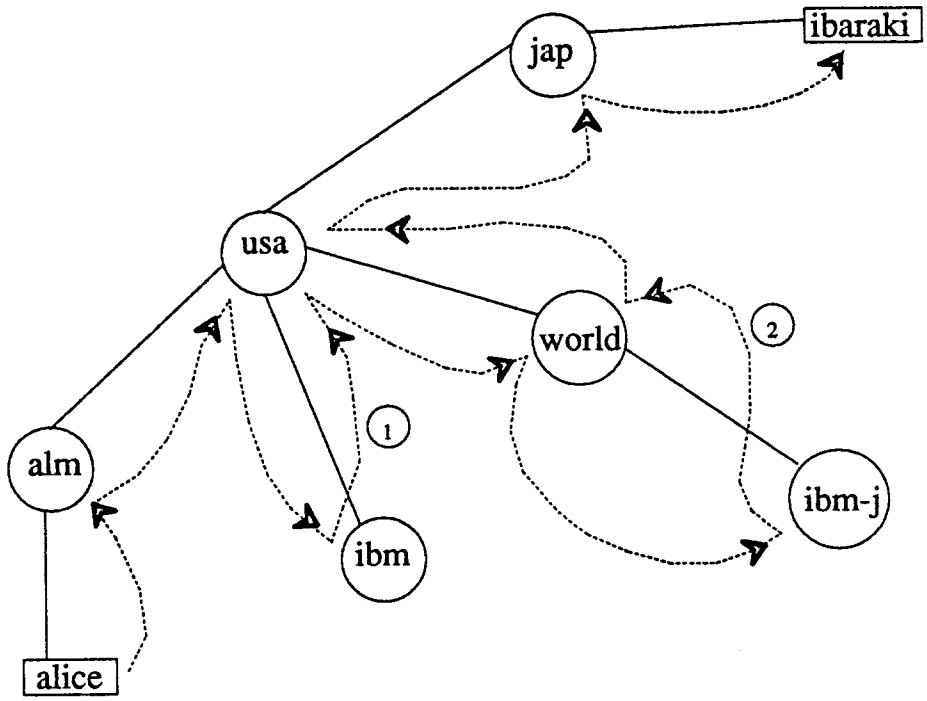

Figure 4.3: Inefficient channel establishment mechanism. In the worst case, Alice backtracks twice while finding a path to Ibaraki.

between itself and any other agent without searching the entire tree. For instance, in Figure 4.3, to establish a channel to *ibaraki*, it should not be necessary for *alice* to establish a channel to *ibm*, backtrack after finding that there is no further path from *ibm* towards *ibaraki*, then establish a path to *ibm−j*, again backtrack since there is no further path from *ibm−j* to *ibaraki*, and then establish a path to *ibaraki* through *jap*. In other words, given the names of two agents, it should be possible to write down the independent channels between them without having to traverse the entire tree.

To accomplish a fast translation from the names of two agents to the independent channels between them, we encode the independent channels into the agents' names. Specifically, one of the agents in the tree is designated as the root of the tree. This agent acts as the reference point for naming the nodes of the tree. The name of an agent in the tree, referred to as its *pathname*, encodes the independent channels from the root to the agent. Given the pathnames of two agents, one can easily write down the sequence of independent channels in the path between them. Figure 4.4 illustrates this mechanism. In the tree shown in the figure, the agent named *world* is designated as the root. Each pathname begins with a "/", which denotes the root node (*world*). The pathname of Alice is */usa/ibm/alm/alice* and that of Ibaraki is */jap/ibm-j/ibaraki*. Given the pathnames */usa/ibm/alm/alice* and */jap/ibm-j/ibaraki*, the independent channels between Alice and Ibaraki are (*alice*, *alm*), (*alm*, *ibm*), (*ibm*, *usa*), (*usa*, *root*), (*root*, *jap*), (*jap*, *ibm_j*), and (*ibm_j*, *ibaraki*). Since the tree of independent channels determines the

pathnames of agents, the tree is referred to as a *name space* of the distributed system. Each node in the name space has independent channels to its children and to its parent. If independent channels are PKE-based, each node keeps a database of public keys of its children and its parent.

In practice, there are several factors other than security, such as administrative and geographical factors, that must be considered in designing a name space for a distributed system. A name space that is optimal from the viewpoint of security may not be so from the viewpoint of the other factors. As explained in Section 1.2, having two separate name spaces, one for security purposes and a second one for other purposes, has significant performance drawbacks. Thus, in practice, it is desirable to design a single name space, and the design must be carried out as a compromise among several objectives, both security and non-security oriented.

It should be noted that a tree-structured name space does not imply a hierarchical trust pattern. To see why, notice that a tree is hierarchical with respect to a property P if in the tree, whenever P holds for a node, P also holds for the node's parent. In a tree-structured name space, the trust relationships of a node need not form a subset of the trust relationships of the node's parent. The number of trust relationships of a node can be much larger than that of the node's parent.

Figure 4.5 illustrates the non-hierarchical nature of a name space tree. Let A be a child of B, and M be a node that is not a descendent of B. B is on the path from A to each of A's non-descendents. Thus, A requires a trust relationship involving B for establishing a channel to each of A's non-descendents. C is on the path from A to each of B's non-descendents. Thus, A requires a trust relationship involving C for establishing a channel to each of B's non-descendents. The set of nodes that are non-descendents of B is a subset of the set of A's non-descendents. Thus, there are more trust relationships involving A and B than those involving A

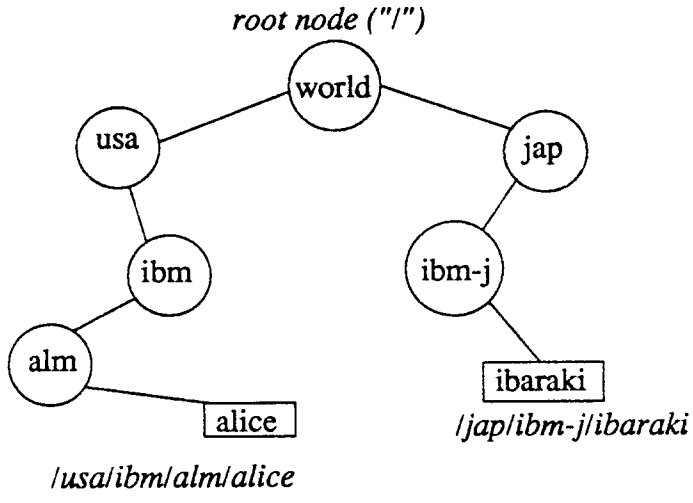

Figure 4.4: Fast path finding mechanism

and C. Since A is a child of B, and the number of B's children can be arbitrarily large, there can be more trust relationships involving B than C, even though C is B's parent in the tree. None of these trust relationships involve A's descendents, and, using similar arguments, it can be shown that a node in the tree need not fully trust all its descendents. Thus, there is no hierarchical pattern with respect to trust relationships in a tree-structured name space. This can also be inferred from the observation that the selection of the root, which determines the parent-child relationships in the tree, can be arbitrary: any node can be designated as the root of the tree. The root just acts as the reference node for naming all other nodes.

4.3. Channel Composition Algorithms

Suppose that a distributed system has a name space such as the one shown in Figure 4.4. Given the names of two agents, say Alice and Ibaraki, we can write down the independent channels in the path between them. There are two possibilities for the order in which these independent channels can be composed to form the required channel between Alice and Ibaraki, called *iterative* and *recursive* channel composition, respectively. These two channel composition orders are illustrated next.

4.3.1. Iterative Channel Composition

Consider the case of channel establishment from Alice to Ibaraki in the name space of Figure 4.4. The *iterative channel composition* algorithm composes channels beginning from Alice (see Figure 4.6) and consists of the following steps (see Figure 4.7):

Alice makes a remote invocation F_1 to the node next in the path from Alice to Ibaraki, namely *alm*, requesting the encryption key of *ibm*. *alm* returns *ibm*'s key in the return message R_1. This in effect composes the channels *alice–alm* and *alm–ibm* to form the channel *alice–ibm*.

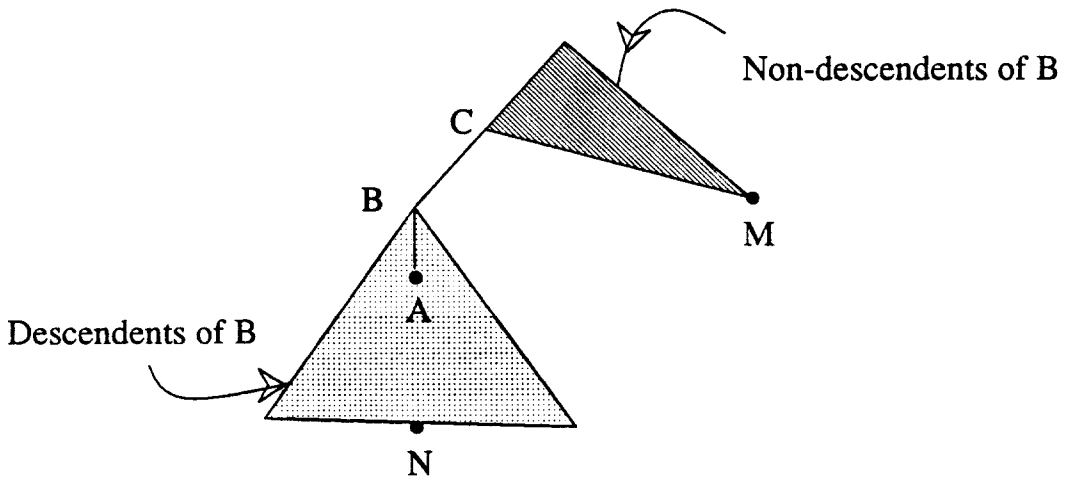

Figure 4.5: Tree-structured name space does not imply hierarchical trust

Alice makes a remote invocation F_2 to *ibm* requesting the key of *usa*. The return message R_2 containing *usa*'s key results in the composition of channels *alice–ibm* and *ibm–usa* to from the channel *alice–usa*.

Alice continues to make such remote invocations, and compositions of channels continue until the channel *alice–ibaraki* is established. Since *alice* repeatedly makes remote invocations in this algorithm, the algorithm is called iterative channel composition.

Figure 4.8 illustrates the trust relationships in iterative channel composition. C is B's parent node, N is any descendent of B, and M is any non-descendent of B (i.e., any node not in the subtree rooted at B). To establish channel M-N using iterative channel composition, M successively establishes channels to nodes in the path from M to N. At some step M establishes a channel to C, and at the successive step it establishes a channel to B by composing channels M-C and C-B. Using the results of Section 3.4, $T_A(M, C, B)$ is true. Similarly, to establish channel N-M, N successively establishes channels to nodes in the path from N to M. At some step N establishes a channel to B, and at the successive step it establishes a channel to C by composing channels N-B and B-C. Hence, $T_A(N, B, C)$ is true. The next theorem summarizes these results. We will use the term "$node_1$ trusts $node_2$ for $node_3$" to mean that $T_A(node_1, node_2, node_3)$ is true.

Theorem 4.1: In iterative channel composition, all non-descendents of a node trust the node's parent for the node, and all descendents of a node trust the node for the node's parent.

□

4.3.2. Recursive Channel Composition

Consider the case of channel establishment from Alice to Ibaraki in the name space of Figure 4.4. The *recursive* channel composition algorithm composes channels beginning from Ibaraki [1] (see Figure 4.9) and consists of the following steps (see Figure 4.10):

Alice makes a remote invocation F_1 to *alm*, which is the next node in the path from *alice* to *ibaraki*, requesting the encryption key of *ibaraki*.

When *alm* receives F_1 request, *alm* makes a remote invocation F_2 to *ibm*, requesting the public key of *ibaraki*.

This sequence of remote invocations continues till finally *jap* makes a remote invocation F_6 to *ibm_j* which is the node just ahead of *ibaraki* in the path from *alice* to *ibaraki*, requesting the key of *ibaraki*.

Ibm_j, which has *ibaraki*'s key, sends the key in a return message R_1. This in effect composes the channels *jap–ibm_j* and *ibm_j–ibaraki* to form the channel *jap–ibaraki*.

This sequence of return messages and channel compositions continues, and towards the end the return message R_5 results in the composition of channels *alm-ibm* and *ibm-ibaraki* to form the channel *alm-ibaraki*.

Finally, the return message R_6 results in the composition of channels *alice-alm* and *alm-ibaraki* to form the required channel *alice-ibaraki*.

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[1] It should however be noted that, even though channel composition begins from Ibaraki, the initiative always starts from Alice.

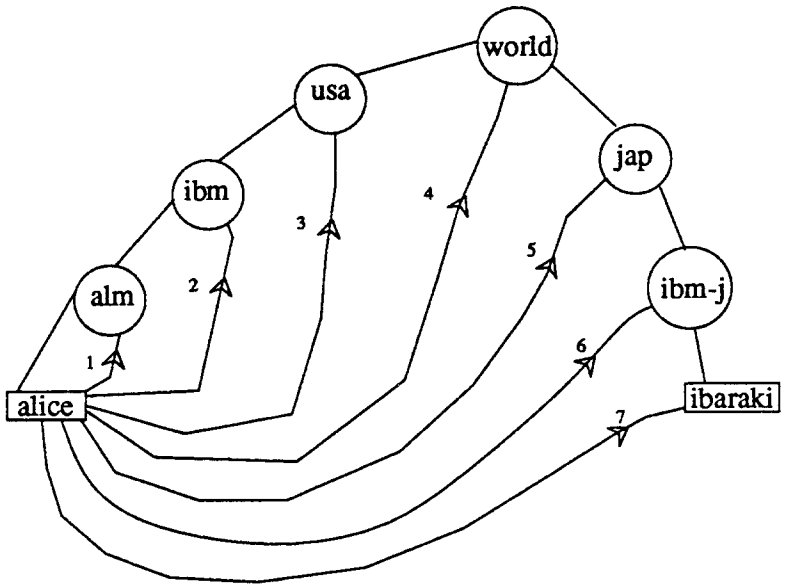

Figure 4.6: An instance of iterative channel composition. In channel establishment from Alice to Ibaraki, channel composition starts from Alice.

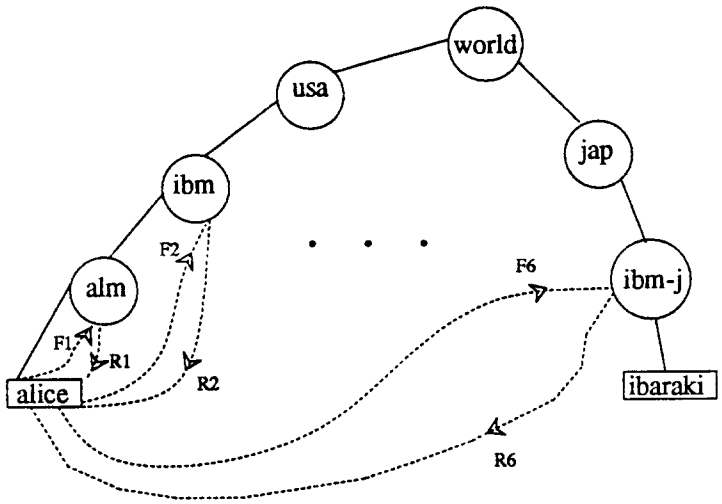

Figure 4.7: Remote invocations in iterative channel composition. In channel establishment from Alice to Ibaraki, Alice successively makes remote invocations to nodes in its path to Ibaraki.

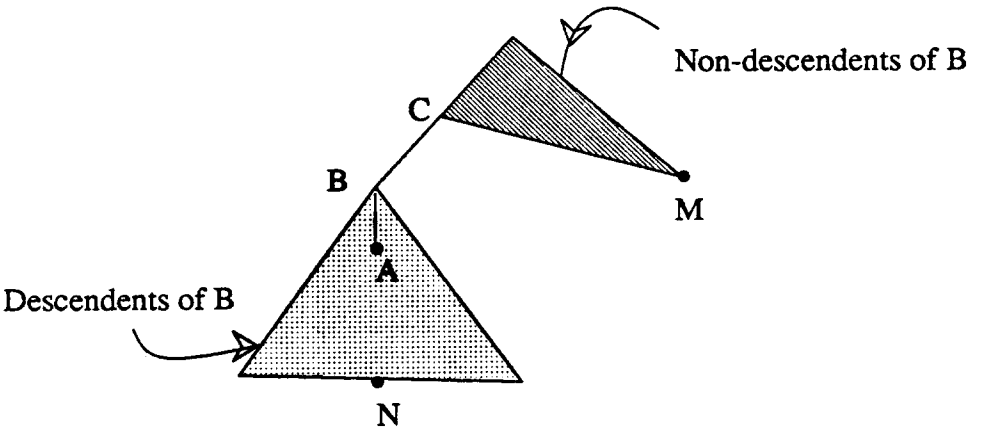

Figure 4.8: Trust relationships in iterative channel composition

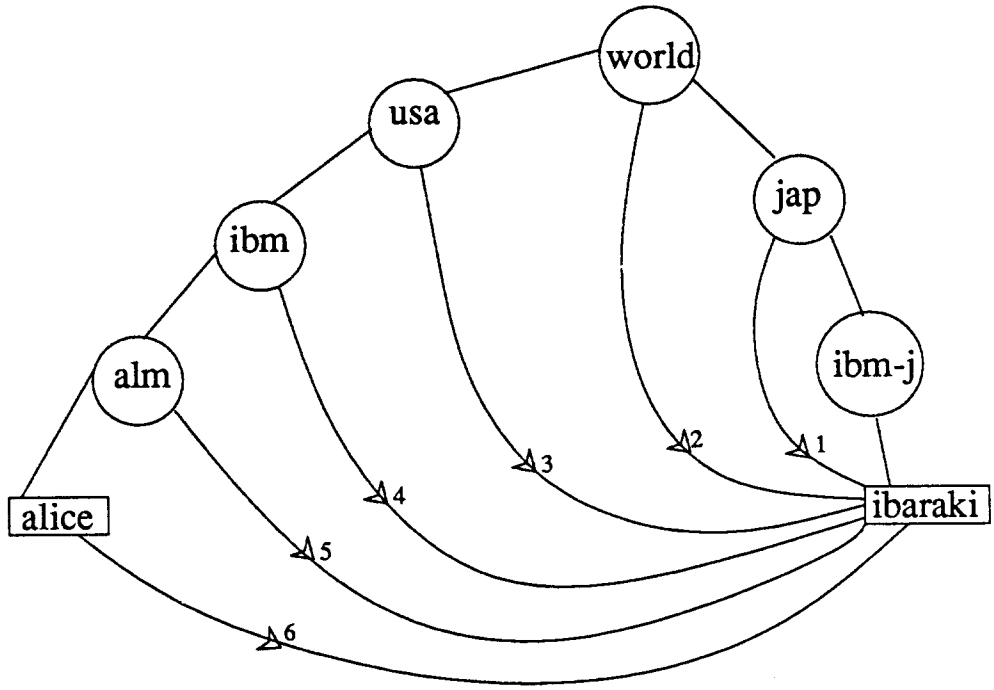

Figure 4.9: An instance of recursive channel composition. In channel establishment from Alice to Ibaraki, channel composition starts from Ibaraki.

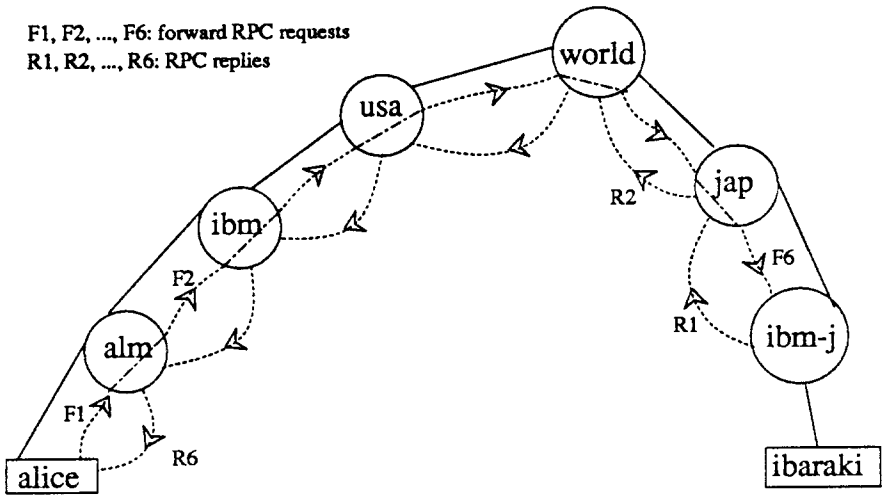

Figure 4.10: Remote invocations in recursive channel composition. In channel establishment from Alice to Ibaraki, Alice makes a recursive remote invocation to its parent.

In this algorithm, *alice* makes a remote invocation F_1 within which there is a remote invocation F_5, and so on. Thus *alice* makes a recursive remote invocation, and the algorithm is called *recursive* channel composition.

Figure 4.11 illustrates the trust relationships in recursive channel composition. C is B's parent node, N is any descendent of B, and M is any non-descendent of B. To establish channel N-M using recursive channel composition, channels are successively established to M from nodes in the path M-N in the name space. At some step C establishes a channel to M, and at the successive step B establishes a channel to M by composing channels B-C and C-M. Using the results in Section 3.4, $T_A(B, C, M)$ is true. Similarly, to establish channel M-N, channels are successively established to N from nodes in the path N-M in the name space. At some step B establishes a channel to N, and at the successive step C establishes a channel to N by composing channels C-B and B-N. Hence $T_A(C, B, N)$ is true. Theorem 4.2 summarizes these results.

Theorem 4.2: In recursive channel composition, a node trusts its parent for the node's non-descendents, and the parent of the node trusts the node for the node's descendents.

□

Having obtained the trusts required by iterative and recursive channel composition in Theorems 4.1 and 4.2 above respectively, we are now ready to tackle the design problem mentioned at the beginning of this chapter: Assuming that the trust relationships of all agents and a channel composition order are given, a tree-structured name space is to be synthesized so that only a subset of the given set of trust relationships is necessary for establishing a channel between any pair of agents in the distributed system. The next section discusses the nature of trust relationships that might be specified in such a design problem.

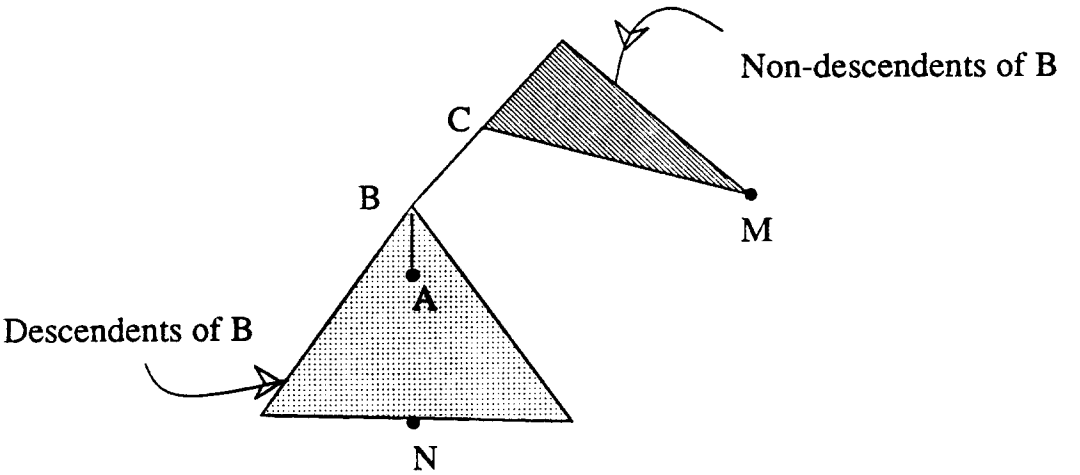

Figure 4.11: Trust relationships in recursive name resolution

4.4. Trust Specifications

In Section 3.7, it was shown that the trust relationships required by PKE-based channel composition protocols form a proper subset of the trust relationships required by SKE-based channel composition protocols. However, current hardware implementations of SKE are several orders of magnitude faster than those of PKE. In the next chapter, we will present protocols that establish channels using PKE but switch-over to SKE once a channel has been established. These protocols have the smaller trust requirements of PKE-based channel composition but have the performance of SKE. Thus, in synthesizing name spaces we assume that the trust requirements are those of PKE-based channel composition. By Section 3.4, we know that PKE-based channel composition requires authenticity trusts, which are (boolean) functions of three agents. Thus, we assume that trust specifications for synthesizing name spaces are in general 3-agent authenticity trust predicates. Nevertheless, the synthesis algorithms that we develop in the following sections can also be used for designing SKE-based name spaces, if, wherever we check for the satisfaction of the authenticity trust involving three agents, we also check for the satisfaction of the forwarding trust and of the key user-possessor trust involving the same three agents.

However, trust specifications can also be functions of two agents. The next section investigates such trust specifications.

4.5. Two-Agent Trust Specifications

When an agent specifies its trust relationships, it is common for the trust relationships to take one of the following two forms:

(1) An agent trusts another agent,

(2) An agent is trusted for another agent.

Such trust relationships involve two agents, and can be thought of as simplifications of the general 3-agent trust predicates required in channel composition. The first of the 2-agent trust relationships above can be thought of as resulting from the elimination of the last argument of a 3-agent trust relationship of the form, "an agent A trusts an agent B for every other agent". We will denote such a 2-agent trust relationship by $T_A(A, B, *)$. The second 2-agent trust relationship can be thought of as resulting from the elimination of the first argument of a 3-agent trust relationship of the form, "every agent trusts an agent B for an agent C". We will denote such a 2-agent trust relationship by $T_A(*, B, C)$.

The permutation of the two types of 2-agent trust relationships with iterative and recursive channel composition results in four combinations. These four combinations have some interesting properties, which we investigate in next.

4.5.1. Iterative and Recursive Channel Composition

Suppose that trust specifications are of the form $T_A(node_2, node_1, *)$, and that the channel composition order is iterative. Consider any node B in the name space. Let N be any descendent of B, and C be the parent of B (see Figure 4.12). By Theorem 4.1, $T_A(N, B, C)$ is true. Since trust specifications are all of the form $T_A(node_2, node_1, *)$, satisfying $T_A(N, B, C)$ requires that $T_A(N, B, *)$ be true. Thus we have the following lemma:

Lemma 4.1: Suppose that trust specifications are of the form $T_A(node_2, node_1, *)$ and that the channel composition order is iterative. In any name space, all the descendents of each node trust the node.

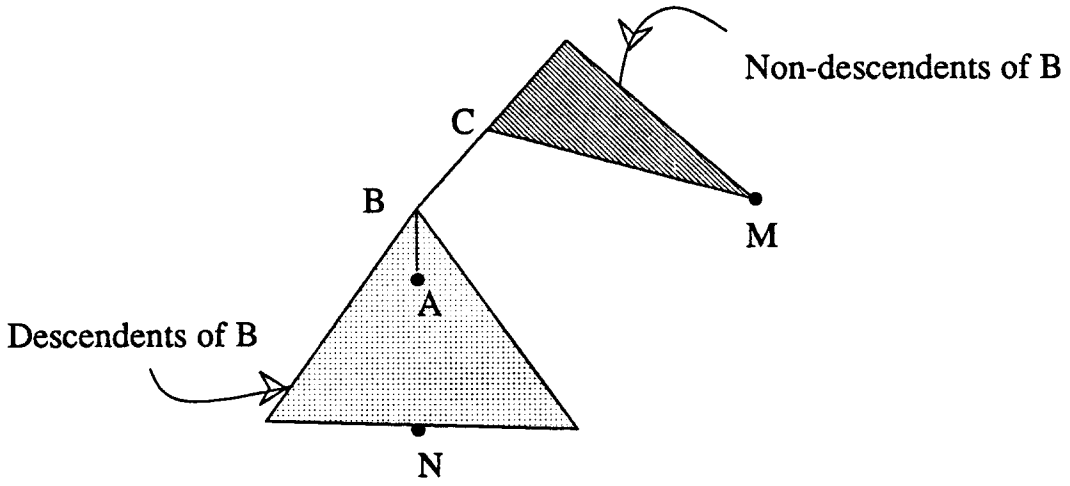

Figure 4.12: Effect of iterative channel composition when trust relationships are of the form $T_A(node_2, node_1, *)$

□

Considering the same figure (Figure 4.12), let M be any non-descendent of B and A be any child of B. By Theorem 4.1, $T_A(M, B, A)$ is true. Since trust specifications are of the form $T_A(node_2, node_1, *)$, satisfying $T_A(M, B, A)$ requires that $T_A(M, B, *)$ be true. Thus we have the following lemma:

Lemma 4.2: Suppose that trust specifications are of the form $T_A(node_2, node_1, *)$ and that the channel composition order is iterative. In any name space, all the non-descendents of each node trust the node.

□

Lemmas 4.1 and 4.2, together with the observation that every node is either a descendent or a non-descendent of a node, yield the following theorem:

Theorem 4.3: If trust relationships are of the form $T_A(node_2, node_1, *)$ and channel composition is iterative, all the nodes in any name space are globally trusted.

□

Now consider the situation when trust specifications are of the form $T_A(*, node_1, node_2)$ and the channel composition is recursive. Let B be any node, A be any child of B and M be any non-descendent of B (see Figure 4.13). By Theorem 4.2, $T_A(A, B, M)$ is true. Since trust specifications are all of the form $T_A(*, node_1, node_2)$, satisfying $T_A(A, B, M)$ requires that $T_A(*, B, M)$ be true. Thus, we have the following lemma:

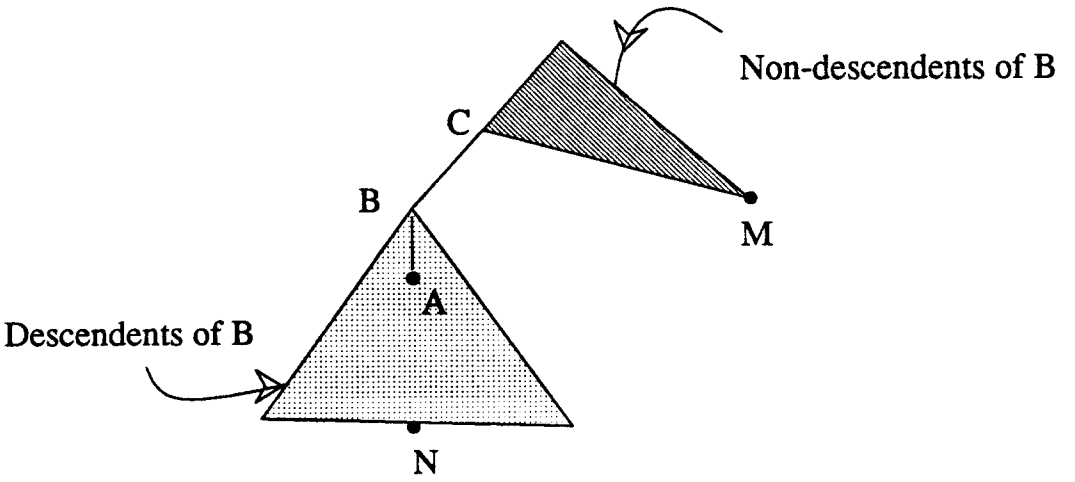

Figure 4.13: Effect of recursive name resolution when trust relationships are of the form $T_A(*, node_1, node_2)$

Lemma 4.3: When trust specifications are of the form $T_A(*, node_1, node_2)$ and the channel composition is recursive, in any name space, each node is trusted for all its non-descendents.

□

Considering the same figure (Figure 4.13), let C be the parent of B and N be any descendent of B. By Theorem 4.2, $T_A(C, B, N)$ is true. Since trust specifications are all of the form $T_A(*, node_1, node_2)$, satisfying $T_A(C, B, N)$ requires that $T_A(*, B, N)$ be true. Thus, we have the lemma:

Lemma 4.4: When trust specifications are of the form $T_A(*, node_1, node_2)$ and the channel composition is recursive, in any name space, each node is trusted for all its descendents.

□

Lemmas 4.3 and 4.4, together with the observation that every node is either a descendent or a non-descendent of a node, yield the following the theorem:

Theorem 4.4: If trust relationships are of the form $T_A(*, node_1, node_2)$ and channel composition is recursive, all the nodes in any name space are globally trusted.

□

Since our primary goal is the elimination of global trust requirements, by Theorems 4.3 and 4.4, it is clear that the combinations $T_A(node_2, node_1, *)$ plus iterative channel composition and $T_A(*, node_1, node_2)$ plus recursive channel composition are not interesting.

Let us now consider the remaining two combinations. We model the combination $T_A(*, node_1, node_2)$ plus iterative channel composition by a directed graph called *IT–graph*,

in which there is an edge $node_1 node_2$ if and only if $node_1$ is trusted for $node_2$, i.e., if $T_A(*, node_1, node_2)$ is true (see Figure 4.14(a)). In the name space, if C is the parent of a node B, M is any non-descendent of B, and N is any descendent of B, by Theorem 4.1 $T_A(M, C, B)$ and $T_A(N, B, C)$ are true (see Figure 4.14(b)). If B is a leaf, then B does not have any descendent N and only $T_A(M, C, B)$ is true. Since trust specifications are of the form $T_A(*, node_1, node_2)$, satisfying $T_A(M, C, B)$ and $T_A(N, B, C)$ requires that $T_A(*, C, B)$ and $T_A(*, B, C)$ be true. If B is a leaf, only $T_A(*, C, B)$ need be true. This result is summarized in the following theorem:

Theorem 4.5: Suppose that the trust specifications are of the form $T_A(*, node_1, node_2)$, and that the channel composition is iterative. A name space satisfies a given set of trust specifications if and only if the following two conditions are satisfied:

(1) If there is a link C-B in the name space and B is not a leaf, then $T_A(*, C, B)$ and $T_A(*, B, C)$ must be true, i.e., there must be edges CB and BC in the IT-graph for the trust specifications.

(2) If there is a link C-B in the name space and B is a leaf, $T_A(*, C, B)$ must be true, i.e., there must be an edge CB in the IT-graph for the trust specifications.

□

The fourth and the final combination is of the form $T_A(node_2, node_1, *)$ with recursive channel composition. We model this combination by a directed graph called *RT–graph*, in which there is an edge $node_1 node_2$ if and only if $node_2$ trusts $node_1$, i.e., $T_A(node_2, node_1, *)$ (see Figure 4.15(a)). In the name space, if C is the parent of a node B, M is any non-descendent of B, and N is any descendent of B, by Theorem 4.2 $T_A(B, C, M)$ and $T_A(C, B, N)$ are true (see Figure 4.15(b)). If B is a leaf, then B does not have any descendent

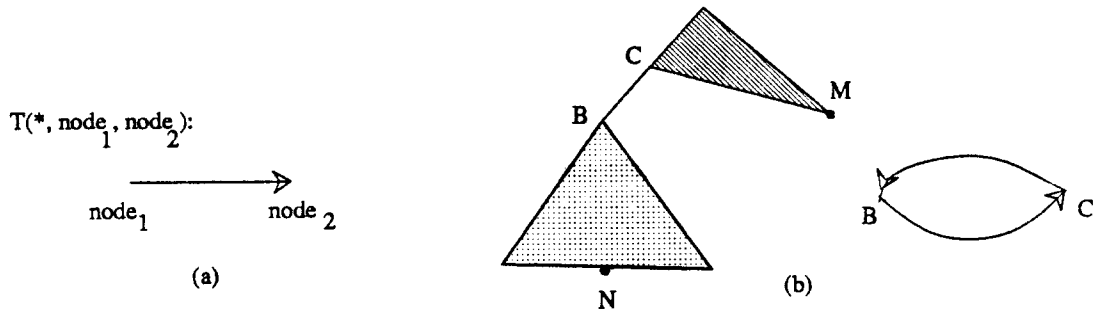

Figure 4.14: IT-graph representation of trust relationships of the form $T_A(*, node_1, node_2)$ when channel composition is iterative. (a) There is a directed edge $node_1 node_2$ in the IT-graph if and only if $T_A(*, node_1, node_2)$ is true. (b) If there is an independent channel C–B in the name space and B is not a leaf, then there must be edges CB and BC in the IT-graph.

N, and only $T_A(B, C, M)$ is true. Since trust specifications are of the form $T_A(node_2, node_1, *)$, satisfying $T_A(B, C, M)$ and $T_A(C, B, N)$ requires that $T_A(B, C, *)$ and $T_A(C, B, *)$ be true. If B is a leaf, only $T_A(B, C, *)$ need be true. The following theorem summarizes these results:

Theorem 4.6: Suppose that the trust specifications are of the form $T_A(node_2, node_1, *)$, and that the channel composition is recursive. A name space satisfies a given set of trust specifications if and only if the following two conditions are satisfied:

(1) If there is a link C-B in the name space and B is not a leaf, then $T_A(B, C, *)$ and $T_A(C, B, *)$ must be true, i.e., there must be edges CB and BC in the RT-graph for the trust specifications.

(2) If there is a link C-B in the name space and B is a leaf, $T_A(B, C, *)$ must be true, i.e., there must be an edge CB in the RT-graph for the trust specifications.

□

4.5.2. Duality

It may be observed that Theorems 4.5 and 4.6 are identical except for the fact that the last and the first arguments to the trust predicates are interchanged. In other words, the combination $T_A(node_2, node_1, *)$ coupled with recursive channel composition is a dual of $T_A(*, node_1, node_2)$ coupled with iterative channel composition, with the first trust argument replacing the role of the last trust argument. This is summarized in the following theorem:

Theorem 4.7 (Duality Theorem): The algorithms for synthesizing name spaces for the combination $T_A(*, node_1, node_2)$ plus iterative channel composition become the algorithms for synthesizing name spaces for the combination $T_A(node_2, node_1, *)$ plus recursive channel composition, if the last and first arguments of the trust specifications are interchanged. The converse

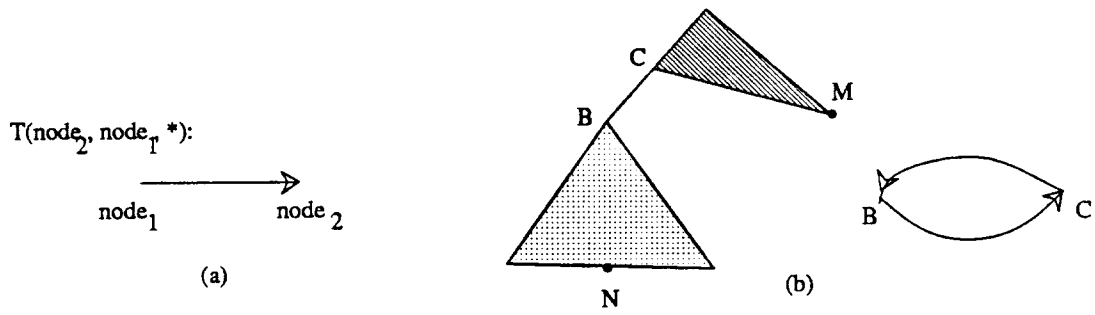

Figure 4.15: Trust relationships are of the form $T_A(node_2, node_1, *)$ and channel composition is recursive. (a) There is a directed edge $node_1 node_2$ in the RT-graph if and only if $T_A(node_2, node_1, *)$ is true. (b) If there is an independent channel C–B in the name space, and B is not a leaf, then there must be edges CB and BC in the RT-graph.

of this statement is also true.

□

A consequence of Theorem 4.7 is that developing name space synthesis algorithms only for the combination $T_A(*, node_1, node_2)$ plus iterative channel composition is sufficient.

The arguments to trust specifications are agents, which represent organizations and individuals sharing a distributed system. These agents occur as nodes in a name space for the system. There are two kinds of nodes in a name space, namely, internal nodes and leaf nodes. The internal nodes serve as managers of databases of keys and have agents as their owners, and hence they are referred to as *name servers*. The leaf nodes represent the agents themselves. A single agent may own several name servers, but each agent is represented by a unique leaf node in a name space. Hence, in synthesizing name spaces, we assume that more than one internal node can correspond to the same agent, but one and only one leaf node must correspond to each agent, and every agent appears as a leaf node.

4.6. Name Space Synthesis Given Two-Agent Trusts and Iterative Composition

In this section we develop an algorithm for synthesizing name spaces for the combination $T_A(*, node_1, node_2)$ plus iterative channel composition. The input to the algorithm is a set of trust specifications of the form $T_A(*, node_1, node_2)$.

4.6.1. The Synthesis Algorithm

The first step of the algorithm is to synthesize the IT-graph for the given trust specifications (Figure 4.16-a). The IT-graph is then transformed into an undirected graph by replacing all bidirectional edges with undirected edges, and by deleting all unidirectional edges (Figure 4.16-b). The resulting undirected graph is converted into a spanning forest (Figure 4.16-c). If there is any isolated node in the spanning forest such that in the original IT-graph there is an edge towards it from another node, an undirected edge is added between these two nodes in the spanning forest (Figure 4.16-d).

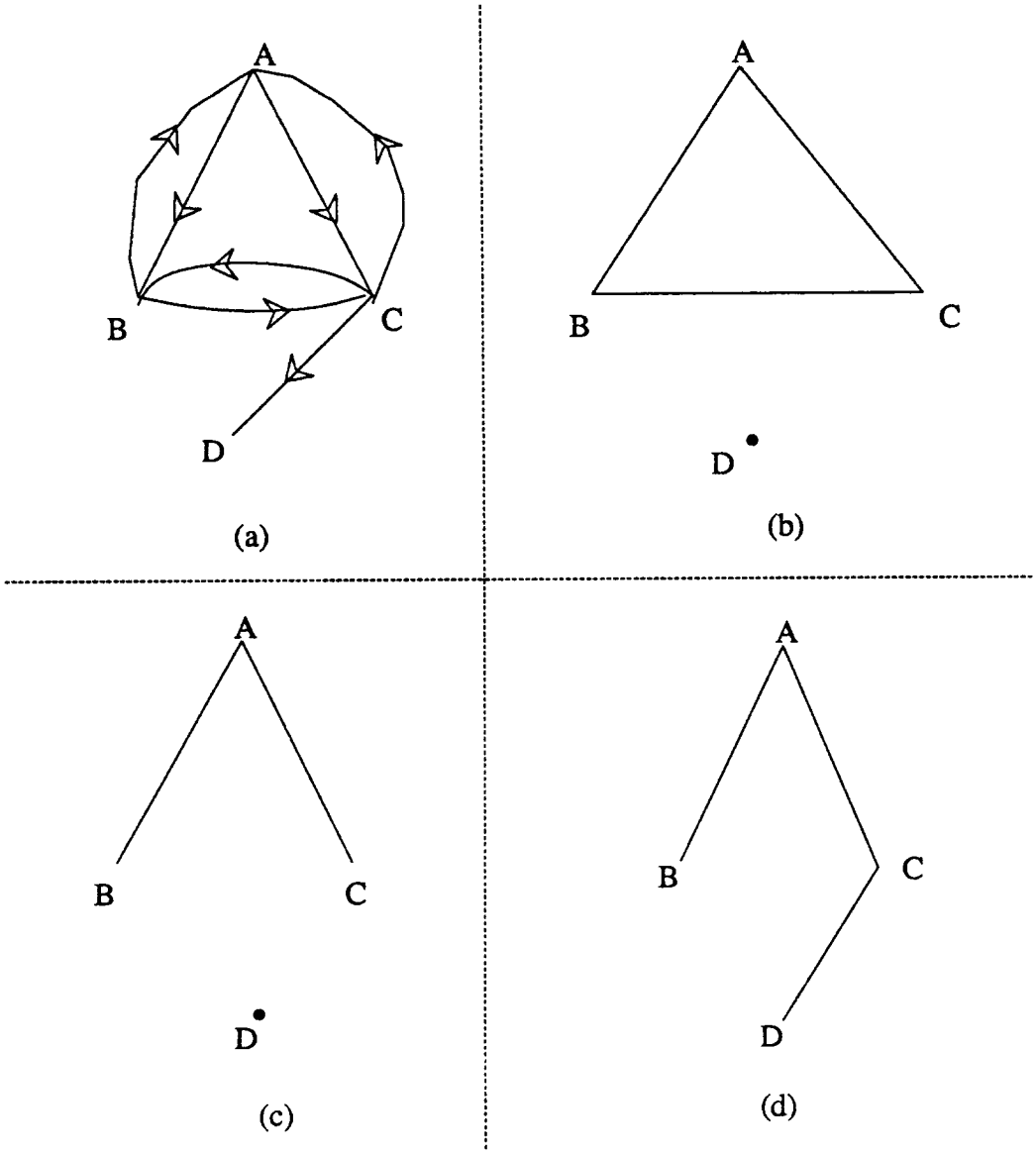

Figure 4.16: Name space synthesis from trust functions of the form $T_A(*, node_1, node_2)$ and iterative channel composition. (a) A sample IT-graph. (b) Bidirectional edges replaced by undirected edges, and unidirectional edges are removed. (c) Transformation of the undirected graph to a spanning forest. (d) An isolated node such as D is re-attached if there is an edge towards it in the IT-graph.

If the resulting spanning forest contains more than one tree, then no tree-structured secure name space is possible. On the other hand, if there is only one tree in the spanning forest, one of the nodes is selected as the root, and all the nodes in the tree are given their pathnames as names. The resulting name space satisfies the given trust specifications when iterative channel composition order is used. The exact algorithm is as follows:

Algorithm 4.1

```
construct IT-graph for the given trust specifications;
for (each edge AB in the IT-graph) do {
        if (there is no edge BA ) then {
                delete AB from the IT-graph;
        } else {
                delete AB and BA ;
                add undirected edge AB ;
        } fi
}
for (each connected component in IT-graph) do {
        transform to a spanning tree;
}
for (each node A in the spanning forest) do {
        if (A is an isolated node) then {
                if (there is an edge NA in the original IT-graph) then {
                        add an undirected edge NA ;
                        mark A as a leaf;
                } fi
        } fi
}
if (there is more than one tree in the forest) {
        print(no name space exists);
        return;
} else {
        select any node R that has not been marked as a leaf;
        mark R as the root of the tree;
        for (each node) do {
                label it with its complete pathname;
        }
}
return the constructed name space;
```

4.6.2. Correctness and Complexity of Algorithm 4.1

In the following theorem, we show the correctness and derive the computational complexity of Algorithm 4.1.

Theorem 4.8: If Algorithm 4.1 constructs a name space, the constructed name space satisfies the given set of trust specifications when iterative channel composition is used. If a name space

exists, Algorithm 4.1 constructs a tree-structured name space. The algorithm's worst-case time-complexity is *O(max(number of trusts, number of agents))*.

Proof: We first prove the first part of the theorem, i.e., that, if Algorithm 4.1 constructs a name space, the constructed name space satisfies the given set of trust specifications when iterative channel composition is used. Suppose the algorithm constructs a name space *NS*. Consider each edge *BC* in *NS*. Let *C* be the parent of *B*. If *B* is not a leaf, *BC* was an outcome of the second for-loop of Algorithm 4.1, hence *BC* was an undirected edge in a connected component at the beginning of that for-loop, and therefore *BC* was an undirected edge in a connected component at the end of the first for-loop. Thus, there are edges *BC* and *CB* in the IT-graph. If *B* is a leaf, then it is an outcome of the third for-loop, and hence there is an edge *CB* in the IT-graph. Applying Theorem 4.5, we obtain that *NS* satisfies the given trust specifications. This completes the proof of the first part of the Theorem.

Suppose that a name space *NS* exists for the given trust specifications. We now show that the algorithm will construct a name space. Applying Theorem 4.5, the IT-graph must contain at least (1) bidirectional edges corresponding to the links between two internal nodes in *NS*, and (2) unidirectional edges corresponding to links between an internal node and a leaf node in *NS*. Thus, at the end of the first for-loop of Algorithm 4.1, there will be a connected graph in which all the internal nodes of *NS* are present, and at the end of the second for-loop, this connected graph will get transformed into a tree. All the nodes not in this tree will get added as leaves to the tree in the third for-loop. Thus, Algorithm 4.1 yields a tree-structured name space if one exists.

Let us now derive the worst-case time complexity of Algorithm 4.1. The number of edges is of the order of the number of trust relationships. Suppose that this number is e. Suppose that the number of nodes, which is the number of agents, is n. The complexity of the first for-loop is $O(e)$, the complexity of the second for-loop is the complexity of constructing a spanning tree, which is $O(\max(e, n))$, and the complexity of the last for-loop is $O(n)$. Thus, the complexity of Algorithm 4.1 is $O(\max(e, n))$.

This completes the proof of Theorem 4.8.

□

Algorithm 4.1 gives one possible name space satisfying the given trust relationships. There may be more than one name space satisfying the same given set of trust relationships. In a name space, each node has to store a database of encryption keys of all its children. In a name space in which the root is the parent of all other nodes (see Figure 4.17-a), the root has to store the entire database containing the keys of all other agents in the system, resulting in a centralized name server. At the other end of the spectrum is a name space corresponding to a hamiltonian path (Figure 4.17-b), in which each node has to store just one key (that of its sole child). Both of these extreme name space configurations are undesirable. Therefore, it is desirable to put bounds on the number of children of each node in a name space. However, the next section derives some NP-completeness results with respect to these bounded-children name space design problems [AHU74, GaJ79].

4.6.3. NP-Completeness Results

The next theorem shows that the problem of putting an upper bound on the number of children of each node in a name space is NP-complete. But before we prove the theorem, we need two graph-theoretic lemmas, which we prove next. The next lemma shows an equivalence between hamiltonian paths and bounded-children spanning trees in graphs.

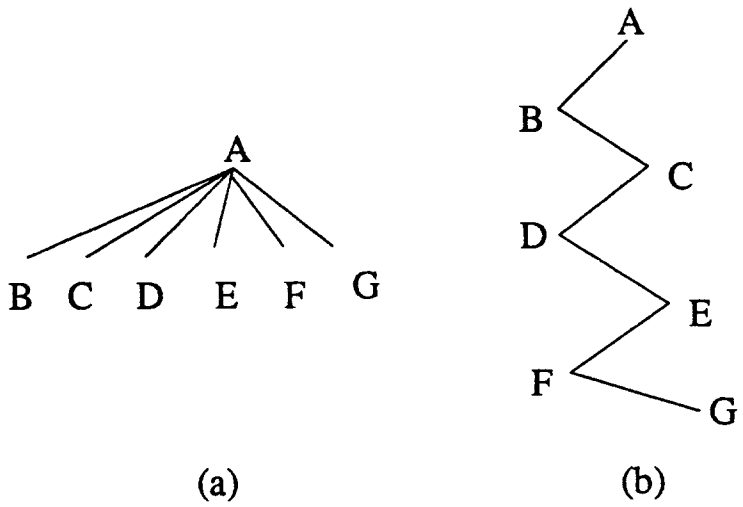

Figure 4.17: Extreme cases of name space configuration when the number of children of a name space node cannot be bounded. (a) Name space in which the root is the parent of all other nodes. (b) Name space that is a hamiltonian path.

Lemma 4.5: Let G be a graph for which the existence of a hamiltonian path is to be determined. Suppose that we construct a graph G' by adding new edges and new nodes as follows (see Figure 4.18): to each node V in G, we add $u-2$ new edges, each edge connecting V and a new node. A hamiltonian path for G is a spanning tree for G', and in the spanning tree, each node has at most u children. The converse of this statement is also true.

Proof: Suppose that there is a hamiltonian path H for G. Let the set of new nodes and the set of new edges added to form G' be denoted by $N_{G'}$ and $E_{G'}$. When we add an edge of $E_{G'}$ to H, a new node gets added to H, and H remains a tree (i.e., no cycles are created). Thus, when we add all the edges of $E_{G'}$ to H, we obtain a tree T' for G'. In T', each node has at most two edges of H and at most $u-2$ edges of $E_{G'}$ incident on it. Thus, there is an upper bound of u on the number of children of each node in T'.

Suppose that there is a spanning tree T' for G' with an upper bound of u on the number of children of each node. Since each edge of $E_{G'}$ connects a new node of $N_{G'}$ to T', and all nodes of $N_{G'}$ must be present in a spanning tree, all the edges of $E_{G'}$ must be present in T'. Each node of $N_{G'}$ is a terminal node in T'. Thus, when we remove the nodes of $N_{G'}$ from T', we obtain a tree T in which all the nodes except those of $N_{G'}$, i.e., all the nodes of G, are present. Hence, T is a spanning tree for G. Each node of T must have had $u-2$ more edges incident on it in T' (since in T', each of these nodes was connected to $u-2$ nodes of $N_{G'}$). But in T', each node has at most u edges incident on it. Thus, each node in T can have at most 2 edges incident on it. A tree in which each node has at most 2 edges incident on it is a hamiltonian path. Hence, T is a hamiltonian path for G. This completes the proof of Lemma 4.5.

□

The next lemma proves equivalence between any spanning tree of a graph and the IT-graph for the graph. This equivalence is used in both Theorem 4.8 and Theorem 4.9.

Lemma 4.6: Given a graph G, suppose that we construct an IT-graph *ITG* by replacing each edge in G with a bidirectional edge. Any name space synthesized for *ITG* is a spanning tree [2] of G, and any spanning tree for G is a name space for *ITG*.

Proof: Using Theorem 4.5 and the fact that *ITG* contains only bidirectional edges, we obtain that for each edge in *NS* there is a bidirectional edge in *ITG*. Since for each bidirectional edge in *ITG* there is an undirected edge in G, for each edge in *NS* there is an edge in G. Thus, *NS* is a subgraph of G.

Consider any spanning tree T for G. For each edge in T, there is a bidirectional edge in *ITG*, and hence, by Theorem 4.5, T is a name space for *ITG*. Thus, any spanning tree for G is a name space for *ITG*. This completes the proof of Lemma 4.6.

□

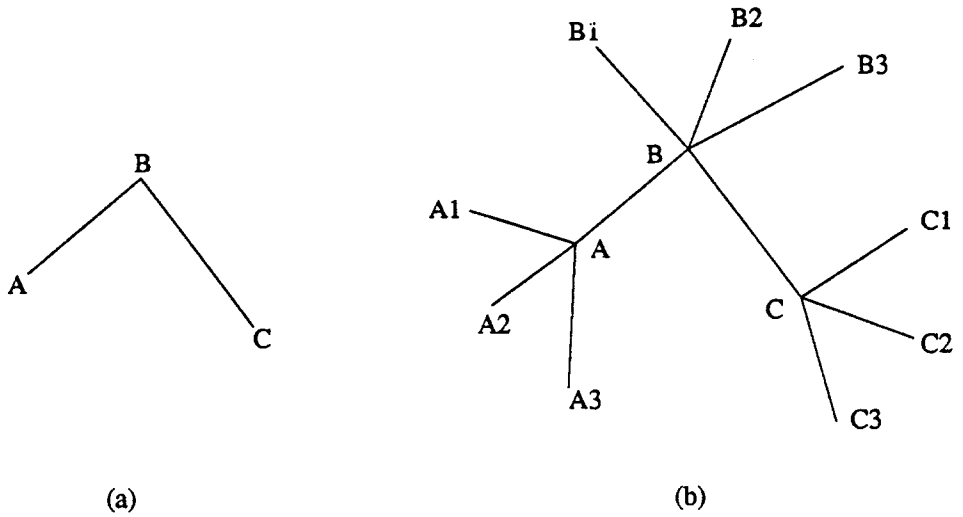

Figure 4.18: Construction of a graph G' from a graph G in Lemma 4.5 when u=5. (a) A sample graph G. (b) G' obtained from G by adding $u-2 = 3$ new edges to each node V in G, each new edge connecting V and a new node.

[2]When we say a name space is a spanning tree for a graph G, we mean that all the nodes of G are present in the name space and there are no cycles in the name space.

Theorem 4.9: For the combination T_A(*, $node_1$, $node_2$) plus iterative channel composition, synthesizing a name space with a given upper bound on the number of children of each node is NP-complete.

Proof: To prove that the problem is in NP, we first show that guessing a solution and checking the validity of the guessed solution has polynomial time complexity [AHU74, GaJ79]. Let the number of agents be V, and the upper bound be u. To build a name space, we have to enumerate V-1 edges, and designate one of the nodes as the root. Checking the validity of the guessed name space consists of the following steps:

(1) The name space must be connected and tree-structured (i.e., there must not be any cycles in the name space).

(2) The name space must satisfy the given trust specifications. Thus for each edge between internal nodes in the name space, there must be bidirectional edges in the IT-graph for the given trust specifications. For each edge between an internal node and a leaf node in the name space, there must be an edge from the internal node to the leaf node in the IT-graph. In all there are V-1 edges in the name space.

(3) The number of children of each node must not exceed u.

Each of these steps can be carried out in O(V) time. Thus the problem is in NP.

It is known that determining the existence of a hamiltonian path in a graph is an NP-complete problem [AHU74, GaJ79]. We reduce this NP-complete problem to our problem of putting an upper bound on the number of children of each node in a name space. To achieve this reduction, given a graph G for which the existence of a hamiltonian path is to be determined, we construct a graph G' as follows (see Figure 4.18): to each node V in G, we add $u-2$ new edges, each edge connecting V and a new node. By Lemma 4.5, to determine the existence of a hamiltonian path for G, it suffices if we determine the existence of a spanning tree for G' with each node having at most u children.

We now construct an IT-graph ITG' by replacing each edge in G' with a bidirectional edge. By Lemma 4.6, a spanning tree with an upper bound of u on the children of each node exists for G' if and only if there is a name space for ITG' with the same upper bound. Constructing G' from G is an $O(n \times u)$ operation, and if e is the number of edges in G, constructing ITG' from G' is an $O(e)$ operation. However, the upper bound u cannot exceed the number of nodes n, and the number of edges cannot exceed the square of the number of nodes. Therefore, the complexity of the two constructions together is $O(n^2)$. Thus we have reduced the problem of determining the existence of a hamiltonian path for G to the bounded children name space problem in polynomial time. Since the hamiltonian path problem is NP-complete, the bounded children name space problem is NP-complete.

□

Now consider the other extreme case (Figure 4.17(b)). We consider two approaches to avoiding such an extreme case. In the first approach, we assume that an agent can occur either as a leaf node or as an internal node in a name space, and try to put a lower bound on the number of leaves in a name space. In the second approach, we try to put a lower bound on the number of children of each node in a name space.

Theorem 4.10: Consider the combination T_A(*, $node_1$, $node_2$) plus iterative channel composition. If an agent can occur either as a leaf node or as an internal node in a name space, synthesizing a name space in which there is a given lower bound on the number of leaf nodes is NP-complete.

Proof: Proving that the problem is in NP is identical to the proof we gave in Theorem 4.9, except that, while checking the validity of a guessed name space, we have to check for the minimum, rather than the maximum, number of children of a node in the name space.

It is known that the following problem is an NP-complete problem [AHU74, GaJ79]: Given a graph G and a positive integer $K < n$ (where n is as usual the number of vertices in the graph), does the graph have a spanning tree such that the number of leaves in the tree is at least K ? A straight-forward application of Lemma 4.6 yields the reduction from this NP-complete problem to the bounded leaf name space problem.

□

Now consider the problem of putting a lower bound on the number of children of each node in a name space. The following algorithm gives a reduction from the bounded leaf problem to bounded children name space problem. Let the given graph in the bounded leaf problem be G having n vertices.

Algorithm 4.2

```
for (each set vert of n–K vertices in the graph G ) do {
        construct a graph G' from G by:
                coalescing the subgraph formed by vert into a single node x;
        construct an IT-graph ITG' by:
                replacing each edge in G' by a bidirectional edge;
        if (ITG' has a name space with children of each node bounded below by K )
        {
          print(G has a spanning tree with number of leaves bounded below by K );
          return(success);
        }
}
print("G does not have a spanning tree with number of leaves ≥ K ");
return(failure);
```

Figure 4.19 illustrates the coalescing step of the algorithm. The subgraph formed by the vertices B, C1 and C2 in the graph of Figure 4.19-a are coalesced to form the graph of Figure 4.19-b. To coalesce the subgraph S formed by a set of vertices $vert_S$ in a graph [3], we carry out the following steps:

(1) A single new node x replaces the nodes in the set $vert_S$.

(2) All edges between nodes within $vert_S$ are deleted.

(3) Each edge between a node w outside $vert_S$ and a node within $vert_S$ is replaced by an edge between w and x.

---

[3] The subgraph S consists of the vertices in $vert_S$ and the edges between nodes within $vert_S$.

(4) All other nodes and edges are retained.

We now show that Algorithm 4.2 returns success if and only if there is a solution for the bounded leaf problem. Suppose that Algorithm 4.2 gives an affirmative answer in the if-step. By Lemma 4.5, a name space for ITG' is a spanning tree for G'. Thus, G' has a spanning tree $T_{G'}$ with the number of children of each node at least K. Since the number of leaves in a graph is no less than the smallest number of children of a node in a tree, the number of leaves of $T_{G'}$ is at least K. To obtain a spanning tree T_G for the original graph G, we de-coalesce the coalesced node n in $T_{G'}$ into its original subgraph S, and transform the subgraph S into a spanning subtree. All the leaves except possibly x of $T_{G'}$ remain as leaves of T_G. If x is a leaf in $T_{G'}$, when x is de-coalesced to obtain T_G, x fans-out into at least one leaf. Thus T_G has a number of leaves at least equal to that of $T_{G'}$, and hence T_G has its number of leaves at least K. Thus, if Algorithm 4.2 gives an affirmative answer, G has a tree in which the number of leaves is at least K. Such a tree is a solution for the bounded leaf problem. Thus, if Algorithm 4.2 gives an affirmative answer, there is a solution for the bounded leaf problem.

We now show that, if there is a solution to the bounded leaf problem, Algorithm 4.2 gives an affirmative answer. Suppose that there is a solution to the bounded leaf problem. Thus, there is a spanning tree T_G for G whose number of leaves is at least K. If we coalesce the interior nodes of tree T_G, we obtain a tree $T_{G'}$ which has only one internal node, and all the leaves of T_G are children of this internal node. Thus, the number of children of the only node in $T_{G'}$ is at least K. By Lemma 4.5, $T_{G'}$ is also a name space for ITG'. Thus, Algorithm 4.2, when it coalesces the nodes of G that occur as interior nodes of T_G, will yield an affirmative answer.

In summary, Algorithm 4.2 yields an affirmative answer if and only if the bounded leaf problem has a solution. Thus, Algorithm 4.2 is a reduction from the bounded leaf problem to our bounded children name space problem.

The complexity of Algorithm 4.2 is as follows. There are $C(n, n-K) = O(n^K)$ possibilities for a set of $n-K$ vertices. Coalescing G to G' involves looking at each of the vertices and

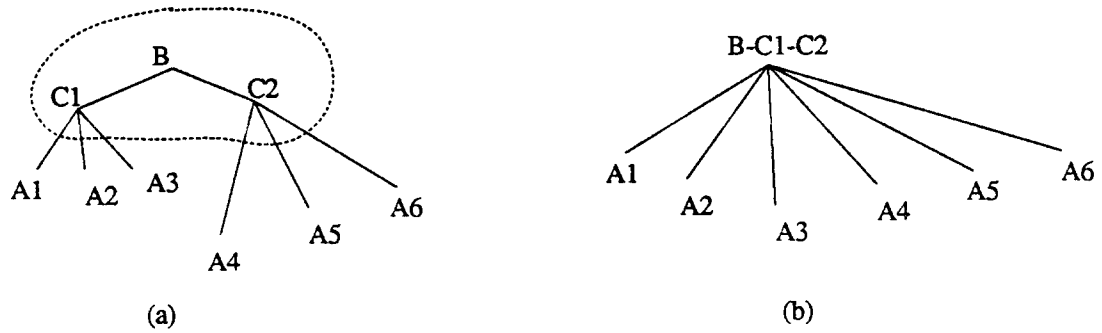

Figure 4.19: Reduction of "bounded leaf" problem to "bounded children name space design" problem by coalescing internal nodes. The internal nodes B, $C1$ and $C2$ in the graph shown in (a) are coalesced to get the graph shown in (b).

edges in G, and hence is of complexity $O(max(n,e))$. Transforming G' to ITG' is an $O(e)$ operation. Thus, the complexity of Algorithm 4.2 is of the order of,

$n^K \times (max(n,e) + complexity\ of\ bounded\ children\ name\ space\ problem)$.

4.7. 3-Agent Trust Specifications

In this section we develop algorithms for synthesizing name spaces given 3-agent trust specifications. Directed graphs are again used to represent the trust specifications. However, a directed edge by itself can only represent a binary relationship between its two vertices. Thus, in representing 3-agent trust relationships by a directed graph, two of the agents in the trust relationship become vertices, and the third agent becomes a label of the directed edge between the vertices. Thus, a labeled directed edge is used to represent a 3-agent trust relationship.

4.7.1. Iterative and Recursive Composition

As explained at the beginning of this chapter, a name space is specific to a channel composition order. When the channel composition order is iterative, we model the given trust relationships by a labeled directed graph called *LIT–graph* [4]. A LIT-graph contains an edge BC labeled with a set of agents set_{BC} if and only if for all agents A in set_{BC} we have $T_A(A, B, C) = true$ in the given set of trust specifications (see Figure 4.20). Consider a name space that satisfies the given set of trust specifications. If B is any node in the name space, and C is its parent, the link B–C divides the set of all agents in the name space into two disjoint subsets containing, (1) the descendents of B, e.g., N, and (2) the non-descendents of C, e.g., M, respectively. By Theorem 4.1, for all descendents N of B, $T_A(N, B, C) = true$, and hence N belongs to set_{BC}, and for all non-descendents M of C, $T_A(M, C, B) = true$, and hence M belongs to set_{CB}. Since every node except B and C is either a descendent of B or a non-descendent of C, and since B and C trivially belong to set_{BC} and set_{CB}, $set_{BC} \cup set_{CB} = the\ universal\ set$ [5].

Thus, if in the LIT-graph for a given set of trust specifications $set_{BC} \cup set_{CB}$ does not equal the universal set, then C cannot be the parent of B.

Interchanging the roles of C and B, we obtain that, if $set_{CB} \cup set_{BC}$ does not equal the universal set, B cannot be the parent of C.

But, since $set_{BC} \cup set_{CB} = set_{CB} \cup set_{BC}$, if $set_{CB} \cup set_{BC}$ does not equal the universal set, the link B–C cannot exist in any name space synthesized for the given trust specifications, and hence the edges BC and CB can be removed from the LIT-graph. These results are summarized in the following theorem:

Theorem 4.11: Given 3-agent trust specifications, if iterative channel composition is used, a link B–C can exist in the name space only if, in the LIT-graph constructed from the trust specifications, the union of the labels of edges BC and CB equals the universal set. Moreover, if C is the parent of B, an agent N that is a descendent of B in the name space must belong to set_{BC}, and an agent M that is a non-descendent of B in the name space must belong to set_{CB}.

□

---

[4] *LIT-graph* stands for *Labeled Iterative Trust graph.*

[5] The symbol "$\cup$" is used to mean the union of sets.

When the channel composition order is recursive, we model the given trust relationships by a labeled directed graph called *LRT–graph*. A LRT-graph contains an edge BC labeled with a set of agents set_{BC} if and only if, for all agents A in set_{BC} $T_A(C, B, A) = true$ in the given set of trust specifications (see Figure 4.21). Consider a name space that satisfies the given set of trust specifications. If B is any node in the name space, and C its parent, the link B–C divides the set of all agents in the name space into two disjoint subsets containing, (1) the descendents of B, e.g., N, and (2) the non-descendents of B, e.g., M, respectively. By Theorem 4.2, for all descendents N of B, we have $T_A(C, B, N) = true$, and hence N belongs to set_{BC}; also, for all non-descendents M of B, we have $T_A(B, C, M) = true$, and hence M belongs to set_{CB}. Since every node is either a descendent or a non-descendent of a node, $set_{BC} \cup set_{CB}$ = *the universal set.* [6]

Thus, if, in the LRT-graph for a given set of trust specifications, $set_{BC} \cup set_{CB}$ does not equal the universal set, C cannot be the parent of B.

Interchanging the roles of C and B, we obtain that, if $set_{CB} \cup set_{BC}$ does not equal the universal set, B cannot be the parent of C.

But, since $set_{BC} \cup set_{CB} = set_{CB} \cup set_{BC}$, if $set_{CB} \cup set_{BC}$ does not equal the universal set, the link B–C cannot exist in any name space synthesized for the given trust specifications, and hence the edges BC and CB can be removed from the LRT-graph. These results are summarized in the following theorem:

Theorem 4.12: Given 3-agent trust specifications, if recursive channel composition is used, a link B–C can exist in the name space only if, in the LRT-graph constructed from the trust specifications, the union of the labels of edges BC and CB equals the universal set. Moreover, if C is the parent of B, an agent N that is a descendent of B in the name space must belong to

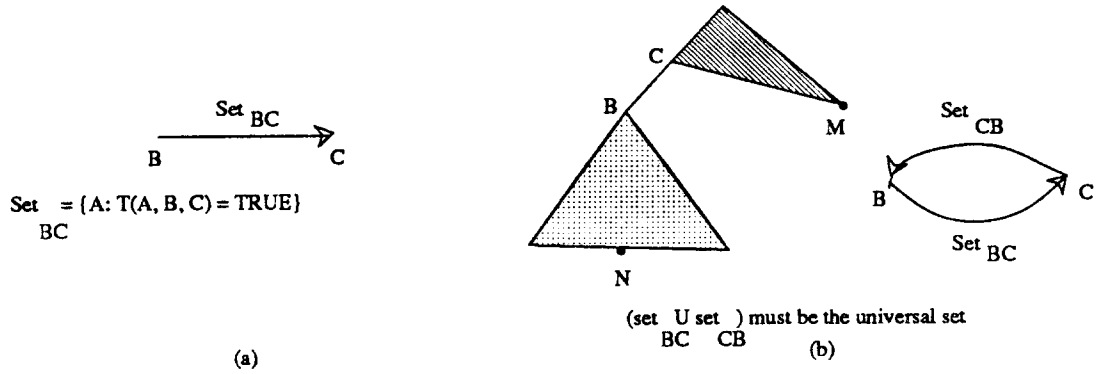

Figure 4.20: LIT-graph representation for the combination consisting of 3-agent trust specifications plus iterative channel composition. (a) The LIT-graph contains an edge BC labeled with set_{BC}, where set_{BC} is the set of all agents A such that $T_A(A, B, C)$ is true. (b) The union of set_{BC} and set_{CB} must be the universal set.

set_{BC}, and an agent M that is a non-descendent of B in the name space must belong to set_{CB}.

□

4.7.2. Duality

It may be observed that Theorems 4.11 and 4.12 are identical except that the sets in Theorem 4.11 are the labels in a LIT-graph whereas the sets in Theorem 4.12 are the labels in a LRT-graph. The difference in the computations of labels in a LIT-graph and those in a LRT-graph is that, in a LIT-graph, a label set_{BC} contains the agents A such that $T_A(A, B, C)$ = true. In a LRT-graph, a label set_{BC} contains the agents A such that $T_A(C, B, A)$ = true. Thus, the conditions for synthesizing name spaces for the cases of iterative and recursive channel composition are identical except for the fact that the last and the first arguments to the trust predicates are interchanged. These results are summarized in the following theorem:

Theorem 4.13 (General Duality Theorem): Any algorithm that synthesizes name spaces from LIT-graphs is also an algorithm for synthesizing name spaces from LRT-graphs, and vice versa. Any algorithm that synthesizes name spaces for 3-agent trust specifications combined with iterative channel composition becomes an algorithm for synthesizing name spaces for 3-agent trust specifications combined with recursive channel composition if the roles of the first and the last arguments to the trust specifications are interchanged, and vice versa.

□

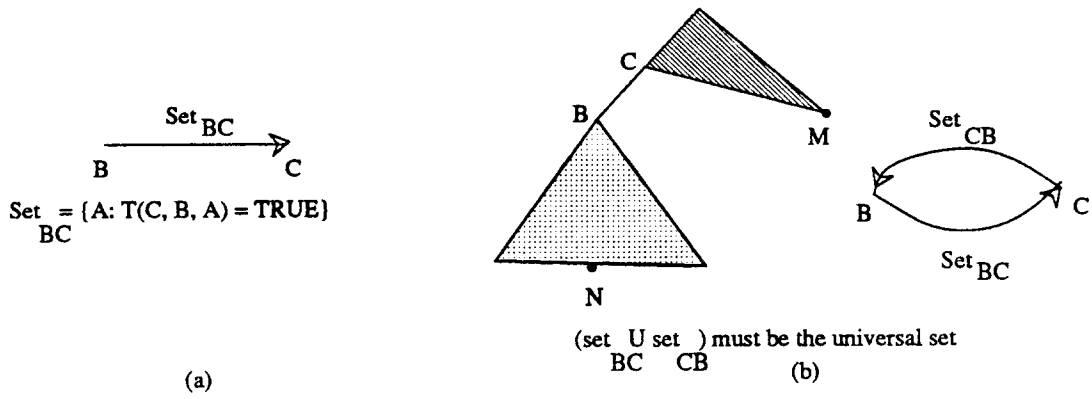

Figure 4.21: LRT-graph representation for 3-agent trust specifications combined with recursive channel composition. (a) The LRT-graph contains an edge BC labeled with set_{BC}, where set_{BC} is the set of all agents A such that $T_A(C, B, A)$ is true. (b) The union of set_{BC} and set_{CB} must be the universal set.

As a consequence of Theorem 4.13, we can limit ourselves to developing name space synthesis algorithms only for 3-agent trust specifications plus iterative channel composition.

4.8. Name Space Synthesis Given Three-Agent Trusts and Iterative Composition

This section gives an algorithm for synthesizing name spaces for 3-agent trust specifications plus iterative channel composition. The algorithm takes a LIT-graph as input, and outputs a name space satisfying the trust specifications represented by the LIT-graph, if such a name space exists.

4.8.1. The Synthesis Algorithm

The algorithm employs a dynamic programming technique to synthesize the name space. Since the algorithm is quite involved, for ease of understanding, we will describe it in a bottom-up fashion with the help of an example.

Algorithm 4.3

Let us assume that there are n agents $l_1, l_2, ..., l_n$ to be named in the name space. $l_1, l_2, ..., l_n$ must occur as leaf nodes in the name space. Let us assume that, out of these n agents, there are m agents $i_1, i_2, ..., i_m$ that can serve as name servers, i.e., as internal nodes in the name space (see Figure 4.22). Whether an agent can serve as a name server or not is the choice of the agent; hence m is determined by the number of agents willing to serve as name servers.

There are at most n steps in the algorithm. At each step there are m trees, each tree rooted at a different internal node.

Step 1: In the first step, m trees are constructed. Each tree has a different internal node as its root and as many leaf nodes as possible as the children of the root. A leaf node has no descendents, and all nodes are its non-descendents. By Theorem 4.11, a leaf node l_B can become a child of an internal node i_C if and only if the edge CB in the input LIT-graph is labeled by the universal set (see Figure 4.23).

In the example, let l_1, l_2 and l_3 become the children of i_1, l_4, l_5 and l_6 become the children of i_2, l_7, l_8 and l_9 become the children of i_3, and l_{10}, l_{11} and l_{12} become the children of i_4 (see Figure 4.24).

This concludes step 1.

Let us assume we have carried out k steps, at the end of which there are m trees, $t_1^k, t_2^k, ..., t_m^k$ rooted at internal nodes $i_1, i_2, ..., i_m$, respectively (see Figure 4.25(a)). Let us further assume that the algorithm does not meet any of the termination conditions to be presented later

Figure 4.22: Internal nodes and leaf nodes for name space design example

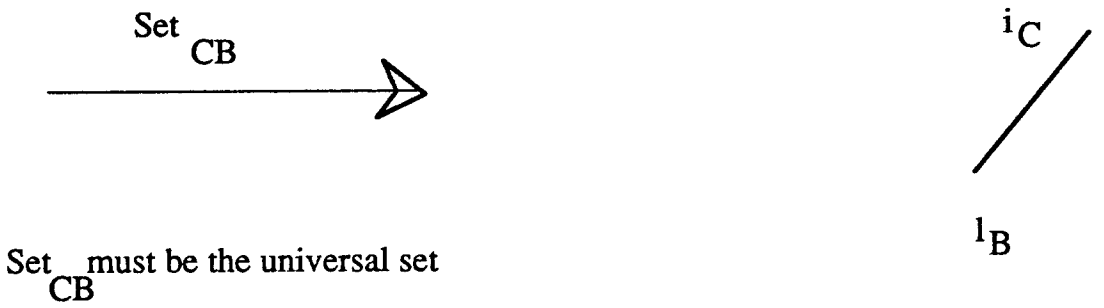

Figure 4.23: Node l_B becomes a child of i_C if and only if set_{CB} is the universal set

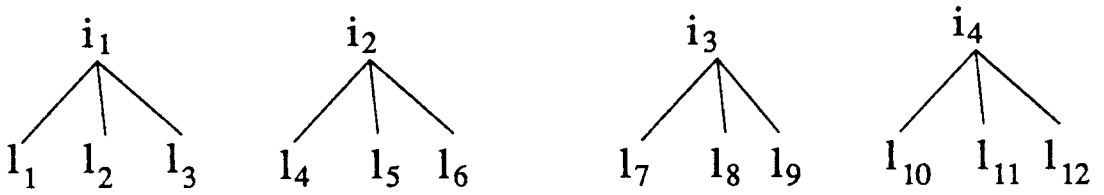

Figure 4.24: Trees at the end of step 1 of Algorithm 4.3 for the example

in this section. (For clarity and ease of understanding, the termination conditions are presented at the end of the description of the $k+1^{th}$ step.) The $(k+1)^{th}$ step of the algorithm is carried out as follows.

Step k+1: We construct m trees ${t_1}^{k+1}$, ${t_2}^{k+1}$, ..., ${t_m}^{k+1}$ in m substeps *substep* $({t_1}^{k+1})$, *substep* $({t_2}^{k+1})$, ..., *substep* $({t_m}^{k+1})$, respectively (see Figure 4.25(b)). Each of these substeps starts from the end of step k, and hence they can all be carried out in parallel. We will describe *substep* $({t_1}^{k+1})$, which consists of constructing ${t_1}^{k+1}$; the other substeps are very similar.

Substep(t_1^{k+1}): Tree ${t_1}^{(k+1)}$ rooted at i_1 is constructed by attaching each of ${t_2}^k$, ${t_3}^k$, ..., ${t_m}^k$ as a subtree of ${t_1}^k$, directly under ${t_1}^k$'s root i_1. Effectively, we are proposing the $m-1$ new independent channels i_1-i_2, i_1-i_3, ..., and i_1-i_m (see Figure 4.25(b-1)). The procedure for attaching ${t_2}^k$ to t_1^k as a subtree is called *attachment* (t_1^k, t_2^k), and is described next. The procedures *attachment* (t_1^k, t_3^k), ... *attachment* (t_1^k, t_m^k) for attaching ${t_3}^k$, ..., ${t_m}^k$ respectively to ${t_1}^k$ are very similar, and can be obtained by modifying in the obvious way the one to be described.

Attachment(t_1^k, t_2^k): When t_2^k is attached as a subtree of t_1^k, root i_2 of t_2^k becomes a child of root i_1 of t_1^k. The nodes in t_1^k and t_2^k must now satisfy the trust relationships represented by the input LIT-graph. The following tests check if the nodes satisfy the required trust relationships, and eliminate the nodes that do not (see Figure 4.26):

(T1): Each node in t_2^k is a descendent of i_2. By Theorem 4.11, each node in t_2^k must belong to set_{21} in the input LIT-graph. Nodes that do not satisfy this condition must be

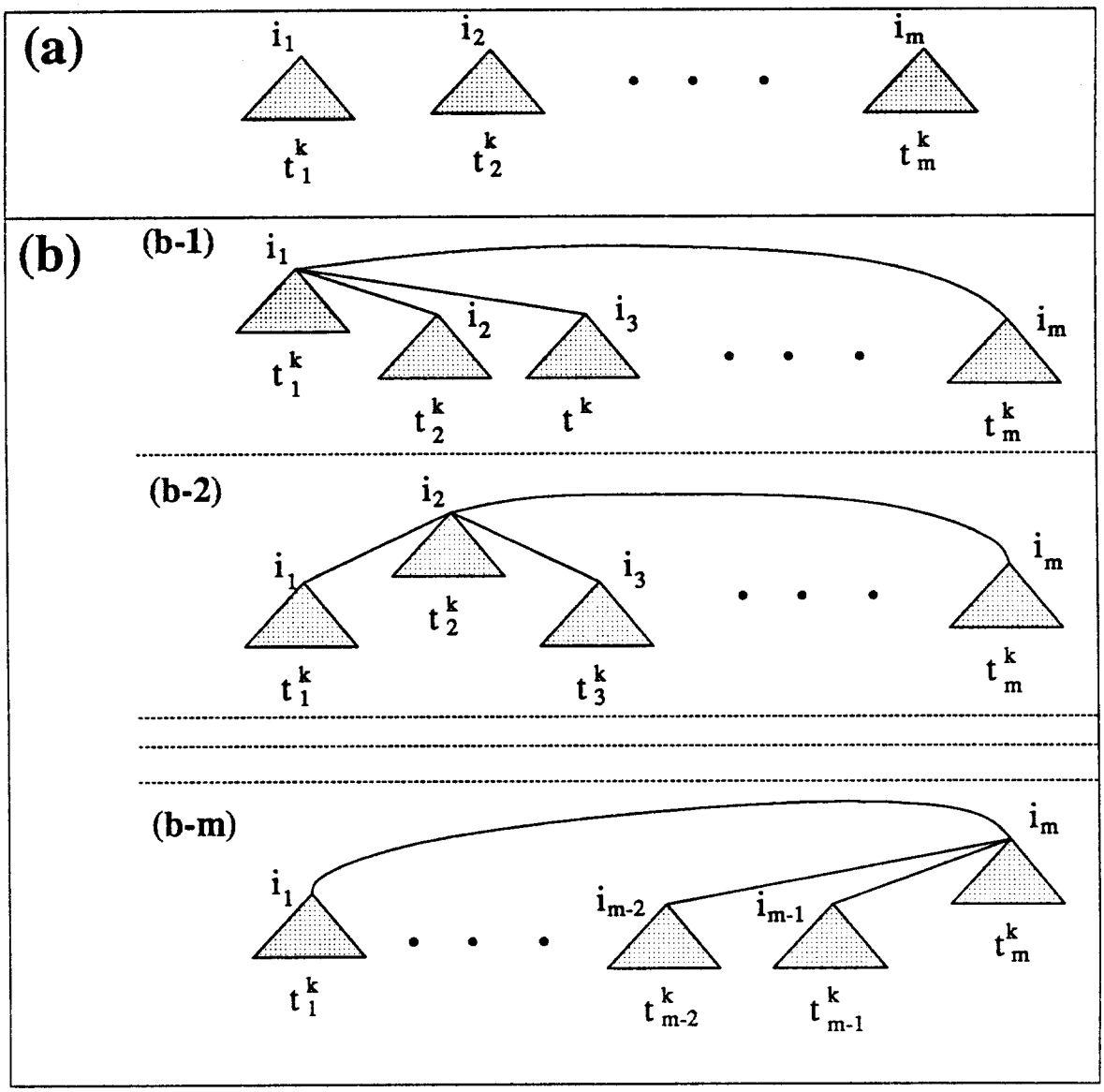

Figure 4.25: Illustration of step k+1 of the name space design algorithm. (a) Trees at the end of step k. (b) Step k+1 consists of substeps *substep* (t_1^{k+1}), *substep* (t_2^{k+1}), ..., *substep* (t_m^{k+1}). Each of these substeps starts from (a), and hence they can all be carried out in parallel. (b-1) *Substep* (t_1^{k+1}), consisting of attachments *attachment* (t_1^k, t_2^k), ... *attachment* (t_1^k, t_m^k) that attach all other trees to t_1^k, (b-2) *Substep* (t_2^{k+1}), consisting of attachments *attachment* (t_2^k, t_1^k), ... *attachment* (t_2^k, t_m^k) that attach all other trees to t_2^k,

deleted from t_2^k. The deletion of a node from a tree is described by Algorithm 4.4 in the

next section, and may not always be possible. Thus, if a node in t_2^k that does not belong to set_{21} cannot be deleted from t_2^k, t_2^k cannot be attached as a subtree of t_1^k, tests T2 and T3 are skipped, and *attachment*(t_1^k, t_2^k) terminates.

(T2): After test T1, each node that is not in t_2^k will be a non-descendent of i_2 in the final tree, and, by Theorem 4.11, such a node must belong to set_{12}. If this is not satisfied, t_2^k cannot be attached as a subtree of t_1^k, test T3 is skipped, and *attachment*(t_1^k, t_2^k) terminates.

(T3): After tests T1 and T2, if a leaf node l_D occurs in both t_1^k and t_2^k, one of the two duplicates of l_D must be eliminated (see Figure 4.26). If $l_D \in set_{21}$, deletion of l_D from t_1^k becomes permissible if the node deletion algorithm, Algorithm 4.4 returns success. If $l_D \in set_{12}$, deletion of l_D from t_2^k becomes permissible if Algorithm 4.4 returns success. If deletion of l_D from either t_1^k or t_2^k becomes permissible, the choice of the tree from which it is to be deleted can be made arbitrarily. That this choice will have no effect on subsequent attachments is shown in Section 4.8.3. If, on the other hand, the deletion of l_D from either t_2^k or t_1^k is not permissible, t_2^k cannot be attached as a subtree of t_1^k, and *attachment*(t_1^k, t_2^k) terminates.

After *attachment*(t_1^k, t_2^k), the succeeding attachments are, in order:

attachment(t_1^k, t_3^k), ..., attachment(t_1^k, t_m^k).

The sequence:

{attachment(t_1^k, t_2^k), ..., attachment(t_1^k, t_m^k)}

forms *substep*(t_1^{k+1}) (see subfigure $b-1$ of Figure 4.25).

The sequence:

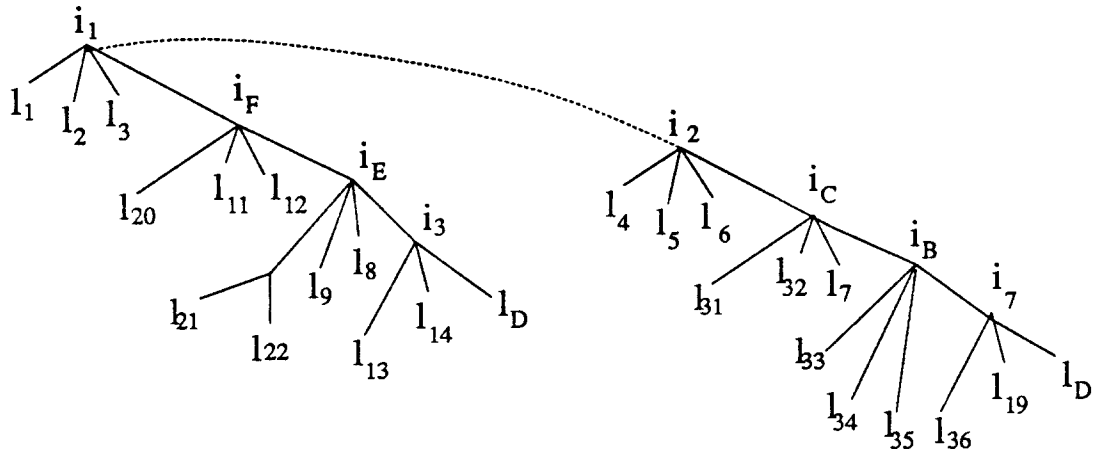

Figure 4.26: Attachment(t_1^k, t_2^k) during step $k+1$

$\{substep(t_1^{k+1}), substep(t_2^{k+1}), ..., substep(t_m^{k+1})\}$

forms *step* $k+1$ (see Figure 4.25).

The algorithm terminates at the end of the $k+1^{th}$ step if any of the following conditions are satisfied:

(1) At least one of $t_1{}^{k+1}, t_2{}^{k+1}, ..., t_m{}^{k+1}$ contains all the leaf nodes $l_1, l_2, ..., l_n$. One of $t_1{}^{k+1}, t_2{}^{k+1}, ..., t_m{}^{k+1}$ that has all the leaf nodes is output as the name space.

(2) $t_1{}^{k+1}, t_2{}^{k+1}, ..., t_m{}^{k+1}$ are identical to $t_1{}^k, t_2{}^k, ..., t_m{}^k$ respectively. In this case, further steps will not yield any new trees, and no name space exists.

This concludes step $k+1$ of Algorithm 4.3. If none of the termination conditions are satisfied, the algorithm proceeds to step $k+2$, without regard for the value of k. However, in Theorem 4.16, we will show that there can be at most m steps in the Algorithm.

□

4.8.2. Leaf Node Deletion Algorithm

Nodes that do not satisfy tests T1, T2 or T3 during an attachment must be deleted from their respective trees. In this section, we present the algorithm for deleting a node from a tree. Note that the deletion of a node from a tree is not always possible.

Algorithm 4.4

Consider an attachment such as *attachment*(t_1^k, t_2^k), in which a leaf node such as l_D is to be deleted from t_2^k (see Figure 4.26). When l_D is in t_2^k, l_D is a descendent of all the nodes that are in the path from the root i_2 of t_2^k to l_D and a non-descendent of all other nodes in t_2^k. For each link $C-B$ in the path from i_2 to l_D, l_D is a descendent of B, and hence, by Theorem 4.11, $l_D \in set_{BC}$. When l_D is deleted from t_2^k, l_D becomes a non-descendent of all nodes in t_2^k; l_D is then a non-descendent of B (see Figure 4.27), and hence by Theorem 4.11, $l_D \in set_{CB}$. Thus, it is permissible to delete l_D from t_2^k only if, for all links $C-B$ in the path from the root i_2 to l_D, $l_D \in set_{CB}$.

This completes the description of Algorithm 4.4.

□

To further visualize the effect of deletion (see Figure 4.27), notice that, when l_D is in t_2^k, for each link $C-B$ in the path from root i_2 to l_D, l_D reaches i_C through i_B, and hence $T_A(l_D, i_B, i_C)$ is true. When l_D is deleted from t_2^k, it has to reach i_B through i_C, and hence $T_A(l_D, i_C, i_B)$ must be true. Recall that deletion is only to be done when there are duplications. Thus, deletion of l_D from t_2^k will *not* cause the disappearance of l_D from the global forest at level k.

4.8.3. Independence Properties of Duplicate Elimination in Algorithm 4.3

Test T3 in an attachment performs deletion of duplicate nodes. If the deletion of a duplicate node from either of the trees involved in an attachment is permissible, a question may arise as to whether the choice will have any effect on subsequent attachments. Suppose that the choice does have an effect. In order to find a name space if one exists, Algorithm 4.3 would have to exhaust the entire choice space, and hence would have to backtrack if it fails to find a name space tree. Consequently, Algorithm 4.3 would become very cumbersome.

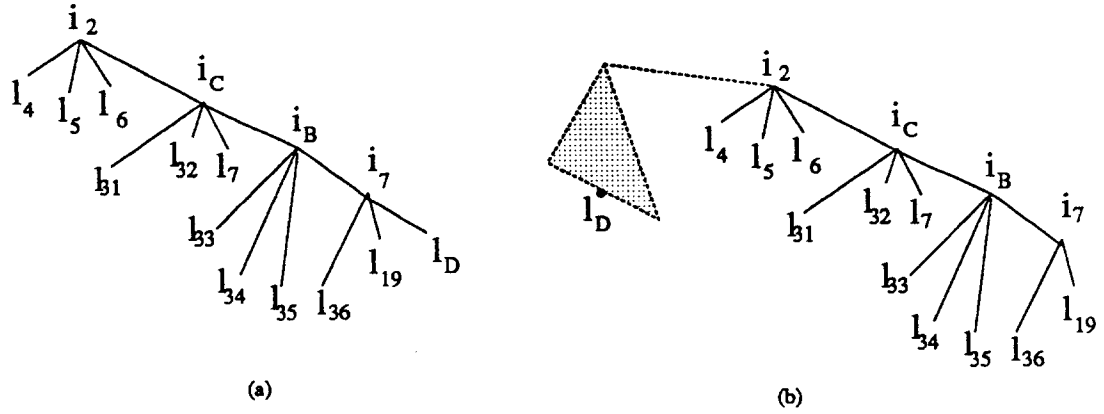

Figure 4.27: Effect of deleting node l_D from tree t_2^{k+1}. For each link C–B in the path from the root i_2 to l_D, (a) prior to deletion when l_D is in t_2^{k+1}, l_D is a descendent of i_B, and (b) after deletion, l_D is a non-descendent of i_B.

Fortunately, the following theorem proves that the choice of the duplicate for deletion will have no effect whatsoever on subsequent attachments, and thus Algorithm 4.3 does not have to backtrack.

Theorem 4.14: Suppose that in an attachment, say *attachment*(t_x^k, t_y^k), l_D occurs as a duplicate, and the deletion of l_D from either t_x^k or t_y^k is permissible, choosing either t_x^k or t_y^k for deleting l_D will have no effect on subsequent attachments and hence the choice between them can be arbitrary.

Proof: To maintain uniformity of description with Algorithms 4.3 and 4.4, we will consider *attachment*$_1$ = attachment(t_1^k, t_2^k) for the purposes of the proof. The same proof holds for any other attachment.

Let *choice*$_1$ denote the deletion of l_D from t_1^k, and *choice*$_2$ denote the deletion of l_D from t_2^k. *Choice*$_1$ requires that the deletion of l_D from t_1^k be permissible in Algorithm 4.4. Hence *choice*$_1$ requires that the following condition be satisfied (see Figure 4.28):

(S1): For each link F–E in the path from i_1 to l_D, $l_D \in set_{FE}$

Choice$_2$ requires that the deletion of l_D from t_2^k be permissible in Algorithm 4.4. Hence *choice*$_2$ requires that the following condition be satisfied (see Figure 4.29):

(S2): For each link C–B in the path from i_2 to l_D, $l_D \in set_{CB}$

Consider the subsequent attachment, namely, *attachment*$_2$ = attachment(t_1^k, t_3^k). Notice that, if l_D does not occur in t_3^k, the deletion of l_D in *attachment*$_1$ has no effect on *attachment*$_2$. Hence making *choice*$_1$ or *choice*$_2$ has no effect on *attachment*$_2$.

Suppose that l_D does occur in t_3^k. l_D must be deleted during *attachment*$_2$. The only effect that *choice*$_1$ or *choice*$_2$ could possibly have on *attachment*$_2$ is on the deletion of l_D during *attachment*$_2$. There are two possibilities for the deletion of l_D during *attachment*$_2$:

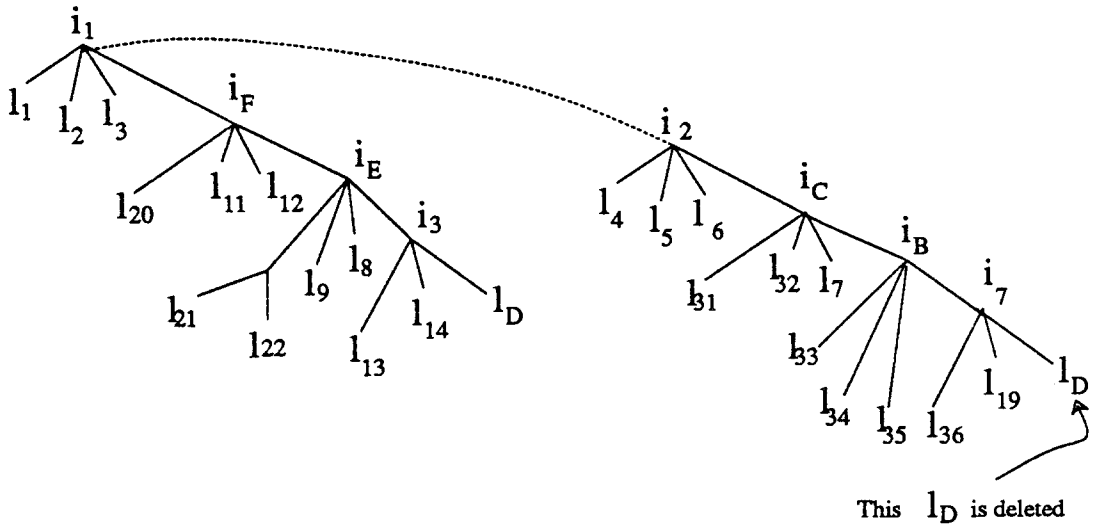

Figure 4.28: *Choice*$_1$: During attachment of t_2^k to t_1^k, duplicate l_D is deleted from t_2^k.

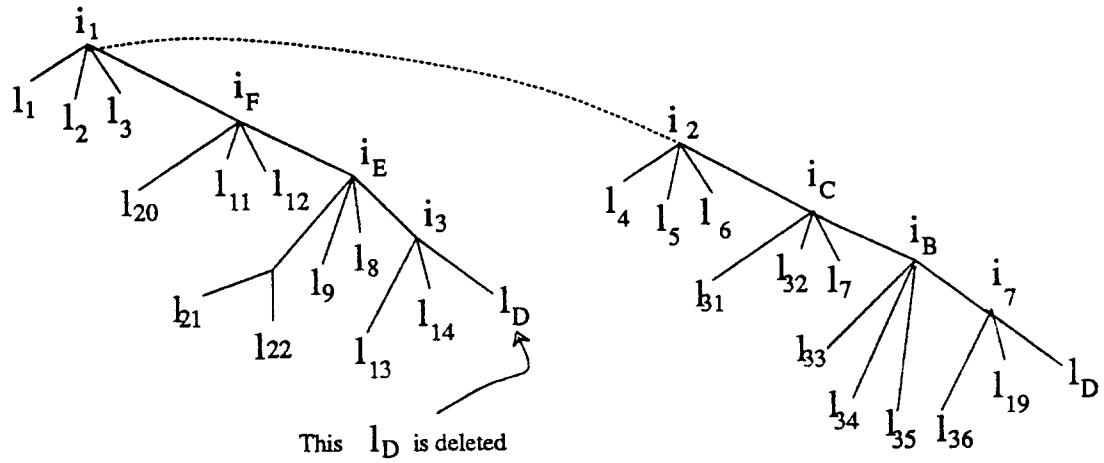

Figure 4.29: *Choice*$_2$: During attachment of t_2^k to t_1^k, duplicate l_D is deleted from t_1^k.

(P1): Deletion of l_D from t_3^k, or

(P2): Deletion of l_D from t_2^k or t_1^k depending on whether $attachment_2$ was preceded by $choice_1$ or $choice_2$, respectively.

Consider the possibility P1. If $choice_1$ was taken during $attachment_1$, deletion of l_D from t_3^k during $attachment_2$ is permissible in Algorithm 4.4 if (see Figure 4.30):

(S3): For each link H–G in the path from i_3 to l_D, $l_D \in set_{HG}$

If $choice_2$ had been taken during $attachment_1$, deletion of l_D from t_3^k during $attachment_2$ is permissible in Algorithm 4.4 if (see Figure 4.31):

(S4): For each link H–G in the path from i_3 to l_D, $l_D \in set_{HG}$

Conditions S3 and S4 are identical. Thus, for possibility P1 during $attachment_2$, making $choice_1$ or $choice_2$ during $attachment_1$ has no effect on $attachment_2$.

Now consider possibility P2. Suppose that $choice_1$ was taken during $attachment_1$. Deletion of l_D from t_2^k during $attachment_2$ is permissible in Algorithm 4.4 if (see Figure 4.30):

(S5): For each link C–B in the path from i_2 to l_D, $l_D \in set_{CB}$

Suppose that $choice_2$ was taken during $attachment_1$. Deletion of l_D from t_1^k during $attachment_2$ is permissible in Algorithm 4.4 if (see Figure 4.31):

(S6): For each link F–E in the path from i_1 to l_D, $l_D \in set_{FE}$

There is a difference in conditions S5 and S6. Suppose that S5 is satisfied. $Choice_1$ must have been taken during $attachment_1$, and hence S1 must be satisfied. But S1 is identical to S6, and hence S6 is satisfied. Thus, S5 => S6.

Suppose that S6 is satisfied. $Choice_2$ must have been taken during $attachment_1$, and

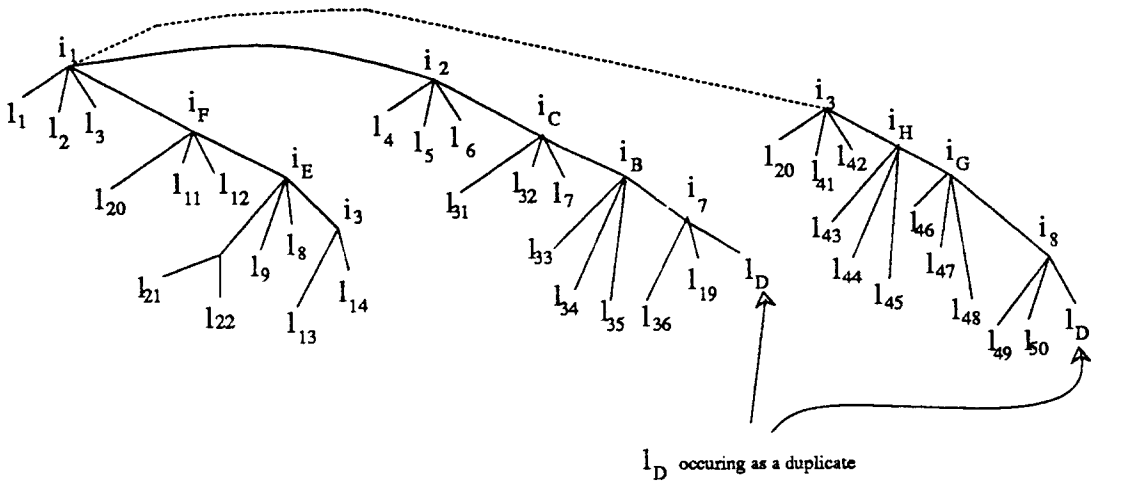

Figure 4.30: $Attachment_2$ after $choice_1$: l_D occurs as duplicates in t_2^k and t_3^k.

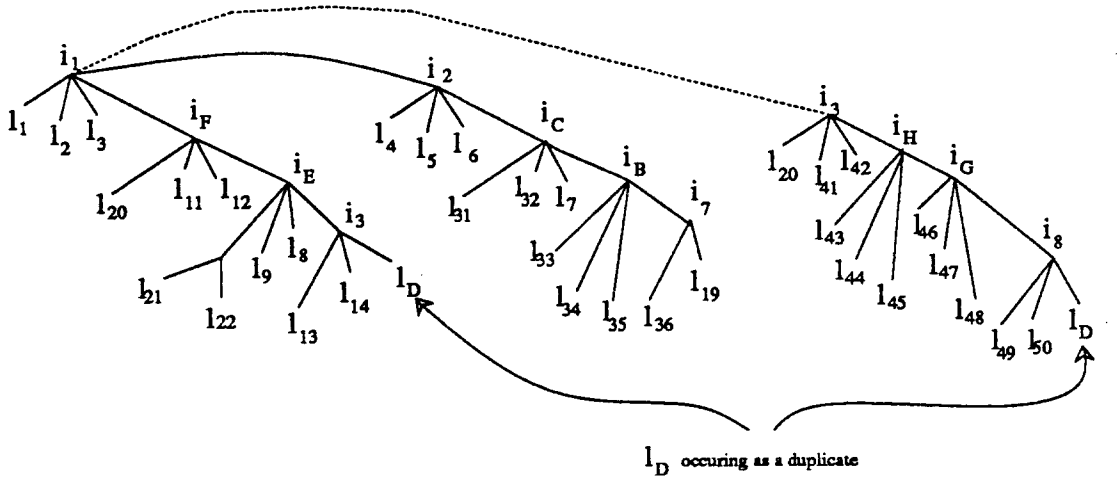

Figure 4.31: *Attachment*$_2$ after *choice*$_2$: l_D occurs as duplicates in ${t_1}^k$ and ${t_3}^k$.

hence S2 must be satisfied. But S2 is identical to S5, and hence S5 is satisfied. Thus, S6 => S5.

In conclusion, S5 <=> S6. Hence, making *choice*$_1$ or *choice*$_2$ does not have any effect in the case of possibility P2.

This completes the proof that making *choice*$_1$ or *choice*$_2$ has no effect on subsequent attachments, and hence can be arbitrary. Thus, in any attachment, if the deletion of either of the duplicates is possible, the choice of the duplicate to be deleted can be arbitrary.

□

4.8.4. Correctness of Algorithm 4.3

The following theorem proves the correctness of Algorithm 4.3.

Theorem 4.15: If the channel composition order is iterative, a name space synthesized by Algorithm 4.3 satisfies the given trust specifications, and Algorithm 4.3 synthesizes a name space if one exists when node deletions are independent.

Proof: The proof is by induction on the number of steps in the algorithm. The induction hypothesis is as follows:

Induction Hypothesis: At step k, for all x from 1 through m, t_x^k satisfies the given trust relationships, and t_x^k contains all the leaf nodes that can possibly be at a distance k or less from its root.

While deriving the complexity of Algorithm 4.3 in Theorem 4.16, we show that, if the number of internal nodes is m, there can be at most m steps in the Algorithm. Thus, when $k = m$, the induction hypothesis becomes the theorem itself. Hence, to prove the theorem, it suffices to prove the induction hypothesis.

Base step: Let $k = 1$ in the induction hypothesis. For each x and y, Algorithm 4.3 adds a leaf node l_y as a child of i_x only if set_{yx} is the universal set. Since l_y is a leaf node and all other nodes are its non-descendents, by Theorem 4.11 the link i_x-l_y satisfies the given trust relationships. As this is true for all x and y, all the trees satisfy the given trust relationships. Since Algorithm 4.3 tries to add each leaf node to each internal node, each tree contains all the leaf nodes that can possibly be at a distance 1 from the root of the tree. This completes the proof of the base step.

Induction step: Let us assume that the induction hypothesis is true for k. We have to show that the hypothesis is true for $k+1$. We will give the proof for $x = 1$ in the hypothesis. The same proof holds for all other values of x.

Consider t_1^k, the tree rooted at i_1 at the end of step k. In each of the attachments (t_1^k, t_2^k), (t_1^k, t_3^k), ..., (t_1^k, t_m^k), tests T1 and T2 are direct applications of Theorem 4.11. Hence, they eliminate all the nodes that do not satisfy the required trust relationships, and t_1^{k+1} satisfies the given trust relationships. This proves the first part of the induction hypothesis.

Since the induction hypothesis is assumed to be true for k, t_1^k contains all the leaf nodes that can possibly be at a distance not exceeding k from i_1. Now consider a leaf node l_x that can possibly be at a distance not exceeding $k+1$ in a tree rooted at i_1. l_x has to be either at a distance not exceeding k or at a distance of $k+1$. If l_x is at a distance not exceeding k, it must be present in t_1^k, and hence it will be present in t_1^{k+1}. If l_x is at a distance of $k+1$ from i_1, it must be at a distance k from some child i_2 of i_1. By the induction hypothesis the tree t_2^k at step k contains all nodes that can possibly be at a distance not exceeding k, and hence contains l_x. During attachment(t_1^k, t_2^k) of step $k+1$, Algorithm 4.3 attaches t_2^k as a subtree of t_1^k, and, when node deletions are independent, l_x becomes part of t_1^{k+1} at a distance of $k+1$ from the root. Thus, t_1^{k+1} contains all the leaf nodes that can possibly be at a distance $k+1$ or less from i_1. This completes the proof of the induction step and of Theorem 4.15.

In a name space, the path from the root to a leaf node cannot contain duplicate internal nodes. This is because, if a path contains duplicate internal nodes, the part of the path between the duplicate nodes together with one of the duplicate nodes can be removed from the path. For example, suppose that a path contains the sequence $i_1, i_2, ..., i_x$, and i_1, in which there is a duplication of i_1. The nodes $i_1, i_2, ..., i_x$ can be deleted from the path, eliminating the duplication. Thus, in a name space, the path from the root to any leaf can contain at most all the m internal nodes (including the root). Therefore, each leaf node must be at a distance m or less from the root. But notice that, when $k = m$, the induction hypothesis that we proved above becomes the theorem itself, and hence each tree at step m contains all the leaf nodes that can possibly be at a distance m or less from the root. Thus, if a name space exists, there will be a tree containing all agents as leaf nodes at the end of step m of Algorithm 4.3. Hence, Algorithm 4.3 synthesizes a name space if one exists.

This completes the proof of Theorem 4.15.

□

4.8.5. Complexity of Algorithm 4.3

At step S of Algorithm 4.3, to each tree all the nodes that can possibly be at distance not exceeding S from the root of the tree are added to the tree. Since there are at most m internal nodes, a leaf node can at most be at a distance of m from the root of the name space. Thus, Algorithm 4.3 synthesizes a name space if one exists in at most m steps, and hence there are at

most m steps in Algorithm 4.3.

Each step of the algorithm consists of m substeps. Each substep consists of $m-1$ attachments. Thus, at each step there are $O(m^2)$ attachments, and there are at most $O(m^3)$ attachments in the algorithm.

In each attachment, tests T1, T2 and T3 are executed once for each leaf node in the tree being attached, and hence they are executed at most n times. T1 and T3 each consist of node deletion, and each deletion involves testing $O(n)$ trust relationships and hence takes $O(n)$ time. T2 consists of checking one trust relationship per leaf node and hence takes $O(n)$ time. Thus each attachment takes $O(n^2)$ time at worst. These results are summarized in the following theorem:

Theorem 4.16: If m is the number of internal nodes and n the number of leaf nodes, there can be at most m steps in Algorithm 4.3, and the worst case complexity of Algorithm 4.3 is $O(m^3n^2)$.

□

When $O(m) = O(n)$, by Theorem 4.16, the worst case complexity of Algorithm 4.3 is $O(n^5)$.

Theorem 4.9, together with the observation that the problem of designing a name space given 3-agent trust specifications is the general case of which the problems of designing a name space given 2-agent trust specifications are special cases, yields that putting an upper bound on the children of each node in the name space for 3-agent trust specifications is NP-complete. This is summarized in the following theorem:

Theorem 4.17: Given 3-agent trust specifications and either iterative or recursive channel composition, the problem of designing a name space with an upper bound on the number of children of each node is NP-complete.

□

4.9. An Example

The name space design algorithms described in this chapter have been implemented and experimented with. Figure 4.32 shows the name space synthesized by Algorithm 4.3 from a sample set of trust specifications. The trust specifications are enumerated in Appendix 1. Only the internal nodes of the name space are shown: each node is assumed to have leaf nodes corresponding to the employees of the organization labeling the node.

The trust specifications were then changed and the name space was reconstructed using Algorithm 1. The changes in trust specifications were that, the trust relationships in which agents trust *ibm* for *ibm−j* and vice-versa were replaced by trust relationships in which agents trust *ibm* for *sony−usa* and vice-versa. Figure 4.33 shows the reconstructed name space.

The two name spaces are quite different, even though the difference in their trust specifications is not significant. Thus, small changes in trust relationships can cause substantial differences in the name space configuration. This shows that trust relationships can have significant effects on the structure of a name space. Name space design that takes into account such non-trivial effects is too complicated to be carried out by manual trial-and-error methods for a large distributed system. Thus, the algorithms described in this chapter are useful for designing real distributed systems.

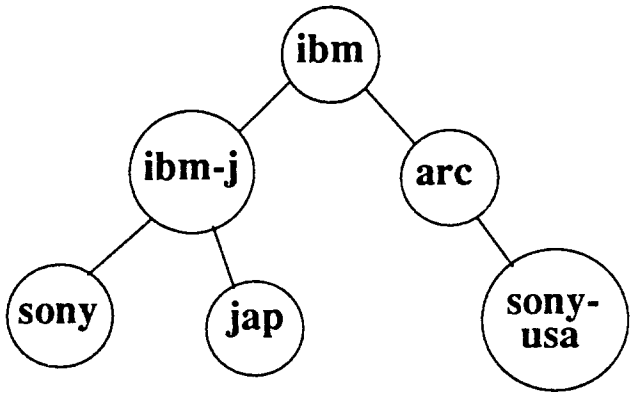

Figure 4.32: Name space for a sample set of trust specifications

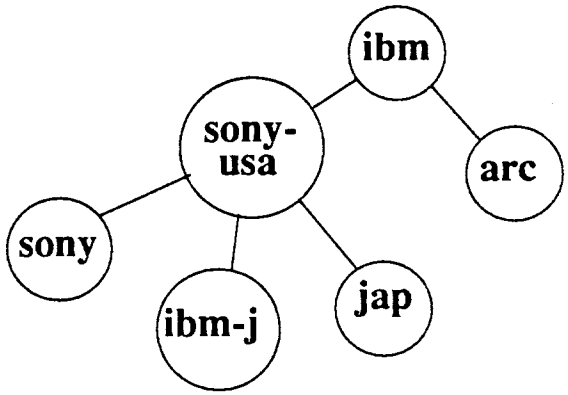

Figure 4.33: Name space reconstructed after slightly changing the sample set of trust specifications.

4.10. Conclusion

In a distributed system, it is desirable to have a tree of independent channels. A tree of independent channels also represents a global name space. There are two channel composition orders, namely, *iterative* and *recursive*. Iterative and recursive channel compositions require different trusts and are duals of each other. As one of the most important applications of a formal theory of trust, we have developed polynomial-time algorithms for synthesizing name spaces so that, given a channel composition order and the trust relationships of agents, channel composition between any two agents requires only a subset of the given set of trust relationships. The trust relationships are in general functions of three agents, but can also be functions of two agents, in which case the algorithms are simpler. Each node in the name space has to store the database of public keys of its children, and hence it is desirable to put an upper bound

on the size of this database. However, this problem is NP-complete. Sample runs of the name space design algorithms show that small differences in trust relationships can cause substantial differences in name spaces, thus demonstrating that trust relationships can have a significant effect on the structure of a name space. Design of a name space that takes into account the non-trivial effects of trust relationships is too complicated to be done by manual trial-and-error methods for a real distributed system (especially a VLDS), from which we can infer the practical utility of the algorithms described in this chapter.

CHAPTER 5

TRADING TRUST REQUIREMENTS FOR PERFORMANCE

No synthesis is complete without performance considerations. Under some conditions, to improve performance of channel establishment mechanisms, we may accept to increase their trust requirements. If channel composition is PKE-based, slightly increasing the trust requirements allows agent-to-agent channels to be built on top of host-to-host channels. Only the host-to-host channels need be established over the network, and this approach can greatly increase the performance of agent-to-agent secure communication with respect to that of establishing agent-to-agent channels directly. The accompanying increase in trust requirements is still always a subset of the set of trust specifications from which the system's name space has been synthesized. However, if channel composition is SKE-based, this approach requires global trusts, which may not be satisfied in the name space. The protocol for establishing host-to-host channels can be handled at the subtransport level of the network protocol hierarchy. A prototype of the subtransport-level channel establishment protocol has been implemented on Sun 3/50 workstations connected by a 10 Mb/s Ethernet. Experimental measurements confirm that both the average latency of messages and the maximum throughput improve substantially when, instead of establishing agent-to-agent channels directly, host-to-host channels are established, and agent-to-agent channels are built on top of host-to-host channels. These improvements are primarily due both to the sharp decrease in the number of channel establishment operations across the network and to piggybacking of messages from several agent-to-agent channels on to a single host-to-host channel message.

5.1. Introduction

In Chapter 3, protocols for PKE- and SKE-based channel composition were analyzed for their trust requirements, and it was shown that PKE-based channel composition has much smaller trust requirements. In the previous chapter, we showed how to construct PKE-based name spaces given the trust relationships of all the agents sharing the distributed system. When a new channel, say channel(A_i, A_k), is established using a PKE-based name space, A_i obtains the public key of A_k. Authentication of a message from A_k to A_i on channel(A_i, A_k) is provided by encrypting the message with A_k's private key. Privacy of a message from A_i to A_k on channel(A_i, A_k) is provided by encrypting the message with A_k's public key.

However, public key encryption is expensive [Koc, NBS77]. An alternative way would be for A_i and A_k to agree upon a single key S_{ik} using the first few messages on channel(A_i, A_k), and then use S_{ik} as the key of channel(A_i, A_k) [Dif82, PoK79]. Authentication of a message from A_k to A_i on channel(A_i, A_k) would in this case be provided by a cryptographic checksum computed using S_{ik}. Privacy of a message from A_i to A_k on channel(A_i, A_k) is provided by encrypting the message with S_{ik}. This *bootstrapped* PKE-based channel composition protocol combines the advantages of PKE and SKE schemes, i.e., it has the efficiency of the SKE scheme while having the smaller trust requirements of the PKE scheme.

The bootstrapped PKE-based protocol, even though it is much more efficient than a pure PKE-based protocol, has significant performance disadvantages with respect to protocols without security mechanisms. Suppose that there are agents A_{i1} and A_{i2} on a host H_A, and there

are agents A_{k1} and A_{k2} on a second host H_B [1]. If each agent on H_A communicates with each agent on H_B and vice versa, eight channels (four bidirectional channels) have to be established. Thus, the number of channels to be established in the worst case grows quadratically with the number of agents on the two hosts (see Figure 5.1). Each channel establishment involves agreeing upon a single key, and each agreement requires a three-way handshake protocol. The cost of such a channel establishment mechanism can become sufficiently prohibitive so as to dissuade agents from using secure communication channels entirely.

The goal of this chapter is to investigate whether trust relationships can be traded for performance; in particular we want to design a protocol with substantially improved performance but with slightly higher trust requirements. We will show how, in a PKE-based name space, by only slightly increasing the trust requirements, the performance can be greatly improved, while the increased trust requirements still form a subset of the set of trust specifications from which the name space has been synthesized. We will also show how, in an SKE-based name space, the requisite increase in trust requirements is so unacceptable as not to permit any practical increase in performance.

The performance disadvantages of pure/bootstrapped PKE-based channel establishment protocols stem from the fact that, for each pair of communicating agents on two hosts, a

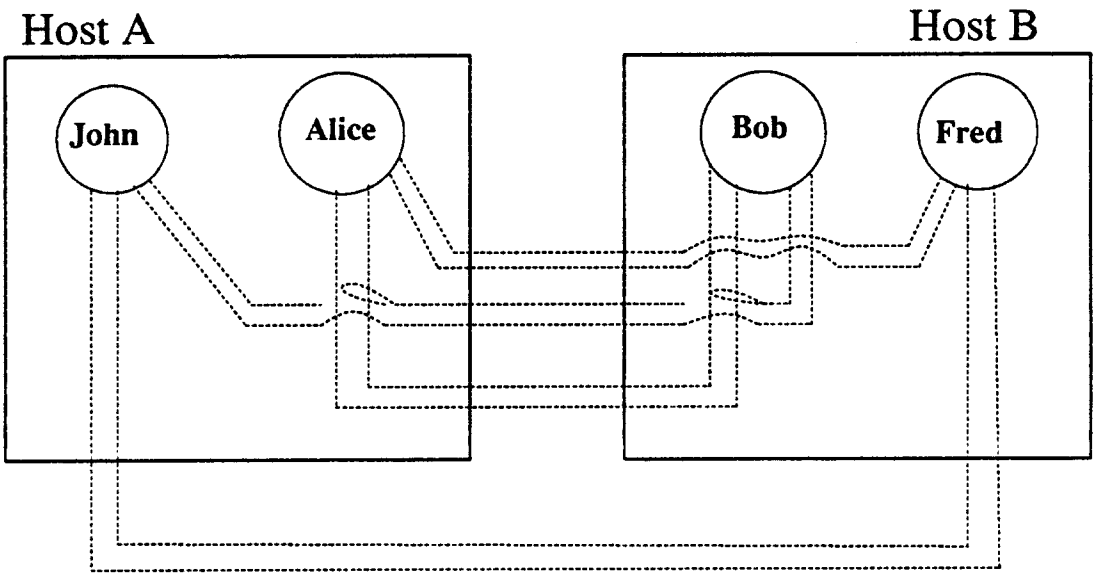

Figure 5.1: Multiple user-to-user channels

[1] When we say an agent is on a host, we mean that a process belonging to the agent is on the host. Similarly, an agent-to-agent channel between two agents means a process-to-process channel between two processes belonging to the two agents.

separate channel must be established across the network. To increase the performance, we must reduce the number of channels established across the network. In this chapter we present a channel establishment protocol called *Authenticated Datagram Protocol (ADP)* [2], which establishes just one host-to-host channel across the network between any two hosts, and builds agent-to-agent channels on top of these host-to-host channels.

The reduction in the number of channels that are established across the network in ADP comes with an accompanying increase in trust requirements. This increase in trust requirements consists of trust relationships involving hosts on which agents have processes. In order effectively to describe these trust relationships involving hosts and agents, we present a high level model of process execution in Section 5.2. In Section 5.3 we describe ADP, and in Section 5.4 we derive ADP's trust requirements, and show how they are noticeably higher than those of a pure PKE-based channel establishment protocol. We then introduce some modifications to ADP that substantially reduce its trust requirements without affecting its performance. With these modifications, ADP's trust requirements become only slightly higher than those of a pure PKE-based channel establishment protocol. Moreover, the increased trust requirements still form a subset of the set of trust specifications from which the name space has been synthesized. In Section 5.5, we show that, if an SKE-based name space is used, building agent-to-agent channels upon host-to-host channels (as in ADP) results in global trust requirements which may not be satisfied in the name space. Section 5.6 defines the concept of a trust domain, and shows how it can be used further to increase the performance of ADP. Section 5.7 details the advantages of ADP over directly establishing agent-to-agent channels across the network, and Section 5.8 presents results of experimental measurements of a prototype of ADP that confirm its expected performance benefits. Finally, Section 5.9 concludes the chapter.

5.2. A Model of Process Execution on Hosts

Each host has a *kernel* running on it. At any point in time, each host has an agent that is the host's *owner*. Host ownership is established at boot time, before network communication takes place; it might be done manually or from a ROM. Usually, the agent who boots the kernel on the host becomes the host owner. Host ownership may change over time, e.g., as different people boot a public workstation. Each host has a (public-key, private-key) pair associated with it, which is the (public-key, private-key) pair of the host owner. The trust relationships of a host are those of its owner. A crash-free period under a single host owner is called a *kernel session*. In the sequel, we shall use the terms "host" and "kernel" interchangeably. We shall also use the terms "agent", "user" and "owner" synonymously.

The host may support multiple *user processes*, each of which has an agent as its owner, perhaps different from the host owner. Processes communicate with each other through messages. Each message has a message sender field containing the name of the owner of the sending process, and a message receiver field containing destination information. A kernel has access to the private keys of the host owner and of the owners of all the user processes it has executed or is executing.

A kernel must satisfy some correctness requirements with regard to security. There has been substantial formal work in the area of kernel security correctness [CGH81, Lan81, Sal74]. Without going into formal descriptions of secure kernels, for the purposes of discussing how

[2] The protocol is so named because it provides message authenticity for all messages, and assumes the existence of an underlying network protocol that provides at least a host-to-host datagram service.

ADP might fit inside a secure kernel, we will give an intuitive set of conditions that a secure kernel must satisfy.

Figure 5.2 represents our model for the organization of the kernel. It consists of modules of code and private data. The passing of messages between modules is handled by a special kernel module called the *message passing module*. The channel establishment functions are handled by a module called the *security module*. Kernel modules which handle either an outgoing message before it is passed to the security module or an incoming message after it has been processed by the security module are called *type-1 modules*. Protocol modules above the layer at which channel establishment mechanisms are handled are examples of type-1 modules. Kernel modules which handle either an outgoing message after it has been processed by the security module or an incoming message before it has been processed by the security module are called *type-2 modules*. In a protocol architecture where channel establishment mechanisms are handled above the data link layer, a network driver is an example of a type-2 module. Kernel modules other than the security module, the message passing module, the type-1 modules, and the type-2 modules are called *type-3 modules*. The private keys are part of the private data storage of the security module. The security module, the message passing module, the type-1 modules, and the type-2 modules are together called *critical modules*.

A kernel is *security-correct* if the following conditions hold:

(1) The only way for a user process to communicate with the kernel is through messages.

(2) When a user process sends a message to a kernel module, the message passing module sets the message sender field to be the owner of that process. Thereafter, the message passing module and the type-1 modules do not change (a) the message sender field, or (b) the message receiver field, (c) the data part of the message.

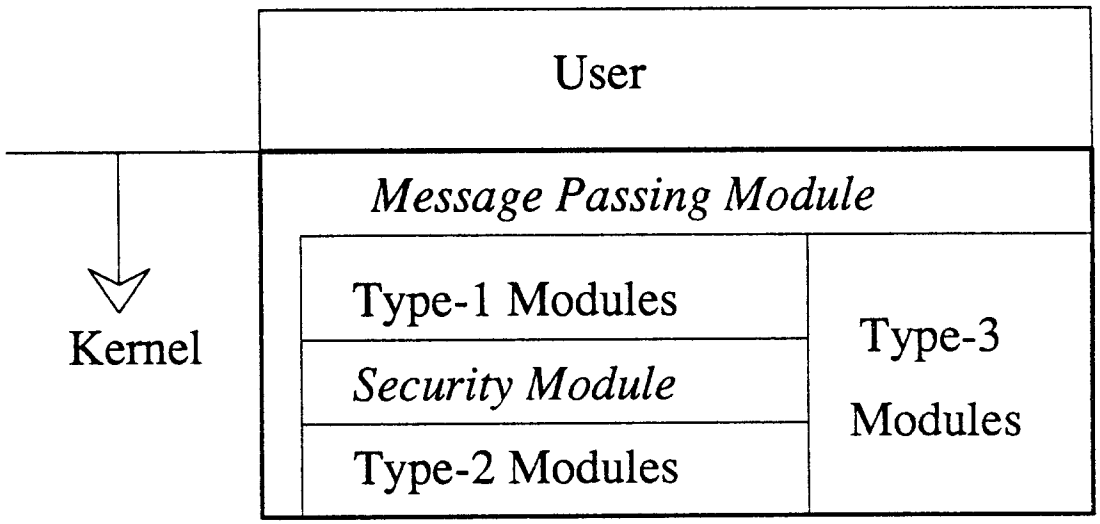

Figure 5.2: Kernel module structure

(3) The message passing module does not deliver a message to a user process if the owner of that user process is different from that indicated in the message receiver field.

(4) The private data storage of the security module is read or written by no other module.

(5) The security module executes its algorithms (to be given later) correctly.

(6) Type-2 modules do not directly communicate with type-1 or type-3 modules or user processes.

These conditions were obtained from intuitive notions of what a non-malicious kernel should provide with respect to secure communication between user processes.

When an agent A_i executes a process on a security-correct host H_A, there are some implications for A_i's trust relationships. Since A_i's private key is accessible to H_A, H_A is assumed not to use the private key to masquerade as A_i or reveal secret messages sent to A_i, and is assumed not to reveal the private key. Thus, a trust relationship that guarantees the following three conditions is required between A_i and the owner of H_A:

For each agent A_x $(x \neq i)$,

(1) When A_x receives a message encrypted with A_i's private key, the message was not sent by H_A masquerading as A_i.

(2) When A_x sends a secret message encrypted with A_i's public key, host H_A, which can decrypt this message with A_i's private key, does not reveal the secret message.

(3) H_A does not reveal A_i's private key to A_x.

If A_j denotes the owner of H_A, the above trust relationship between A_i and A_j can be formally expressed using the key user-possessor trust defined in Chapter 3. The first aspect of the trust is expressed by message privacy trust, the second by trust against masquerading and the third by key privacy trust. The three together form key user-possessor trust, which with universal quantification over A_x defines the **Universal Trust:**

$T_U(A_i, A_j)$ (Universal Trust): $T_U(A_i, A_j)$ is true if and only if $\forall\ A_x\ x \neq i$, $T_{KUP}(A_x, A_j, A_i)$ = true.[3]

$T_U(A_i, A_j)$ is required to be true whenever a host owned by A_j has access to A_i's private key, and vice versa.

Universal trust is transitive, as shown by the following theorem:

Theorem 5.1 (Transitivity Theorem): For all agents A_i, A_j and A_k, if $T_U(A_i, A_j)$ = true and $T_U(A_j, A_k)$ = true, then $T_U(A_i, A_k)$ = true.

Proof: The proof is fairly simple.

Since $T_U(A_i, A_j) = true$, a host H_j owned by A_j has access to A_i's private key in H_j's storage. (5.1)

Since $T_U(A_j, A_k) = true$, a host H_k owned by A_k has access to A_j's private key. With A_j's private key in its possession, H_k has access to all of H_j's storage. (5.2)

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[3] $T_{KUP}(A_x, A_j, A_i)$ is trivially true for $x=j$.

By (5.1) and (5.2), H_k has access to A_i's private key. Thus $T_U(A_i, A_k)$ must be true.

□

If we view the universal trust as a binary relation on agents, we can define a set of agents, denoted by *key-closure*, as the following union of transitive closures of the universal trust.

key-closure(A_i): Union of the transitive closures of $T_U(A_i, A_y)$ for all A_y.

Key-closure(A_i) will contain the owners of all hosts that have access to A_i's private key.

5.3. The Authenticated Datagram Protocol

ADP [AnV87] is a host-to-host channel establishment protocol, and hence is handled at the subtransport level of a network protocol hierarchy [AFV87c]. ADP has been designed and implemented [AFV87b] as part of DASH, an experimental distributed operating system [AFV87a] being designed at the University of California at Berkeley.

DASH is an open system in which many transport-level protocols [Tan81, Tan88], both stream-oriented and request/reply, may exist. The clients of ADP are kernel-level transport protocol modules, and ADP in turn is a client of multiple network-level services that provide at least a host-to-host datagram service [Tan81, Tan88] (see Figure 5.3).

ADP maintains two kinds of channels, *host-to-host channels* and *agent-to-agent channels*, with the latter being built on top of the former. Host-to-host channels are also called *ADP channels*. A summary description of ADP's operation, as it would be carried out between two hosts H_A and H_B, is as follows. The two hosts establish an ADP channel using a bootstrapped PKE-based channel composition protocol. No agent-specific channels are established across the network - all user messages between H_A and H_B are sent on the ADP channel between them. This reduces the worst case channel establishment overhead from being a quadratic function of the number of users to being a constant factor. H_A and H_B build agent-to-agent channels upon their ADP channel by sending to each other the PKE-based certificates [Akl83, Den84b]

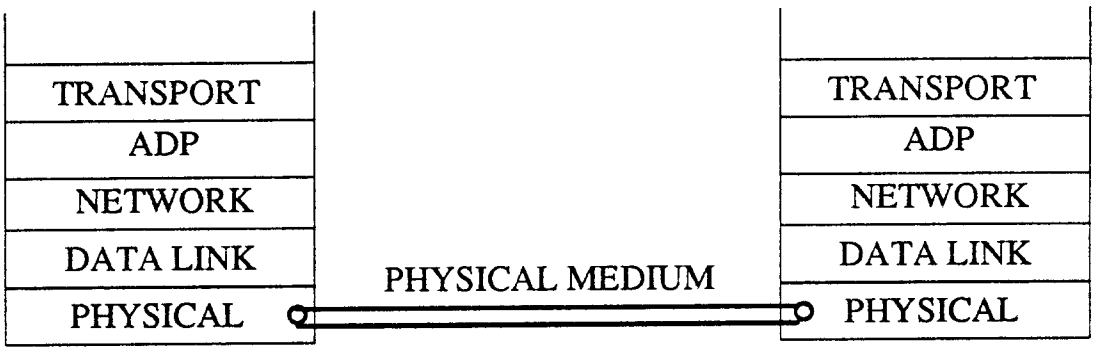

Figure 5.3: Position of ADP in the ISO/OSI model of network architecture

(described below) of their respective users. The two hosts cache the PKE-based certificates sent and received, thereby reducing the overhead of building agent-to-agent channels over their ADP channel.

5.3.1. ADP Channels

ADP establishes an *ADP channel* between two hosts H_A and H_B when they communicate for the first time, and thereafter the channel continues to exist until one of the hosts fails. The protocol for channel establishment consists of the following steps (see Figures 5.4 and 5.5):

(1) H_A sends an *ADP channel request message* to H_B. This message contains two random strings S and T. S is encrypted with H_B's public key for privacy. T may be sent in cleartext. The entire message is cryptographically checksummed with H_A's private key for authenticity [Akl, Den84a]. S will be used as the single key of the ADP channel between H_A and H_B, and T will be used for certificates from H_B to H_A.

(2) H_B sends an *ADP channel acknowledgement message* containing a random string R to be used for certificates from H_A to H_B. The first certificate sent from H_A to H_B serves to complete a three-way handshake for the ADP channel establishment. If both H_A and H_B simultaneously try to establish an ADP channel to each other, the host with the lexicographically greater name determines the channel key S.

In Section 5.4, we derive the trust requirements necessary if this protocol is to result in the establishment of a host-to-host channel H_A-H_B, i.e., channel(H_A, H_B) and channel(H_B, H_A).

5.3.2. Sending Certificates of Agents

If A_k is an agent, we say that A_k is *certified* from H_B to H_A if H_B sends the string $\{H_B, R\}$, which is a concatenation of the name H_B and the random number R specified by H_A, encrypted with A_k's private key on the ADP channel between H_A and H_B (see Figure 5.6). When H_A receives the certificate, H_A decrypts it with A_k's public key, and compares the result with $\{H_B, R\}$. In Section 5.4, we derive the trust requirements necessary if the certification of A_k from H_B to H_A is to result in the establishment of channel(A_x, A_k), for all agents A_x having processes on H_A.

The sending of A_k's certificate from H_B to H_A is normally done only once on an ADP channel. H_A and H_B both maintain identical tables of agents that have been certified from H_B to H_A, and separate tables for agents certified in the reverse direction (see Figure 5.7). This *caching of certificates* means that expensive PKE-based encryption is done only once per agent per host per ADP channel.

5.3.3. Messages on an ADP Channel

Three levels of messages must be distinguished (Figure 5.2):

Client messages are the messages read or written by clients of ADP.

ADP messages are a logical unit of exchange between ADP instances on different hosts. An ADP message consists of a header followed by one or more *items*, each of which may be 1) a client message; 2) an agent's certificate or a request for an agent's certificate; 3) a request to establish a ADP channel, or the acknowledgement of such of a request; 4) a request to change the key of a ADP channel.

Network messages: the network facility underlying ADP is assumed to provide an insecure and unreliable datagram service. If the size of an ADP message exceeds the maximum size allowed by the network layer beneath ADP, ADP divides the ADP message into multiple network

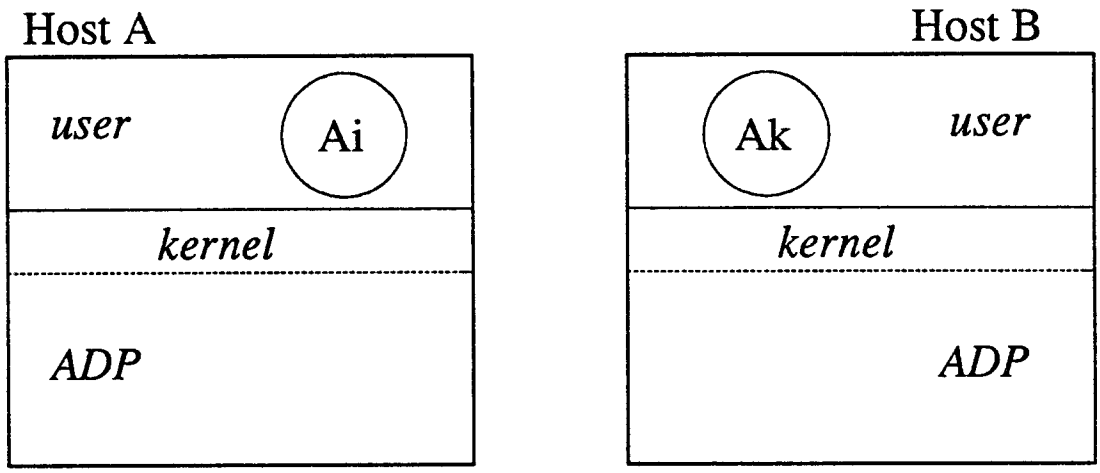

Figure 5.4: Hosts H_A and H_B just before establishing an ADP channel

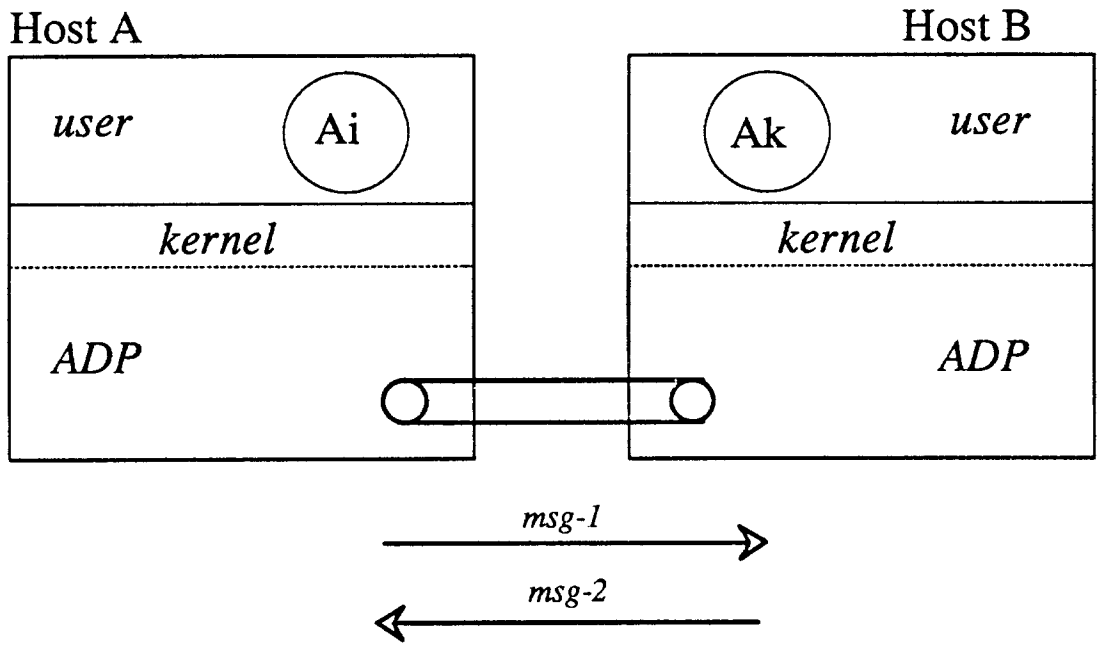

Figure 5.5: Establishment of an ADP channel between H_A and H_B. H_A sends the channel request msg_1 consisting of the doubly encrypted channel key S (encrypted first with H_A's private key and then with H_B's public key) and a random number T. H_B sends the channel reply msg_2, consisting of a random number R.

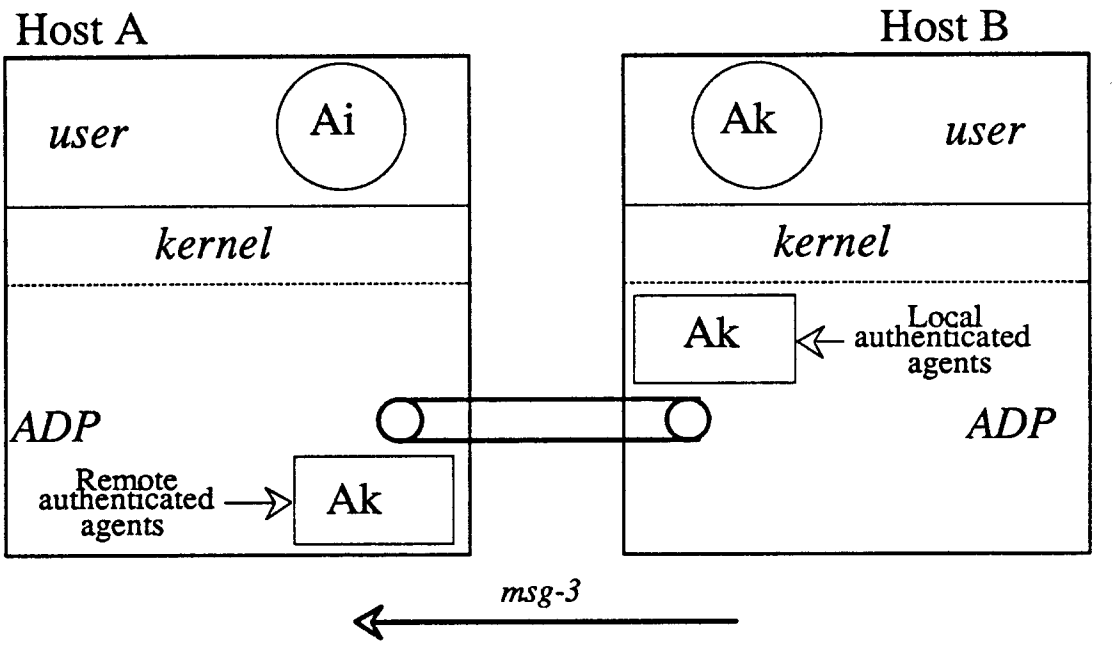

Figure 5.6: Certification of agent A_k from H_B to H_A. H_B sends a certificate msg_3 consisting of the string $\{H_B, T\}$ encrypted with A_k's private key.

messages.

5.3.4. The ADP Client Interface

Message addressing is done on the basis of network-dependent *host addresses* and, on a particular host, multiple *ports*. Ports have identifiers (port ID's) that are guaranteed to be unique on a given host between crashes. ADP clients inform ADP that messages can be delivered to the given port using

```
register_port(
      port_ID port,    // the port being registered
      char *local_agent,    // agent associated with the port
      );
```

where *local_agent* is an agent whose private key is known to the host. ADP may then deliver messages to the port. Each message is prepended with the name of its sender. Clients of ADP can send messages using

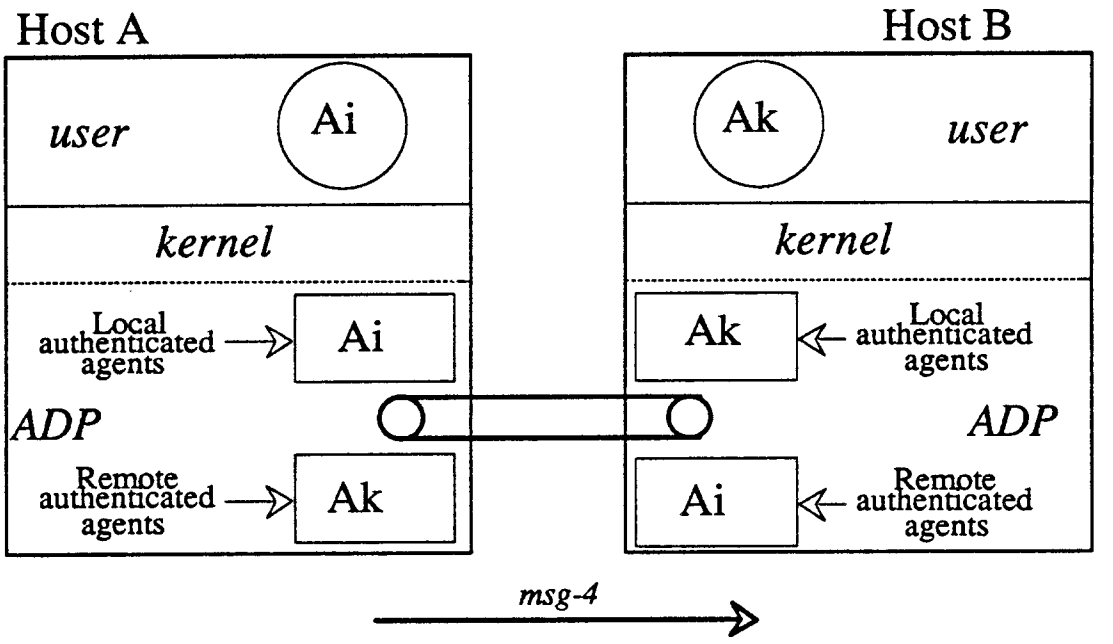

Figure 5.7: Certification of agent A_i from H_A to H_B. H_A sends a certificate msg_4 consisting of the string $\{H_A, R\}$ encrypted with A_i's private key.

```
ADP_send(
      MESSAGE *msg,     // the message being sent
      char *local_agent,     // name of sender
      char *remote_host,     // destination host name
      char *remote_port,     // destination port ID
      char *remote_agent,    // name of recipient
      BOOLEAN privacy, // whether message is private
      int max_delay    // maximum local queueing delay
```

The **remote_agent** argument is used only if **privacy** is true; in this case ADP will obtain a certificate of the agent on the remote host before sending the message. The *max_delay* parameter is a time interval (in microseconds) for which this message can be queued locally (see Section 5.3.6).

5.3.5. Transmission of Client Messages

ADP's handling of client messages depends on the nature of the intervening network. A *physical broadcast network* (PBN) is one in which there is a single transmission medium. In the absence of packet loss due to buffer overrun, if any node on a PBN receives a packet in its entirety, then the node to which it is addressed also does so. A single Ethernet, for example, is a PBN. Token rings and bridged Ethernets, though they may support logical broadcast, are not

PBN's.

ADP messages to a destination on the same PBN as the sender are transmitted as a sequence of network packets (fragments), each of which ends with a *security trailer* [4] containing a sequence number encrypted with the channel key. When the node to which a fragment is addressed receives a packet, the node decrypts the security trailer to obtain the packet's sequence number. If the sequence number is greater than that of the previously received packet, this is the first packet on the network with this sequence number. Since the sequence number is encrypted with the channel key, and the host at the other end of the ADP channel must have sent the packet, the packet is authentic and is accepted by the destination node. Thus, security trailers provide message authentication on PBN's. The destination ADP module handles reassembly. Strictly increasing sequence numbers are used; when the space of sequence numbers is exhausted, a new channel key is negotiated. Client messages for which privacy was requested are sent encrypted with the channel key; others are sent in cleartext.

If the destination host is not on a common PBN, ADP uses a lower-level Internet Protocol [81b] module to handle routing and fragmentation. ADP delivers complete ADP messages to IP with a security header that includes a cryptographic checksum [Akl, Den84a] of the entire message, encrypted with the channel key. The IP module at the destination host reassembles the ADP message and delivers it to the ADP module, which recomputes the cryptographic checksum and verifies that it matches the encrypted version. As before, private client messages are encrypted.

5.3.6. Piggybacking

In some cases, system performance can be increased by *piggybacking* multiple client messages into a single ADP message (see Figure 5.8). This is made possible by allowing ADP clients to specify a maximum queueing delay for each message. Many types of messages, such as retransmissions, asynchronous write operations, and some types of acknowledgements, can be be delayed a small amount (a fraction of a second) with no loss in system performance or functionality. These "non-urgent" messages can therefore be queued in the sender for this period and merged with other client messages on the same channel. In this case, one ADP message may include several client messages. If the client messages do not require secrecy, then in general less encryption is required, since a single encrypted sequence number or checksum will serve to authenticate multiple client messages. Piggybacking may also reduce CPU overhead, since the per-message costs of piggybacking (queueing and timers) are likely to be lower than those of network packet transmission.

The maximum delay of a client message is supplied by the process sending it (usually a transport protocol). If the delay is zero (i.e., for "urgent" messages) ADP will send the message as soon as possible. If the delay is nonzero the message may be queued for a period not exceeding the delay. The queueing period will be less if the queue exceeds the maximum ADP message size, or if there is a shorter-delay message in the queue. This maximum ADP message size will depend on the amount of buffer space available, and may be limited by the maximum size of the messages that can be accepted by the lower protocol layers.

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[4] Either a *security trailer* or a *security header* can be used.

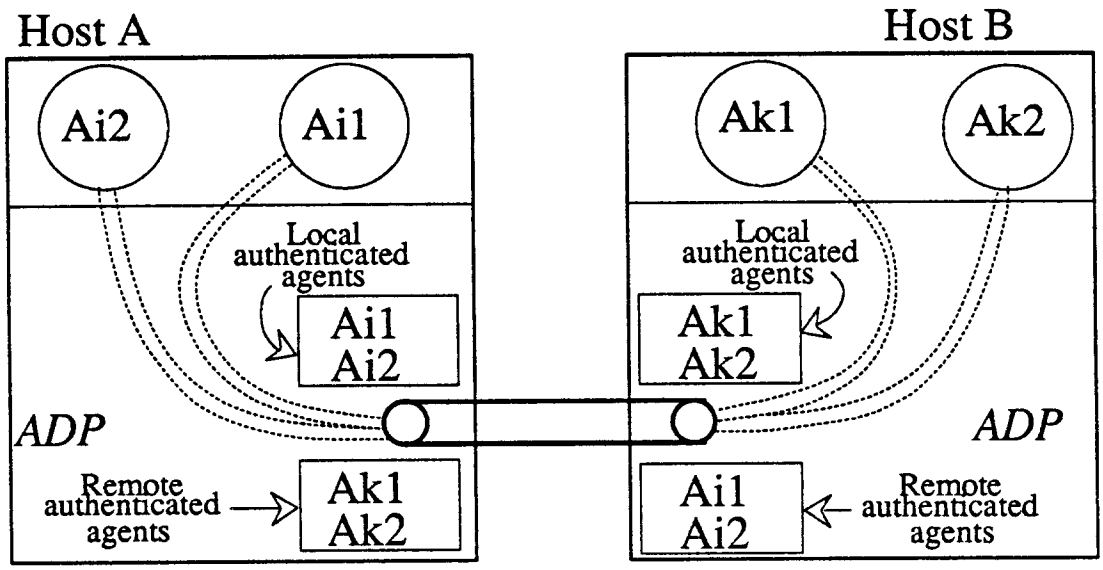

Figure 5.8: Several agent-to-agent channels multiplexed on to an ADP channel

5.4. Trust Requirements of ADP

The establishment of an ADP channel between two hosts H_A and H_B results in the logical establishment of two channels (H_A, H_B) and (H_B, H_A), if some trust requirements are satisfied. Let us investigate these trust requirements.

In the ADP channel establishment protocol, let H_A send the ADP channel request. In order to send the request, H_A must obtain H_B's public key using name resolution in the name space. But notice that obtaining H_B's public key results in the establishment of a PKE-based channel(H_A, H_B) (see Section 3.4). Using results of Section 3.7, security of this channel requires the satisfaction of a trust predicate, which we denote by $pred_{AB}$.[5]

When H_B receives the ADP channel request from H_A, H_B must obtain H_A's public key to decrypt the request. Obtaining H_A's public key results in the establishment of a PKE-based channel(H_B, H_A). Let the trust predicate that must be satisfied for the security of this channel be denoted by $pred_{BA}$.

If both $pred_{AB}$ and $pred_{BA}$ are true, H_A and H_B correctly possess each others' public keys, and the single key S sent by H_A in the ADP channel request is known only to agents/hosts that might possess either H_A's private key or H_B's private key, i.e., the agents/hosts in key-

[5] The trust predicate is determined by the sequence of channel compositions (in the name space) used in establishing the channel.

closure(H_A) [6] or in key-closure(H_B). Since the agents in key-closure(H_A) and key-closure(H_B) possess the private keys of H_A and H_B respectively, we obtain that the following must be true (recall the meaning of T_U from Section 5.2):

$$T_U(H_A, key\text{-}closure(H_A)) \wedge T_U(H_B, key\text{-}closure(H_B)) \tag{5.3}$$

If H_A and H_B were to use S as their channel key, H_A and H_B must have key user-possessor trust in all the agents that might possess S, so as to ensure that these agents will not use S to compromise the security of the ADP channel between H_A and H_B. Since the agents that might possess S are those in key-closure(H_A) or key-closure(H_B), we obtain that the following must be true:

$$T_{KUP}(H_A, key\text{-}closure(H_A), H_B) \wedge T_{KUP}(H_A, key\text{-}closure(H_B), H_B) \wedge$$

$$T_{KUP}(H_B, key\text{-}closure(H_A), H_A) \wedge T_{KUP}(H_B, key\text{-}closure(H_B), H_A) \tag{5.4}$$

But notice that, using the definition of the universal trust (see Section 5.2),

$$T_{KUP}(H_A, key\text{-}closure(H_B), H_B)$$

follows from:

$$T_U(H_B, key\text{-}closure(H_B)),$$

and

$$T_{KUP}(H_B, key\text{-}closure(H_A), H_A)$$

follows from:

$$T_U(H_A, key\text{-}closure(H_A))$$

Hence, in eq (5.4),

$$T_{KUP}(H_A, key\text{-}closure(H_B), H_B) \wedge T_{KUP}(H_B, key\text{-}closure(H_A), H_A)$$

follows from eq (5.3).

Summarizing these results, we obtain the following theorem:

Theorem 5.2: Establishment of an ADP channel between two hosts H_A and H_B results in the logical establishment of channels (H_A, H_B) and (H_B, H_A) if and only if:

(1) the trust requirements for establishing channels (H_A, H_B) and (H_B, H_A) using channel compositions in a PKE-based name space are satisfied,

(2) H_A has universal trust in all agents in key-closure(H_A) and H_B has universal trust in all agents in key-closure(H_B), and

(3) $T_{KUP}(H_A, key\text{-}closure(H_A), H_B)$ and $T_{KUP}(H_B, key\text{-}closure(H_B), H_A)$ are satisfied.

□

[6] The following short-hand notations are used throughout: A host's name mentioned in a place where an agent's name would be expected refers to the host's owner, an agent's name mentioned in a place where a host's name would be expected refers to all the hosts owned by the agent, and a set mentioned in a place where a member of the set would be expected refers to all the members in the set.

Now consider agent certification. When H_A receives a certificate of an agent A_k from H_B, for all agents A_x that have processes on H_A, channel(A_x, A_k) becomes established if some additional trust requirements are satisfied. Let us investigate these trust requirements.

When H_A receives A_k's certificate, H_A must obtain A_k's public key. Obtaining A_k's public key results in the establishment of a PKE-based channel(H_A, A_k). Let the trust predicate that must be satisfied for the security of this channel be denoted by $pred_{Ak}$.

If $pred_{Ak}$ is satisfied, H_A correctly possesses A_k's public key, and hence some agent that has A_k's private key sent A_k's certificate to H_A. If $T_U(A_k, key\text{–}closure(A_k))$ is satisfied, A_k must have sent the certificate. Since the certificate contains the name of H_B, A_k on H_B must have sent the certificate. Since the certificate contains the random number T, A_k on H_B must have sent the certificate during the kernel session of the current ADP channel. Thus, H_B has a process owned by A_k during the current kernel session.

Now consider a message msg_{kx} sent from H_B to H_A with the message sender field equal to A_k, and the message recipient field equal to A_x. Since H_B has a process owned by A_k during the current kernel session, H_B possesses A_k's private key, H_B belongs to key-closure(A_k), and hence $T_U(A_k, H_B)$ is satisfied. Thus, H_B does not masquerade as A_k, and hence msg_{kx} must have been sent by A_k. If the trust requirements of Theorem 5.2 are satisfied, the authenticity of msg_{kx} remains intact between H_B and H_A. If A_x has a process on H_A and H_A is security-correct, the authenticity of msg_{kx} remains intact from H_A to A_x.

A similar derivation can be carried out for the privacy of a secret message sent from A_x to A_k.

The following theorem summarizes the above derivations for the trust requirements of channel(A_x, A_k).

Theorem 5.3: Suppose A_k is an agent having processes on a host H_B. For all agents A_x that have processes on a host H_A, channel(A_x, A_k) is established when H_A receives A_k's certificate on its ADP channel to H_B if and only if H_A is security-correct and the following trust requirements are satisfied:

(1) the trust requirements specified by Theorem 5.2 for establishing channels (H_A, H_B) and (H_B, H_A),

(2) the trust requirements for establishing channel(H_A, A_k) using compositions in a PKE-based name space, and

(3) $T_U(A_k, key\text{–}closure(A_k))$.

□

In the trust requirements given by Theorem 5.3 for channel(A_x, A_k), the trust predicates $pred_{Ak}$, $pred_{AB}$ and $pred_{BA}$ arise from channel compositions in the name space. Since the name space is designed so as to satisfy the trust relationships in any channel composition carried out through it, $pred_{Ak}$, $pred_{AB}$ and $pred_{BA}$ are automatically satisfied. But the universal and key user-possessor trust requirements which involve the various key-closures can potentially greatly increase the trust requirements, and hence it is desirable to eliminate these trust requirements.

Figure 5.9 illustrates an effect of a universal trust requirement involving a key-closure. Alice has a process on host H_A owned by Riccardo, and Bob has a process on host H_B owned by Stuart. The channel request CR_{AB} of the ADP channel between H_A and H_B was sent by H_A, encrypted with Riccardo's private key and Stuart's public key. Stuart himself has a process on

a host H_C owned by Peter. Since a host has access to its users' storage, Peter has access to Stuart's private key on H_C. Thus Peter can obtain the single key SK_{AB} of the ADP channel between H_A and H_B by decrypting CR_{AB} with Stuart's private key and Riccardo's public key. Since messages from Bob to Alice are encrypted using SK_{AB}, Peter can compromise the security of communication between Bob and Alice. In other words, since Bob has placed universal trust in Stuart, and Stuart has placed universal trust in Peter, Bob has to place universal trust in Peter. In fact, Bob must place universal trust in owners O_1 of all hosts on which Peter might have user processes, in owners O_2 of all hosts on which owners O_1 might have user processes, and so on. Thus, the requirement of universal trust in key-closures can be a serious disadvantage.

Let us see if we can eliminate the universal and key user-possessor trust requirements involving the various key-closures. The primary cause for these trust requirements in the above example is the accessibility of Stuart's private key by Peter. Suppose Stuart's host uses a (public-key, private-key) pair that is different from the (public-key, private-key) pair used by Stuart's user-level process on Peter's host. H_C no longer has access to the private key used by H_A, Peter can no longer decrypt the channel request from H_A to H_B, and hence Peter can no longer obtain the key of the ADP channel between H_A and H_B. Consequently, the trust requirements involving key-closures vanish.

Let $ADP_{modified}$ denote ADP with the modification that each agent has two (public-key, private-key) pairs, one of which is used by the agent's hosts and the other is used by the agent's user-level processes. Key-closure(H_A) and key-closure(H_B) become empty. Key-closure(A_k) becomes the set of hosts, $hosts(A_k)$, on which A_k has processes. Using these substitutions in Theorems 5.2 and 5.3, we obtain the next two theorems for $ADP_{modified}$:

Theorem 5.4: Establishment of an $ADP_{modified}$ channel between two hosts H_A and H_B results in the establishment of channels (H_A, H_B) and (H_B, H_A) if and only if the trust requirements for establishing channels (H_A, H_B) and (H_B, H_A) using a PKE-based name space are satisfied.

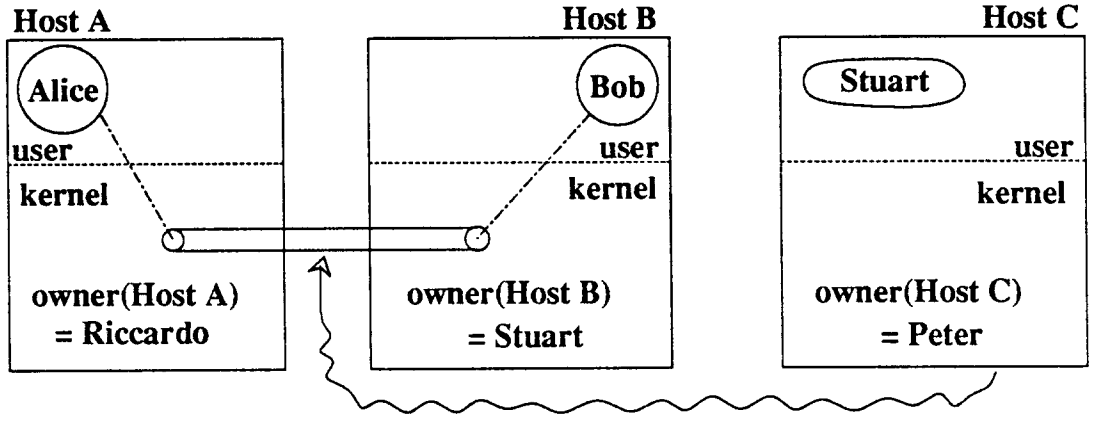

Figure 5.9: Effect of key-closure trust requirements

□

Theorem 5.5: Suppose A_k is an agent having processes on a host H_B. For all agents A_x that have processes on a host H_A, channel(A_x, A_k) is established when H_A receives A_k's certificate on its $ADP_{modified}$ channel to H_B, if and only if H_A is security-correct and the following trust requirements are satisfied:

(1) the trust requirements specified by Theorem 5.4 for establishing channels (H_A, H_B) and (H_B, H_A),

(2) the trust requirements for establishing channel(H_A, A_k) using channel composition in a PKE-based name space, and

(3) $T_U(A_k, hosts(A_k))$.

□

Notice that the first two trust requirements of $ADP_{modified}$ [7] (as given by Theorem 5.5) are automatically satisfied in the name space. The third trust requirement involves only those hosts on which A_k has/had processes, and, given that a host has access to all the data of an agent having processes on the host, this trust requirement cannot be eliminated by any channel establishment protocol.

If agent-to-agent channels are established directly, establishing channel(A_i, A_k) requires that a trust predicate $pred_{ik}$, which is determined by the sequence of channel compositions between A_i and A_k in the name space, be satisfied. In comparison, the trust requirements of ADP (as given by Theorem 5.5) are more numerous. In Section 5.7, we justify the increased trust requirements of ADP by its significant performance advantages over protocols that establish agent-to-agent channels directly.

5.5. Trust Requirements of ADP When Name Space is SKE-based

We now show that if the name space is SKE-based as in [BLN86], ADP requires global trust. Consider a system consisting of hosts H_A and H_B, agents A_i, A_{k1} and A_{k2}, and an SKE-based name space in which H_A, H_B, A_i, A_{k1} and A_{k2} are leaf nodes (see Figure 5.10). Let A_i have processes on H_A, and A_{k1} and A_{k2} have processes on H_B. Let hosts H_A and H_B establish an ADP channel with a channel key S_{AB}. As pointed out earlier, establishing the ADP channel involves the establishment of SKE-based channel(H_A, H_B) and SKE-based channel(H_B, H_A) using compositions in the name space. Let the set of name space nodes between H_A and H_B be denoted by NS_{A-B}. The nodes in NS_{A-B} are involved in establishing channel H_A-H_B. If the name space is SKE-based, as shown in Chapter 3, the nodes in NS_{A-B} might possess channel key S_{AB} of channel H_A-H_B.

When H_A receives a certificate of A_{k1}, SKE-based channel(H_A, A_{k1}) must be established using compositions in the name space. The key of channel(H_A, A_{k1}) becomes known to all name space nodes in the path between H_A and A_{k1}. But ADP uses the same single key S_{AB} for channel(H_A, A_{k1}). Thus S_{AB} is now known to agents in any of NS_{A-B} or NS_{A-k1}.

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[7] In the sequel, ADP will be used to mean $ADP_{modified}$.

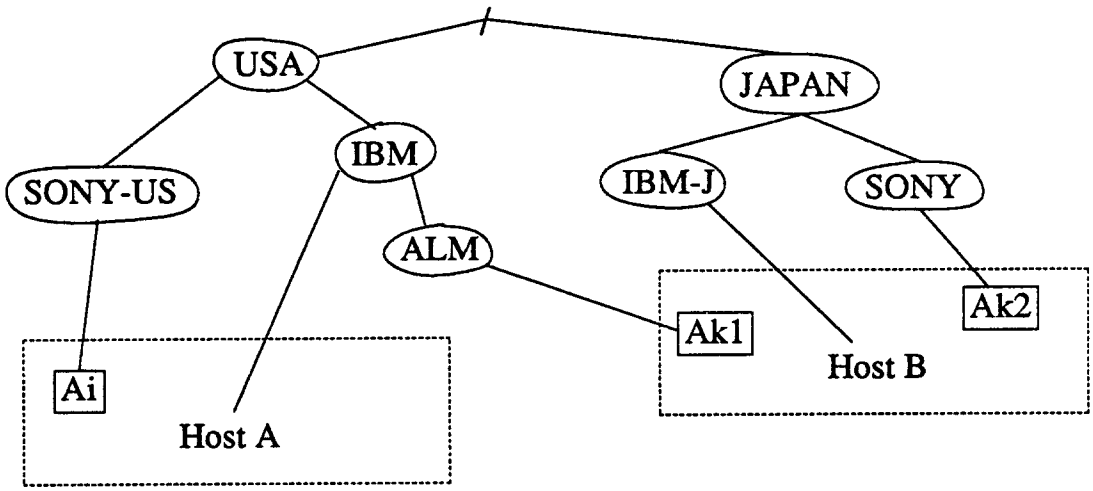

Figure 5.10: Global trust requirements when ADP is used with SKE-based name space

Next, when H_A receives a certificate of A_{k2}, channel(H_A, A_{k2}) is established using compositions in the name space. Using similar arguments as above, we obtain that S_{AB} is now known to agents in any of NS_{A-B}, NS_{A-k1} or NS_{A-k2}.

When A_i on H_A sends a secret message to either A_{k1} or A_{k2}, S_{AB} is used for encryption. Since S_{AB} is known to agents in any of NS_{A-B}, NS_{A-k1} or NS_{A-k2}, the following key user-possessor trusts are required:

$$T_{KUP}(A_i, \{NS_{A-B}, NS_{A-k1}, NS_{A-k2}\}, A_{k1}) = true \tag{5.4}$$

$$T_{KUP}(A_i, \{NS_{A-B}, NS_{A-k1}, NS_{A-k2}\}, A_{k2}) = true \tag{5.5}$$

Continuing these arguments it can be shown that, if an agent having processes on H_B can reside at any position in the name space, each agent on H_A will be required to have key user-possessor trust in all the name space nodes (the middle argument to T_{KUP} above becomes the universal set), and hence will be required to have global key user-possessor trust. This is summarized by the following theorem:

Theorem 5.6: ADP, if used in a system whose name space is SKE-based, requires global key user-possessor trust.

□

As a result of Theorem 5.6, ADP plus an SKE-based name space is an unacceptable combination in distributed systems without global trust.

5.6. Trust Domains

The set of hosts in many distributed computing environments may contain subsets with the following property: Within a subset, the hosts and the communication channels between them are physically secure, and agents with access to the hosts all place universal trust in one another (Figure 5.11). By Theorem 5.1, universal trust is transitive, and hence the same host cannot belong to two domains.[8] Across subsets, the communication links may not be physically secure, and agents in one subset may not place universal trust in hosts in the other subset. We call such subsets *trust domains*. Suppose also that all communication across a subset boundary is routed through one or more hosts called *domain gateways*. Within a trust domain, no channel establishment mechanisms are necessary. Between two domains, the two domain gateways [9] can establish a channel, and multiplex messages from, and demultiplex messages to, agents on various hosts within each domain. A special ADP module on the domain gateway performs these functions. This has the following advantages:

- Efficiency: Communication within the domain has no encryption overhead. Only the domain gateway does encryption, so only it need to have encryption hardware.
- Flexibility: The channel establishment mechanism between domain gateways can be changed at any time. Intra-domain communication will not see any changes.

5.7. ADP versus Direct Establishment of Agent-to-Agent Channels

Channel establishment mechanisms must be introduced into some levels of the network protocol architecture [Tan81, Tan88]. ADP being a host-to-host channel establishment protocol, these mechanisms can be introduced at the subtransport level. Protocols that establish agent-to-agent channels directly across the network must be introduced at transport or higher levels, because the lowest level at which processes (belonging to agents) rather than hosts can be communicating entities, is the transport level [SRC84, VoK83]. If agent-to-agent channels are established directly, establishing channel(A_i, A_k) requires that a trust predicate $pred_{ik}$, which is determined by the sequence of channel compositions between A_i and A_k in the name space, be satisfied. In comparison, the trust requirements of ADP (as given by Theorem 5.5) are more numerous.

We will now justify the increased trust requirements of ADP (as compared to those of protocols that establish agent-to-agent channels directly) by the performance advantages of subtransport level channel establishment over channel establishment at transport or higher level protocols. The advantages can be grouped as follows:

1) general advantages of subtransport level channel establishment,

2) specific advantages relative to transport level channel establishment, and

3) specific advantages relative to putting channel establishment above the transport level.

---

[8] Suppose a host H_A belongs to two domains. The hosts of the first domain place universal trust in H_A, but H_A places universal trust in hosts of the second domain. By transitivity of universal trust, hosts of the first domain place universal trust in those of the second. Similarly, we can show that hosts of the second domain place universal trust in those of the first. Consequently, the two domains can in this case be coalesced into a single domain.

[9] Recall that a host can only belong to a single domain. Thus, two domains must have two different domain gateways.

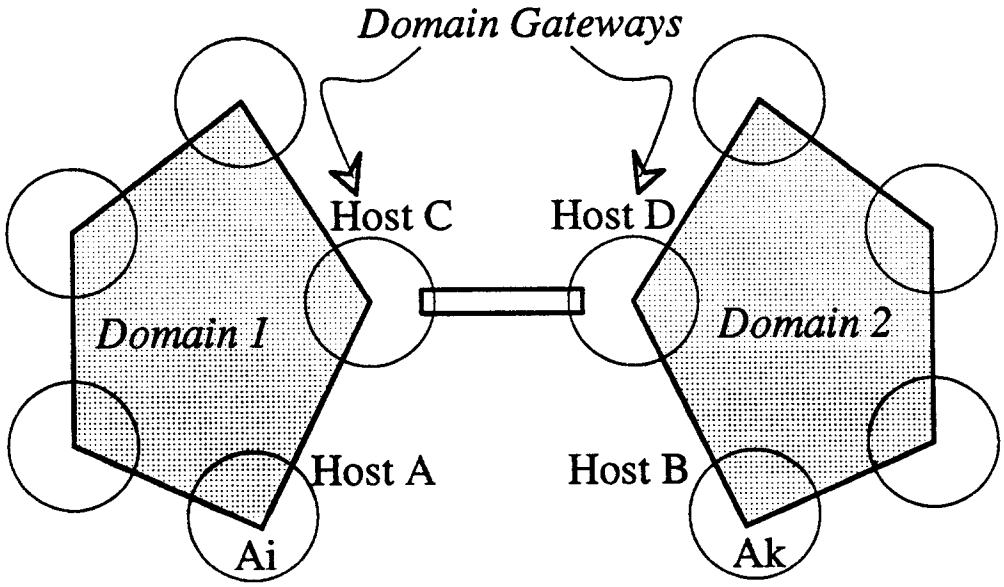

Figure 5.11: Trust domains

5.7.1. General Advantages of Subtransport Level Channel Establishment

Putting channel establishment at the subtransport level has several advantages relative to putting it at higher protocol levels:

- It simplifies transport level protocols. When a host crashes, its channels are destroyed. Thus, remote host crashes can be detected at the host-to-host level at the time of channel establishment, and transport level protocols do not have to employ elaborate timer mechanisms to detect them [Che86, 81b]. If transport protocols above ADP employ a sequence number that is monotonically increasing within a channel, message duplicates and replays may be eliminated. Since a host crash initiates a new channel, duplicates across crashes are eliminated. Thus, 3-way handshakes are not required in transport protocols for the purpose of duplicate elimination. This also means that 3-way handshakes can often be eliminated from transport-level protocols. A short transaction then requires just two messages in the best case, as opposed to at least six in TCP [Dif85, Ken77] and four in secure RPC [BiN84, Bir85].
- More than one protocol may exist at higher layers, and different protocols may require different channel establishment mechanisms. Thus, unlike in the subtransport layer, channel establishment mechanisms may have to be duplicated in higher layers.
- There are two public-key operations per agent per remote host per kernel session. Often these operations can be done at boot time or during idle periods. There are no per-process or per-operation public-key operations, resulting in a substantial performance gain.
- Since messages from all client processes and higher level protocols pass through the subtransport layer, a number of these messages destined to a common remote host can all be

combined into a single datagram and sent as a single ADP message. This can reduce the number of single key operations.

- In the presence case of trust domains, handling channel establishment at the subtransport level drastically reduces the number of transport level connections necessary for communication between two processes in two different domains (see Figure 5.12).

5.7.2. Disadvantages of Transport Level Channel Establishment

Transport level protocols are used to implement a variety of communication paradigms. Request/reply (RPC) [BiN84] and full duplex byte streams [81a] are two of the popular communication paradigms. We examine secure RPC [Bir85] as an instance of channel establishment in an RPC protocol, and secure TCP [Dif85, Ken77] as an instance of channel establishment in a full duplex byte stream protocol. Both secure RPC and secure TCP are transport level protocols.

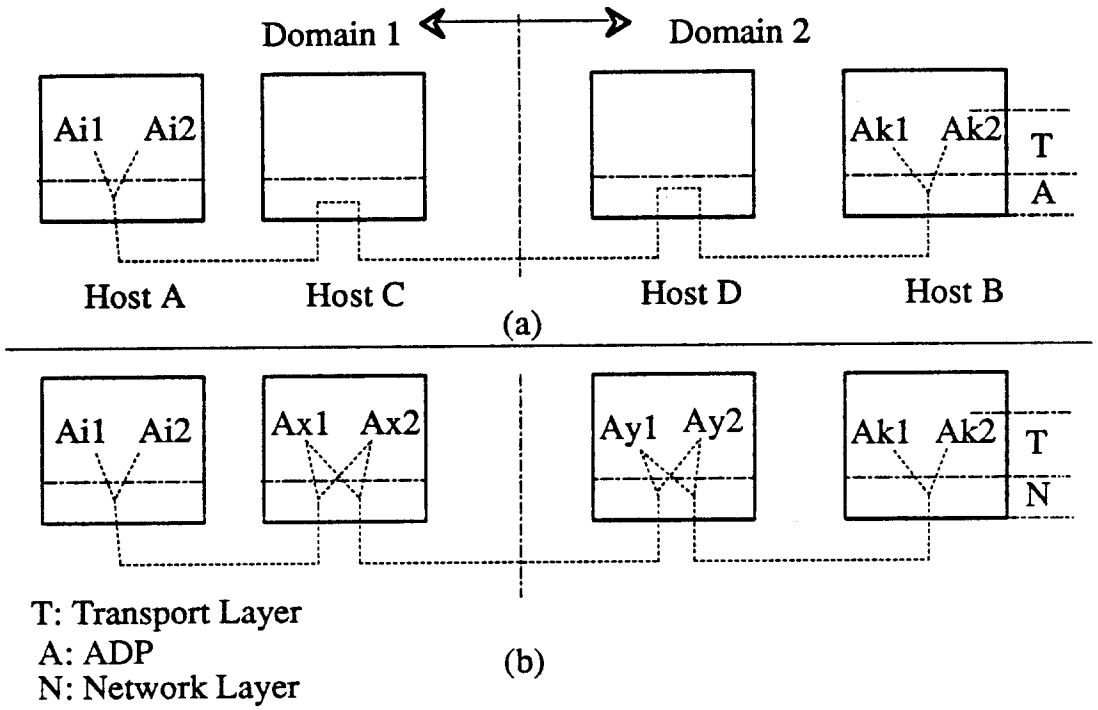

Figure 5.12: Comparison of ADP (Figure (a)) and transport level channel establishment (Figure (b)) with regard to trust domains. In ADP, the number of transport level connections required for inter-domain channels A_{i1}-A_{k1} and A_{i2}-A_{k2} is much smaller.

5.7.2.1. Secure RPC

When a client issues its first RPC request to a remote server, the RPC mechanism establishes a channel between the two processes. This consists of agreeing on a channel key to be used for encrypting RPC requests and replies. There are several disadvantages of such a scheme:

- For each channel, the RPC system must maintain long-term state information consisting of a channel key and sequence numbers of requests within the channel. This converts simple stateless RPC into one with long-term state information.
- A three-way handshake is necessary to agree upon the channel key. There are $O(n^2)$ encryption keys to be agreed upon. The cost of this three-way handshake is small if it is amortized over many RPC's. If, however, there are lots of short-lived processes making just one or two remote procedure calls, the performance penalty due to a three-way handshake is substantial. This can reduce the efficiency of RPC for short transactions.
- There are four public key operations for each channel. If the channel is established for just a single RPC, the relative cost is substantial.
- There is a single key encryption and a decryption for each RPC request, reply, and acknowledgement. Since messages from different processes use different channel keys, it is not possible to reduce the encryption cost by piggybacking messages from different processes that are all destined to the same host.

5.7.2.2. Secure TCP

TCP is a DARPA Internet transport protocol [81a] providing full duplex byte stream connections between processes on different hosts. Secure TCP [Dif85] requires an initial agreement upon a single key to be used during the lifetime of the TCP connection after the end points are authenticated to each other. In addition to those mentioned in Section 5.7.1, there are two more disadvantages associated with this scheme:

- Four public key operations are performed for each TCP connection.
- Encryption cost reduction by piggybacking is impossible since keys are not per host-pair.

5.7.3. Disadvantages of Having Channel Establishment above the Transport Level

There are several disadvantages in placing channel establishment mechanisms above the transport level:

- Transport level protocols like TCP do connection establishment using three-way handshakes. If channel establishment mechanisms are above the transport layer, they require their own handshake to agree upon keys after the transport level has established a connection. This duplication of handshaking entails higher message overhead.
- Transport level protocols do error detection using (insecure) checksums. Channel establishment mechanisms above the transport layer must do their own cryptographic checksumming. This is an unnecessary duplication of effort as error detection at higher layers can be avoided if checksumming is done at the subtransport or transport level.
- Transport level protocols employ sequencing to eliminate duplicates and out-of-sequence messages. Since an intruder could change the transport level headers and hence the transport level sequence numbers, channel establishment mechanisms above the transport layer must also do sequencing to detect such an intrusion, again resulting in an unnecessary duplication of effort.

- If an intruder sends a false message with the correct transport level sequence number, the transport level protocol will accept it as the next message and reject the true message which may arrive later. The channel establishment mechanisms above will reject the false message correctly, but will never get the true message. False acknowledgements at lower levels can disrupt the sequencing. The only way to recover from such situation is to re-establish the connection at both the transport and the secure communication levels. This has the potential for much unnecessary tearing down of connections and the associated performance overhead.
- Unauthenticated messages are detected only at the level where channel establishment mechanisms are. These messages are unnecessarily processed at all lower levels of the protocol hierarchy. Thus, if the channel establishment mechanisms are at a high level, the amount of this unnecessary work can be large (but this should be a rare occurrence).
- Public key operations are more numerous than those required by ADP, and single key operations cannot be reduced by piggybacking.

5.8. Experimental Verification

No design is complete without performance evaluation [Fer78]. It is quite clear from what has been said in the previous sections that the performance advantages of ADP can be expected to be primarily due to:

(a) the reduced total overhead for channel establishment: in ADP, expensive public-key encryption and three-way message handshake overhead are needed only for setting up a host-to-host channel and once per agent per host (for sending certificates), rather than for every agent-to-agent connection or session; ADP channels will be many fewer in number and much longer lived; and

(b) the much higher likelihood that the benefits of piggybacking will be felt, as the traffic intensity on a host-to-host channel is never lower than that on an agent-to-agent channel involving the same two hosts, and is often much higher; one can easily speculate that the effectiveness of piggybacking grows with the traffic intensity, as more client messages can be shipped within one ADP message; also, with channel establishment mechanisms at a higher level, each channel will have its own channel key, and client messages traveling on two different channels between the same two hosts cannot be bundled together in the same ADP message, as their encrypted portions will require two different keys.

However, given that ADP is better than direct agent-to-agent channel establishment, an important question is: How much better is it ?

To give this question an empirical answer, we measured the performance of a prototype of ADP implemented as part of the DASH Project at the University of California at Berkeley [AFV87d]. The implementation is written in C++ and runs on Sun 3/50 workstations connected by 10 Mb/s Ethernet.

Since we had not yet built any transport protocols on top of ADP, we could not implement agent-to-agent channel establishment mechanisms in them. We therefore transformed ADP for some of the experiments into an agent-to-agent channel establishment protocol, i.e., we had ADP establish a channel (using public key encryption) every time a process started communicating with another process on another host.

Because of the influences on ADP performance of client message sizes and arrival times, we could not use a synthetic input such as those of some previous studies, where all messages have the same size and arrive at regular intervals. Thus, it was decided to run trace-driven

measurement experiments. Figure 5.13 shows the experimental setup.

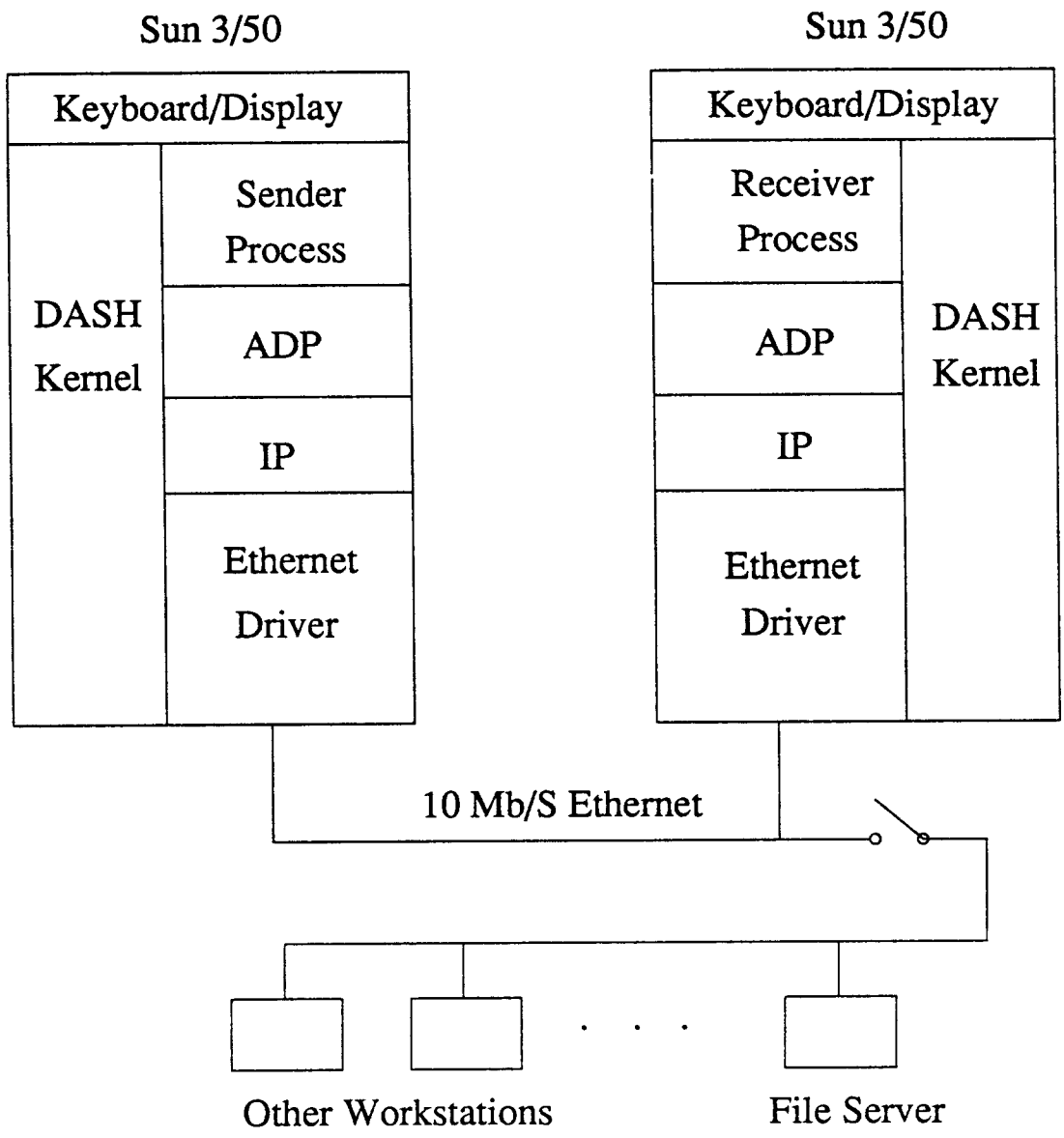

Figure 5.13: ADP experimental setup

Since a complete DASH system incorporating ADP does not exist yet, a real ADP input trace cannot be measured. The assumption was made that the message traffic on a local-area network interconnecting a variety of machines, including diskless workstations and file server, would represent a reasonable approximation to the type of traffic that an ADP module will experience in a DASH system.

A trace of all packets transmitted on a 10 Mb/s Ethernet among 96 machines of various types, 49 of which were diskless Sun workstations and 6 were Sun file servers, was converted into the corresponding client message trace, and also decomposed into traces containing only the messages generated by a given transport level protocol. In particular, in the experiments whose results are summarized below, we used the following three traces:

- ALL: a trace including all client message types;
- TCP: a trace containing only TCP messages (TCP was taken as an example of a transport level agent-to-agent full-duplex byte stream protocol).
- NFS: a trace containing only SUN NFS messages (NFS was taken as an example of a transport level agent-to-agent request/response protocol).

The primary performance indices we measured were:

Latency L: the average delay incurred by a message between the instant it is given to the sending ADP module for transmission and the instant it is delivered by the receiving ADP module to the destination process on the destination host. To compute L, we averaged the delays of the messages in a given finite sequence.

Throughput T: the maximum rate at which information can be transmitted by ADP on the sending host and received by ADP on the destination host.

In a throughput experiment, the client messages in the trace arrive at such a high rate that the input queue of ADP is never empty. In the agent-to-agent channel establishment case, when the arrival rate of a message trace is increased with respect to the measured one, a decision must be made about whether and how the process creation rate should be modified. There are two extreme cases: (1) The process creation rate is kept constant while the rate of message production by the existing processes is increased. This is one end of the spectrum and represents the best possible case for an agent-to-agent channel establishment protocol. The throughput for this scenario will be denoted by T1. (2) The mean message production rate of processes is fixed. Thus, when the message transmission rate is increased to its maximum value, the process creation rate must be increased linearly. This represents the worst case for agent-to-agent channel establishment. The throughput for this scenario will be denoted by T2. These two cases are of interest only for agent-to-agent channel establishment.

Figure 5.14 shows the latency and throughput values for the following cases: (1) ADP (2) direct establishment of agent-to-agent channels in the TCP trace, and (3) direct establishment of agent-to-agent channels in the NFS trace. From the figure, we conclude that the performance gains of ADP over both instances of agent-to-agent channel establishment are substantial. The inferior performance of agent-to-agent channel establishment approaches in the table is to be attributed entirely to the much higher rate of PKE-based channel establishment operations that these approaches require with respect to that caused by ADP, since even the ADP experiments were performed without piggybacking. PKE-based channel establishment is quite time-consuming: we have measured in our system an average establishment time of 1.75 seconds.

In the agent-to-agent channel establishment experiments, the TCP trace had 76 new connection establishments, and the NFS trace had 41 new RPC transactions from new processes, both in a sequence of 10,000 messages. Corrections introduced to remove edge effects reduced

	Latency (ms)		Throughput T1 (kB/s)		Throughput T2 (kB/s)	
	TCP	NFS	TCP	NFS	TCP	NFS
Subtransport	6	8	90	325	90	325
Transport	30	42	76	305	18	152

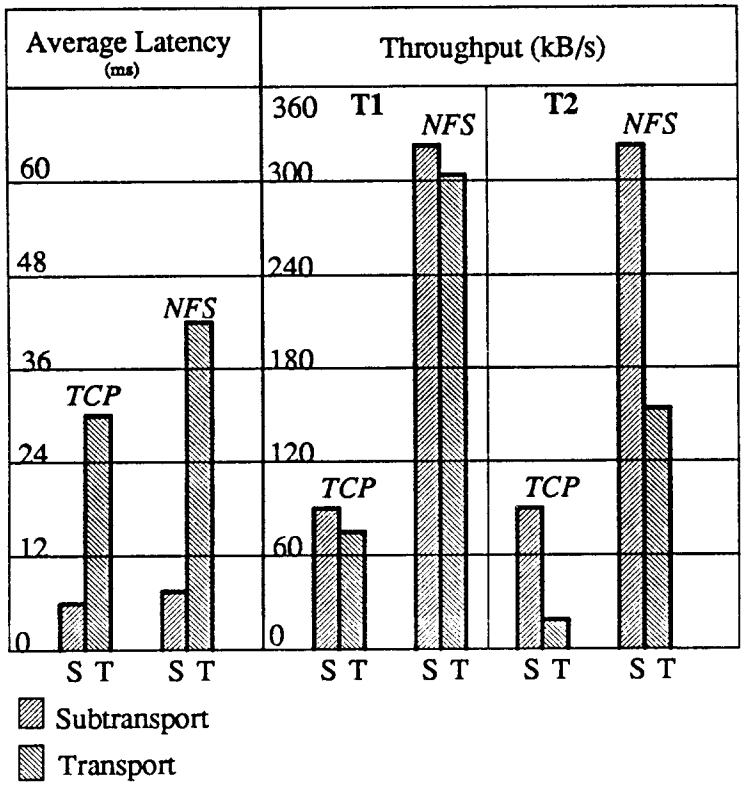

Figure 5.14: Table and histogram showing latency and throughput values for TCP and NFS traces with subtransport and transport approaches to channel establishment. T1 is the throughput with constant process creation rate. T2 is the throughput with a process creation rate linearly increasing with the arrival rate.

the values of the numbers of new connections slightly in the latency and T2 experiments. In the T1 experiments, there were 7 new connections in the TCP trace and 4 new RPC transactions in the NFS trace.

Figure 5.15 confirms the conjectures made at the beginning of this section about the effect of piggybacking in ADP. The ALL input trace was used. Among the many experiments we performed, an interesting one was that intended to determine the variation of the latency as the arrival rate of messages in the input trace was progressively increased. Figure 5.15 shows that the effect of piggybacking is insignificant at low arrival rates. Without piggybacking, an increase in the message arrival rate causes a rapid increase in the latency, whereas with piggybacking the latency starts increasing for much higher arrival rates. Figure 5.16 shows the latencies, throughputs and CPU utilizations for an unmodified client message trace (ALL) with an average message arrival rate of 250 messages/s, for the following cases: (1) without any channel establishment mechanisms, (2) without channel establishment mechanisms but with message piggybacking, (3) with ADP channel establishment but without message piggybacking, and (4) with ADP channel establishment and with message piggybacking. The difference in performance between cases 1 and 2 is considerable. The performance of case 4 is very close to that of case 2, whereas the performance of case 3 is less than that of case 1. This shows that message piggybacking can keep the performance cost of channel establishment very small.

The results of our experiments therefore show that the performance gains of ADP, due both to the reduction in the total overhead of channel establishment and to the advantages of piggybacking, are indeed substantial.

5.9. Conclusion

Trust requirements can be traded for performance of channel establishment protocols. If channel composition is PKE-based, slightly increasing the trust requirements allows agent-to-agent channels to be built on top of host-to-host channels. This host-to-host approach to channel establishment can greatly increase the performance of agent-to-agent secure communication. The accompanying increase in trust requirements is still satisfied in the distributed system's name space. However, if channel composition is SKE-based, this approach requires global trusts which may not be satisfied in the system's name space. Protocols for establishing host-to-host channels can be handled at the subtransport level of a network protocol hierarchy. Experimental measurement of a prototype of a host-to-host channel establishment protocol confirms its expected performance advantages.

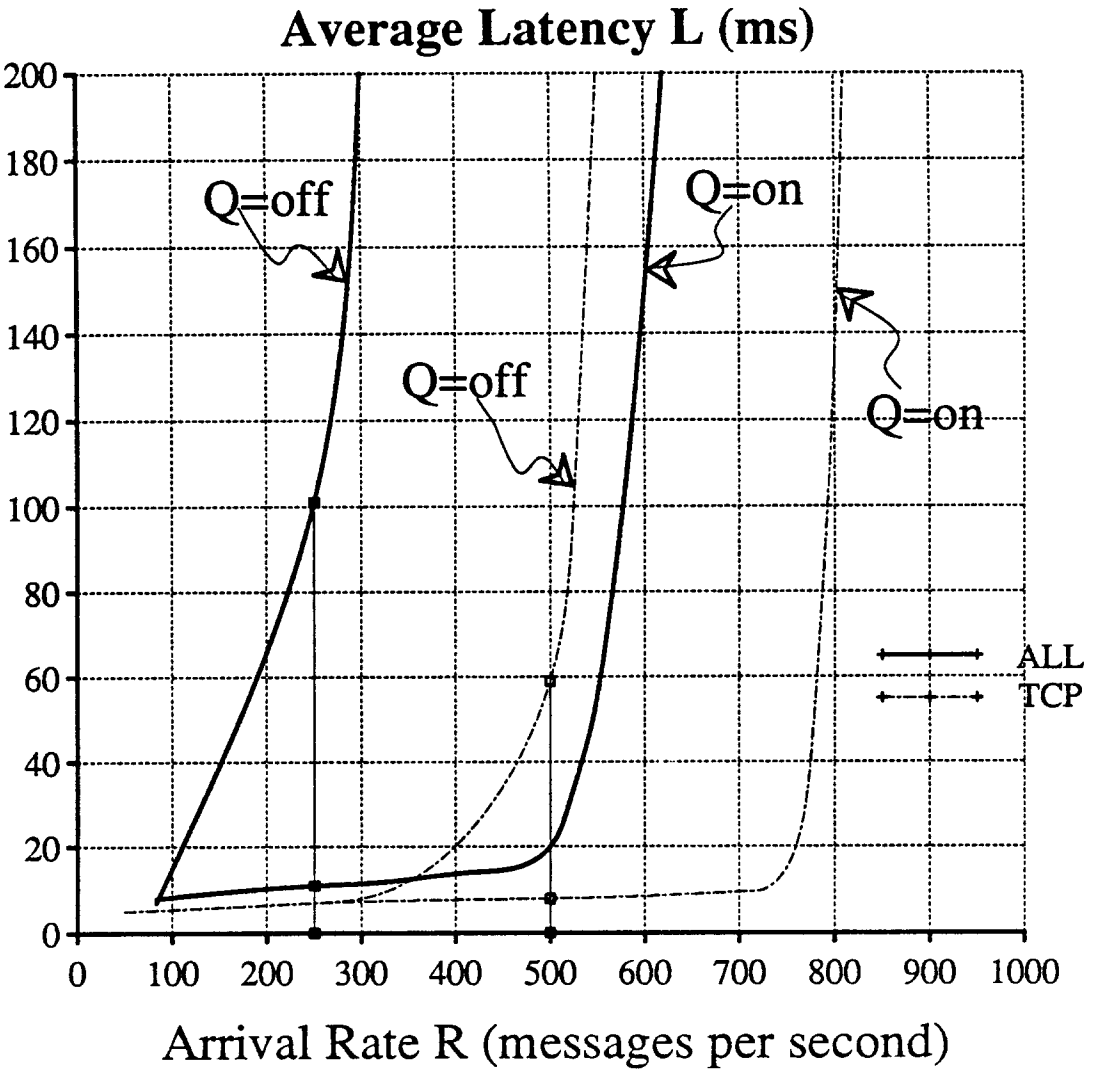

Figure 5.15: Effect of piggybacking on latency with increasing message arrival rates (ALL and TCP traces; piggybacking is denoted by Q=on)

	Latency (ms)	Throughput (kB/s)	CPU Overhead (%)
No security mechanisms No piggybacking	67	350	39.9
No security mechanisms Piggybacking present	11	760	20.09
Subtransport security No piggybacking	107	328	59.79
Subtransport security Piggybacking present	11	750	20.3

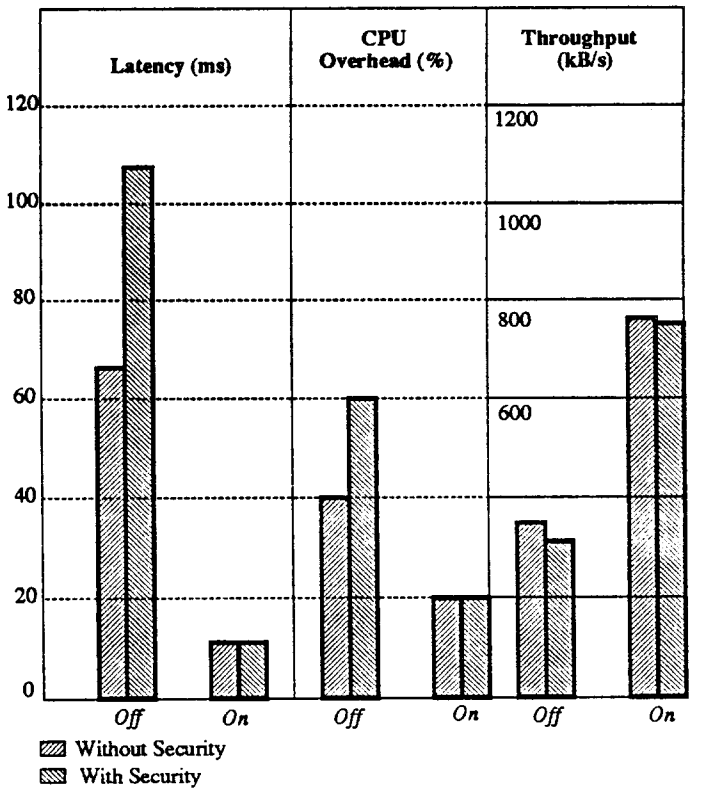

Figure 5.16: Table and Histogram showing performance effects of piggybacking (ALL trace)

CHAPTER 6

CONCLUDING REMARKS

6.1. Conclusion

We have developed an axiomatic theory of trust in distributed systems. Our theory of trust is based on modal logics of belief. Any well formed formula assumed to be valid in addition to the axioms of the logic is considered as a trust specification. This gives a lot of power and generality in expressing trust relationships. We have presented systematic methods for synthesizing protocols that are necessary and sufficient for implementing a given trust specification in a distributed system.

Trust arises primarily in establishing channels for secure communication. The only way to establish a new channel is by composing a sequence of existing adjacent channels. There are two kinds of channels: independent channels, which are provided at system configuration and do not have any trust requirements, and dependent channels, which are composed from independent channels and have trust requirements. Channel composition mechanisms are commonly based on either public key encryption (PKE) or single key encryption (SKE). PKE-based channel composition requires ternary trust relationships known as *authenticity trusts*. SKE-based channel composition has much larger trust requirements than PKE-based channel composition. The differences in the trust requirements of PKE and SKE-based channel compositions translate into several advantages of PKE-based over SKE-based channel composition with regard to replication, caching, permanence of trust requirements, and so on. Within each channel composition mechanism, the trust requirements are not symmetric with regard to the agents involved in the mechanism. Our analyses provide insight into the basic structure and limitations of mechanisms with regard to their trust requirements.

In a distributed system, it is desirable to have a tree of independent channels. It is convenient for the tree of independent channels to represent also the global name space of the system. There are two channel composition orders, namely, *iterative* and *recursive*. Iterative and recursive channel composition orders require different trusts and exhibit interesting duality properties. As one of the most important applications of a formal theory of trust, we have developed polynomial-time algorithms for synthesizing name spaces so that, given a channel composition order, and the trust relationships among agents, PKE-based channel composition between any two agents requires only a subset of the given set of trust relationships. The trust specifications are in general functions of three agents, but can also be functions of two agents, in which case the algorithms become simpler. Each node in a name space has to store the database of the public keys of its children, and it is desirable to put upper and lower bounds on the size of this database. However, the problems of putting upper or lower bounds on the number of children of each node in a name space are NP-complete.

The polynomial-time name space synthesis algorithms have been implemented and experimented with. Sample runs of these algorithms show that small differences in trust relationships can cause substantial differences in name spaces, thus demonstrating the practical usefulness of these algorithms.

No synthesis is complete without performance considerations. Trust requirements and performance of channel establishment mechanisms can be traded for each other. If the channel composition is PKE-based, slightly increasing the trust requirements allows agent-to-agent channels to be built on top of host-to-host channels. This host-to-host approach can greatly increase the performance of agent-to-agent secure communication. The accompanying increase in trust requirements is still satisfied in the distributed system name space. However, if channel composition is SKE-based, this approach requires global trusts, which may not be satisfied in the system's name space. Protocols for establishing host-to-host channels can be handled typically in the top portion of the network layer or in a special subtransport layer of a network protocol hierarchy. The experimental measurement of a prototype of a host-to-host channel establishment protocol confirms its expected performance advantages.

6.2. Future Work

In Chapter 2, we showed that the implementation of trust specifications requires constraints on message transactions among agents. Many of these constraints are of the form: send/receive a particular message before/after sending/receiving some other message. A more general approach to representing such constraints would involve temporal reasoning. We propose to investigate the possibility of combining temporal reasoning with modal logic for this purpose.

The trust relationships considered in Chapter 3 were functions of at most three agents. Trusts can also involve more than three agents. Figure 6.1 shows a scenario in which a trust involves four agents. Suppose it is known that, when *IBM* queries *IBM–J* for the key of *ibaraki*, *IBM–J* either returns the correct key of *ibaraki* or collaborates with *jap* to return *jap*'s key. When *IBM–J* returns a key key_1 in answer to *IBM*'s query for *ibaraki*'s key, *IBM* obtains *jap*'s key key_2 through an independent path, namely, *IBM-USA- / -jap*. *IBM* then compares key_1 and key_2, and accepts key_1 as *ibaraki*'s key only if the two keys are not identical. Here a trust relationship involving *IBM*, *IBM–J*, *ibaraki* and *jap* is necessary. We propose to study the formalization of such complex trust relationships that may involve more than three agents.

In Chapter 4, we developed algorithms for synthesizing global name spaces from trust specifications. Additional considerations, such as fault tolerance, may be used in these synthesis algorithms. In a fault-tolerant name space, some minimum number of trust relationships must become false before the name space becomes disconnected. Redundancies in trusts will have to be used in constructing such fault-tolerant name spaces. Another desirable feature of name spaces is the localization of dynamic reconfiguration when trust relationships change.

In Chapter 5, we outlined the trust requirements involving user processes and their local hosts. An interesting extension would be to study trust relationships involving user processes and remote hosts, such as those involving a client and a server's kernel, or a server and a client's kernel.

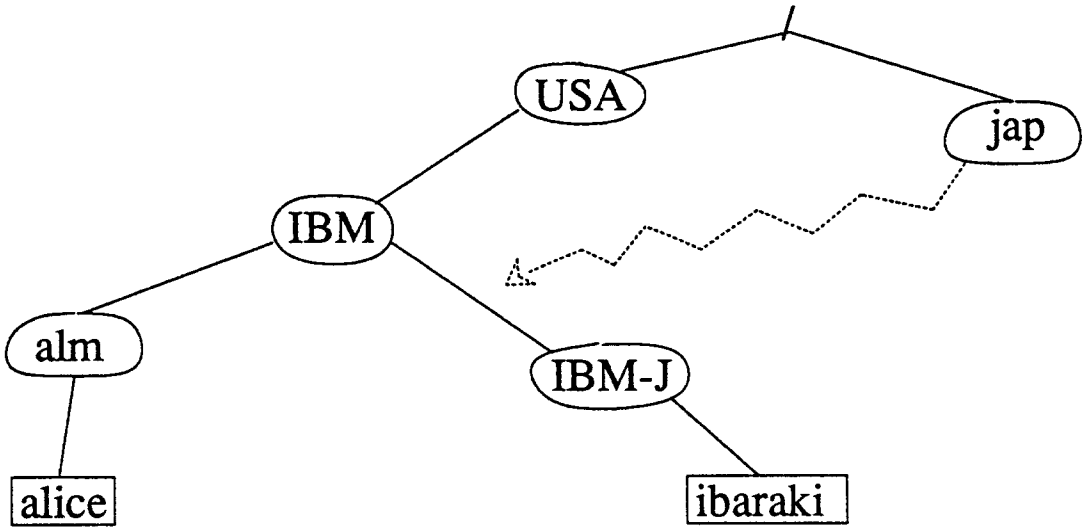

Figure 6.1: Illustration of a trust that involves more than three agents

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APPENDIX A

Trust Specifications for Name Space Design Example of Section 4.9

The sample set of trust specifications used in the example of Section 9 of Chapter 4 are as follows. For brevity, only those trust relationships that are assumed to be true, are enumerated.

$T(IBM\text{–}J, IBM, ARC)$ = true	$T(Jap, IBM, ARC)$ = true
$T(Sony, IBM, ARC)$ = true	$T(Sony\text{–}USA, IBM, ARC)$ = true
$T(IBM\text{–}J, ARC, IBM)$ = true	$T(Jap, ARC, IBM)$ = true
$T(Sony, ARC, IBM)$ = true	$T(Sony\text{–}USA, ARC, IBM)$ = true
$T(ARC, IBM, IBM\text{–}J)$ = true	$T(Jap, IBM, IBM\text{–}J)$ = true
$T(Sony, IBM, IBM\text{–}J)$ = true	$T(Sony\text{–}USA, IBM, IBM\text{–}J)$ = true
$T(ARC, IBM\text{–}J, IBM)$ = true	$T(Jap, IBM\text{–}J, IBM)$ = true
$T(Sony, IBM\text{–}J, IBM)$ = true	$T(Sony\text{–}USA, IBM\text{–}J, IBM)$ = true
$T(IBM\text{–}J, ARC, Sony\text{–}USA)$ = true	$T(IBM, ARC, Sony\text{–}USA)$ = true
$T(Jap, ARC, Sony\text{–}USA)$ = true	$T(Sony, ARC, Sony\text{–}USA)$ = true
$T(ARC, IBM\text{–}J, Jap)$ = true	$T(IBM, IBM\text{–}J, Jap)$ = true
$T(Sony, IBM\text{–}J, Jap)$ = true	$T(Sony\text{–}USA, IBM\text{–}J, Jap)$ = true
$T(ARC, IBM\text{–}J, Sony)$ = true	$T(IBM, IBM\text{–}J, Sony)$ = true
$T(Jap, IBM\text{–}J, Sony)$ = true	$T(Sony\text{–}USA, IBM\text{–}J, Sony)$ = true
$T(ARC, Sony\text{–}USA, Jap)$ = true	$T(IBM\text{–}J, Sony\text{–}USA, Jap)$ = true
$T(IBM, Sony\text{–}USA, Jap)$ = true	$T(Sony, Sony\text{–}USA, Jap)$ = true
$T(ARC, Sony\text{–}USA, IBM\text{–}J)$ = true	$T(IBM, Sony\text{–}USA, IBM\text{–}J)$ = true
$T(Jap, Sony\text{–}USA, IBM\text{–}J)$ = true	$T(Sony, Sony\text{–}USA, IBM\text{–}J)$ = true
$T(ARC, Sony\text{–}USA, Sony)$ = true	$T(IBM\text{–}J, Sony\text{–}USA, Sony)$ = true
$T(IBM, Sony\text{–}USA, Sony)$ = true	$T(Jap, Sony\text{–}USA, Sony)$ = true