"... but will RISC run LISP??"
(a feasibility study)

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ABSTRACT

The Berkeley RISC microprocessor, developed under the direction of David Patterson & Carlo Sequin [1], is targeted for efficient execution of C programs. The architecture has competed successfully with existing systems such as the Vax-11/780 and MC68000. A major question about such a reduced, targeted architecture is how well it extends to other languages. An important language in symbolic computation is Lisp. Lisp is a functional language which has little in common with the standard block structured languages, such as C. This has led to the often-asked question — "will RISC run Lisp?".

The purpose of this paper is to explore the feasibility of a Lisp system running on RISC. The major parts of this include a look at the behavior of large-scale "typical" Lisp programs, and an examination of current Lisp implementations.

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1. Introduction

Lisp is the second oldest "high-level" language in popular use. It was designed to perform symbolic manipulation, particularly for problems in artificial intelligence. The main features of Lisp are its simple structure, extensibility, and the equivalence of programs and data. The language has been implemented on many general-purpose machines (IBM 370, PDP-10, VAX), as well as a few special purpose ones (CDC 7600, CADR). Several "high-level language" computers have been designed to run Lisp, interpreting Lisp instructions directly in the microcode; these have received widespread attention in the computer industry.

A new perspective on "high-level language" computers has been popularized with the RISC I design; a simple instruction set for high-speed execution is combined with a radical "register window file" for minimizing procedure call overhead. The exclusionary use of high-level languages on the machine allows the compiler to hide from the user any complicated or counter-intuitive properties of the underlying architecture.

These conflicting approaches to high-level language architectures has been characterized as the RISC-CISC controversy. RISC standing for Reduced Instruction Set Computer, and CISC standing for Complex Instruction Set Computer. On the RISC side is the Berkeley RISC I, the IBM 801 [2], and the Stanford MIPS [3] processor; the projected performance of the final Berkeley RISC is competitive with modern general purpose processors such as the VAX 11/780 and Motorola 68000. Two notable CISC processors are the Intel iAPX-432 and the MIT SCHEME chip; the Intel 432 has shown feeble performance, and the SCHEME chip will be examined later on in a Lisp perspective to the RISC-CISC controversy. In the meantime I will study the feasibility of Lisp on the Berkeley RISC processor.
2. Why Lisp is not like C

In the next section, we will look at the RISC architecture and estimate how useful it would be for the properties of Lisp; to do this we must explore the differences between Lisp and C.

Table 1 contrasts the features of the two languages. Lisp is intended to exhibit the full generality and flexibility available to interpreted languages, while C is designed for efficient compilation and fast execution. For example, dynamic scoping, typeless variables, and dynamic storage allocation are relatively easy to implement in an interpreter, whereas static scoping, strong typing, and iterative control constructs are well adapted to compiletime semantics checking and efficient object code generation.

<table>
<thead>
<tr>
<th>Table 1 -- Lisp vs C</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Recursion - based control structures</td>
</tr>
<tr>
<td>2 Dynamic scoping</td>
</tr>
<tr>
<td>3 call-by-value (lambda), closure or funarg supported parameters</td>
</tr>
<tr>
<td>4 typeless variables, explicit checking required to determine types</td>
</tr>
<tr>
<td>5 runtime support important for space allocation</td>
</tr>
<tr>
<td>6 executable data, requiring presence of interpreter</td>
</tr>
<tr>
<td>7 operators correspond to function calls in interpreted code, often in compiled code as well. Exceptions are simple control structures and logical operations.</td>
</tr>
<tr>
<td>8 lists as fundamental data structure. parameters are always pointers to objects, requiring some degree of fetching.</td>
</tr>
<tr>
<td>9 exotic procedure exits cause variable pops of activation records - throw, return, nonlocal goto, etc.</td>
</tr>
</tbody>
</table>

Lisp can be fairly efficient as a compiled language; some Lisp dialects run competitively with Pascal and C for given benchmarks (Table 6). This efficiency is necessary to obtain tolerable performance from large Lisp systems. Simple extensions to the language make compilation easier, such as optional declarations; furthermore, clever compilers manage to replace inefficient constructs with more efficient ones (such as replacing recursion with iteration).

Many of the differences listed in table 1 have little impact on the performance of compiled Lisp; here I address each of them:

(1) Iterative control structures in Lisp, which are defined using equivalent recursive structures, actually map into iterative forms in compilation. Furthermore, recursion is in many cases transformed into equivalent iteration.
control-flow analysis at compilation can determine whether or not variables must remain dynamically scoped. Some Lisp dialects specify static scoping (NIL, Scheme, and the new Common Lisp), while others consider it the default in compiled modules (UCI and Franz Lisp). Dynamic scoping is then made available through declarations.

Closures and funargs were not used in any of the programs studied here (Franz, GLEAN, Liszt, PHRAN, and Vaxima). An object-oriented style of Lisp programming may use them heavily.

Using typed segments, as in Franz Lisp, typechecking is a simple operation — shift the address and load from a type table. Other schemes use typed pointers, when only part of an address field is used; this can be done in one operation, although it is only possible on machines with subfield addressing mechanisms.

The memory manager is necessary for Lisp. Making it as efficient as possible is important. Garbage collection is largely a matter of linked list and bit operations.

Calls to "eval" may be faster if the Lisp interpreter is microcoded, but such implementations tend to run much slower than compiled Lisp. The tradeoff involved depends upon the ratio of time spent in the compiled code vs. the amount of time spent in the interpreter. Macsyma, for example, spends most time doing list operations when in the kernel.

This merely suggests that a Lisp program will make more procedure calls than a C program for the same computation. In some cases the extra routines can be expanded in-line for maximal efficiency, but this may cause large object files to be created. The procedure call overhead is often minor in relation to the operations contained within a function.

The implied memory overhead is a very important point. I shall take this up in the next section. It is worth noting that the memory speed of a machine must be fast to guarantee fast list operations.

Table 2 shows the frequency of occurrence of exotic functions exits. Reasonably inefficient implementations should be tolerable.

<table>
<thead>
<tr>
<th>contrived examples</th>
<th>calls/returns</th>
<th>exotic returns</th>
<th>ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>throw-catch (compiled)</td>
<td>812</td>
<td>101</td>
<td>12%</td>
</tr>
<tr>
<td>goto (interpreted)</td>
<td>3644</td>
<td>200</td>
<td>5%</td>
</tr>
</tbody>
</table>

We see, then, that Lisp can be like C in such things as scoping and control structures. In some places where they differ, such as pointer manipulations and typechecking, the operations are simple enough to be performed efficiently on most machines. Use of other features, such as funargs and eval, are a matter of style; systems inefficiently supporting them can competitively execute a wide class of Lisp programs.
3. The C machine as a Lisp machine

In this section I will address the problems involved in an efficient Lisp implementation on RISC. Three questions are of importance here:

- Is the memory speed of RISC sufficient for list processing?
- Is the reduced instruction set capable of supporting Lisp operations?
- And will the register window scheme succeed in reducing procedure-call overhead?

The third question is deferred until the fifth section.

Table 3 shows the timings on several C-coded benchmarks, executing on different machines. In all but one case, RISC I is favored, however little. The linked-list, bit-test, and Ackermann benchmarks represent cases we would expect to appear in a running Lisp system—linked-list operations as in memory management and structure manipulation, bit manipulation as in type checking and storage marking, and excessive procedure calls as might occur in interpreting Lisp or making kernel calls from compiled code. Furthermore, the slowest operation (byte manipulation) is not a major part of Lisp, so the RISC architecture appears to support the demands of Lisp.

<table>
<thead>
<tr>
<th>BENCHMARK</th>
<th>RISC I</th>
<th>68000</th>
<th>Z8002</th>
<th>VAX-11/780</th>
<th>11/70</th>
<th>C/70</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>msecs</td>
<td></td>
<td></td>
<td>Number of Times Slower Than RISC I</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E - string search</td>
<td>.48</td>
<td>2.6</td>
<td>1.6</td>
<td>1.3</td>
<td>0.9</td>
<td>2.2</td>
</tr>
<tr>
<td>F - bit test</td>
<td>.06</td>
<td>4.8</td>
<td>7.2</td>
<td>4.8</td>
<td>8.2</td>
<td>9.2</td>
</tr>
<tr>
<td>H - linked list</td>
<td>.10</td>
<td>1.8</td>
<td>2.4</td>
<td>1.2</td>
<td>1.9</td>
<td>2.5</td>
</tr>
<tr>
<td>K - bit matrix</td>
<td>.43</td>
<td>4.0</td>
<td>5.2</td>
<td>3.0</td>
<td>4.0</td>
<td>9.3</td>
</tr>
<tr>
<td>I - quicksort</td>
<td>50.4</td>
<td>4.1</td>
<td>5.2</td>
<td>3.0</td>
<td>3.8</td>
<td>5.8</td>
</tr>
<tr>
<td>Ackermann(3,6)</td>
<td>3200</td>
<td>---</td>
<td>2.8</td>
<td>1.6</td>
<td>1.6</td>
<td>---</td>
</tr>
<tr>
<td>recursive qsort</td>
<td>800</td>
<td>---</td>
<td>5.9</td>
<td>2.3</td>
<td>3.2</td>
<td>1.3</td>
</tr>
<tr>
<td>puzzle(subscript)</td>
<td>4700</td>
<td>---</td>
<td>4.2</td>
<td>2.0</td>
<td>1.6</td>
<td>3.4</td>
</tr>
<tr>
<td>puzzle(pointer)</td>
<td>3200</td>
<td>4.2</td>
<td>2.3</td>
<td>1.3</td>
<td>2.0</td>
<td>2.1</td>
</tr>
<tr>
<td>sed(batch editor)</td>
<td>5100</td>
<td>---</td>
<td>4.4</td>
<td>1.1</td>
<td>1.1</td>
<td>2.6</td>
</tr>
<tr>
<td>towers Hanoi(18)</td>
<td>8800</td>
<td>---</td>
<td>4.2</td>
<td>1.8</td>
<td>2.3</td>
<td>1.6</td>
</tr>
<tr>
<td>Average±S.D.</td>
<td>3.5±1.8</td>
<td>4.1±1.8</td>
<td>2.1±1.1</td>
<td>2.6±1.5</td>
<td>4.0±2.8</td>
<td></td>
</tr>
</tbody>
</table>

In [4], Fateman asserts that in Lisp programs, memory operations are the dominant factor; the performance of Lisp on a given machine is bounded by its ability to do them quickly. Figure 1 shows a C-coded "pseudo" benchmark to measure the memory speed of a given system; the results for several machines appear in table 4. The memory speed of RISC compares favorably with the others. The Macsyma benchmarks seem to agree, except in the case between the CDC 7600 and the KL-10. Here Fateman suggests three contributing factors:
Figure 1 – the c-coded PSEUDO benchmark

```c
int h[1000], j[1000], k[1000];

main()
{
    register int i;
    register int *hp, *kp;
    int *jp;
    int tv1[8], tv2[8];

    for (i=1; i<=1000; i++) {
        h[i] = 0;
        k[i] = i;
        j[i] = i+1;
    }
    h[1000] = 1;
    times(&tv1);
    hp = h; jp = j; kp = j;
    i = 1;
    while (hp[kp[i]] != 1) {
        hp[kp[i]] = hp[i];
        i = j[i];
    }
    times(&tv2);
    printf("%d, (tv2[0] - tv[0])*16);"
}
```

<table>
<thead>
<tr>
<th>Table 4 -- comparisons of memory &amp; Lisp speeds</th>
</tr>
</thead>
<tbody>
<tr>
<td>machine</td>
</tr>
<tr>
<td>---------</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>KA 10</td>
</tr>
<tr>
<td>KL 10</td>
</tr>
<tr>
<td>11/750</td>
</tr>
<tr>
<td>11/780</td>
</tr>
<tr>
<td>KL 10</td>
</tr>
<tr>
<td>RISC I</td>
</tr>
<tr>
<td>CDC 7600</td>
</tr>
</tbody>
</table>

The CDC & PDP-10 pseudo tests were done in fortran, and the RISC & VAX in C.
Benchmark A was macsyma/vaxima performing a symbolic expansion of \((x+y)^{12}\);
Benchmark B was the expansion of \((x+y+z)^{20}\).
(a) the KL-10 data cache, with an access time near the speed of the CDC 7600 memory cycle,
(b) a vastly superior compiler for the PDP-10, and
(c) a better instruction set.

In [5], a high degree of static locality is shown in lists in PDP-10 Interlisp for five benchmarks. 85-90% of the time, successive cars and cdrs occupy the same page. 79-98% of the time, successive cars and cdrs occupy adjacent locations. Dynamic locality was not measured, but sequential accesses of successive list elements would show locality on a fifo basis. This would make a data cache successful only with fast parallel block fetches, a luxury not available to microprocessors.

The small CDC instruction set bears little resemblance to the RISC I; we must satisfy ourselves that it is not an obstacle to Lisp performance. The CDC architecture distinguishes address/index registers from data registers. In simple tasks such as traversing linked lists, an extra operation must be performed at each fetch to move the fetched pointer into an address register for the next fetch. In the 7600, the register-register move takes 25% of the time required to perform the memory fetch [6]. In the macsyma comparisons, the CDC ran ~25% slower than the KL-10; this may explain a large part of the difference, but the KL-10 case was still able to compensate for time lost in cache misses.

The RISC architecture is not crippled by the address/data register distinction. As a further note, it doesn't seem to suffer from lack of double indirect addressing. This mode was used in the Vax-compiled "pseudo" benchmark, but the VAX still lost to RISC.

Table 5 is from [7], a study of macsyma by John Foderaro and Richard Fateman. It shows the dynamic opcode frequencies of vaxima, running on an 11/780 in Franz Lisp. 22% of all movl's were used in stacking. As will be shown later, the RISC must use registers to be competitive -- in which case parameter stacking is replaced by register-register or memory-register operations, a one-for-one exchange of opcodes. For each of the cases, the opcodes have simple analogs in RISC; the problem is the addressing modes.

The static frequencies for Lisp show that 56% of all instructions are nothing but loads and stores (movl, movab, crrl); again, each of the instructions in the list is simple in nature.

Figure 2 shows the frequency of calls to each procedure in the vaxima system; interestingly, 60% of the time was spent in the (C coded) Lisp system and 40% was spent in (Lisp coded) vaxima. This explains in part why the dynamic opcode frequency leans more toward C than Lisp. Another item of interest is that the notable spikes in the graph show that the most popular procedures did nothing but the simplest operations -- creating integers and cells, checking inequalities, garbage collecting, and simple list primitives.

The two major spikes on the chart were coded in VAX assembly language, rather than C; the versions coded for RISC were less than twice the size of the original VAX-code, consistent with several of the C-coded benchmarks.

We see that the RISC has the major feature for good Lisp performance -- memory speed. This puts it in the ball park with VAX and pdp-10, aside from data cache considerations. Current microprocessors have no such edge, so the comparison lies with the instruction sets. A simple benchmark is tested in the next section, where RISC shows encouraging performance.
**Table 5: Instruction usage**

<table>
<thead>
<tr>
<th>Instruction</th>
<th>C coded pct</th>
<th>Lisp coded pct</th>
<th>Begin demo Instruction</th>
<th>Dynamic pct</th>
</tr>
</thead>
<tbody>
<tr>
<td>movl</td>
<td>20</td>
<td>movl</td>
<td>movl</td>
<td>27</td>
</tr>
<tr>
<td>pushl</td>
<td>12</td>
<td>movab</td>
<td>cmpl</td>
<td>7</td>
</tr>
<tr>
<td>calls</td>
<td>10</td>
<td>calls</td>
<td>bnequ</td>
<td>8</td>
</tr>
<tr>
<td>pushal</td>
<td>7</td>
<td>brb</td>
<td>bequ</td>
<td>5</td>
</tr>
<tr>
<td>cmpl</td>
<td>4</td>
<td>elt</td>
<td>ashl</td>
<td>5</td>
</tr>
<tr>
<td>bequ</td>
<td>4</td>
<td>jeb</td>
<td>movab</td>
<td>4</td>
</tr>
<tr>
<td>bnequ</td>
<td>3</td>
<td>beq</td>
<td>teli</td>
<td>4</td>
</tr>
<tr>
<td>brb</td>
<td>3</td>
<td>bneq</td>
<td>erbl</td>
<td>3</td>
</tr>
<tr>
<td>ret</td>
<td>3</td>
<td>teli</td>
<td>beq</td>
<td>3</td>
</tr>
<tr>
<td>elt</td>
<td>2</td>
<td>bneq</td>
<td>elt</td>
<td>3</td>
</tr>
<tr>
<td>other</td>
<td>32</td>
<td>other</td>
<td>other</td>
<td>34</td>
</tr>
</tbody>
</table>

100 Unique instr. 32 Unique instr. 109 Unique instr.
4. aTAKing a current benchmark

As the Franz Lisp system could not be made operational on RISC, hand coding was used to compare performance. A valuable result of this was the realization that Franz Lisp (which makes minimal use of registers) [8] was less suitable for the RISC architecture than the approach used for PSL (Portable Standard Lisp, which uses registers to pass parameters) [9].

Figure 3 shows the TAK benchmark, a heavily recursive function of unquestionable usefulness. It shows the efficiency of procedure call, as well as the difference in speed between fixnum and bignum arithmetic. Fixnum arithmetic refers to integers of bounded length, where operations are tuned to run faster than the unbounded bignum arithmetic on some Lisps. Table 6 shows the execution times for a wide range of machines running a wide range of Lisps. An interesting item to note is the case where 11/750 PSL INUM outruns C; this is probably due to the Lisp compiler removing tail-recursion, while the C compiler is not so sophisticated.

Figure 3 - the TAK benchmark

(tak 18 12 8)
(defun tak (x y z)
  (cond ((not (lessp y x)) z)
        (t (tak (tak (subl x) y z))
           (tak (subl y) z x))
        (tak (subl z) x y))))

Four entries for RISC are on the list. A C-coded version for RISC performed outrageously well. The Franz benchmark was prepared as follows:

The function was compiled on the Vax using LISP to produce symbolic assembly. This was converted into RISC code on an instruction-by-instruction basis -- no special models of compilation or RISC-based optimizations were assumed. Two stack pointers, called np and lbot, were passed as parameters. Normally they occupy reserved global registers, but the RISC C compiler does not allow this. The kernel function “lessp” had to be modified to work without the rest of the kernel. This was done in such a way as to force it to use the same set of operations, so we get a valid timing, although an optimizer will affect the final performance. The process is shown step-by-step in appendix I. The kernel functions and the assembly code were compiled and run on the RISC simulator.

The projection for Franz running on RISC is mediocre compared to C performance. I don’t feel safe in “tuning” the code as a real RISC-Lisp compiler might, because the performance may be unrealistically fast. The result is a valid lower bound on performance; it was sufficient to beat the 11/750 in C, and the MC68000 in both Franz Lisp and Pascal. The problem is the excessive amount of memory traffic due to stacking and unstacking Lisp parameters, which are not passed in registers in Franz.

The next stab was to do the same thing in PSL. The PSL kernel is written in a more obscure “SYSLISP”, so the two support routines were instead taken from Franz. This benchmark gives a valid lower bound on performance if RISC-Lisp passed parameters in registers, and is like Franz in all other ways. The only difference comes in memory management, where pointers in registers also reference active data.
<table>
<thead>
<tr>
<th>System/Implementation</th>
<th>Time (seconds)</th>
</tr>
</thead>
<tbody>
<tr>
<td>11/750 in Franz, ord. arith</td>
<td>19.9</td>
</tr>
<tr>
<td>11/780 in Franz, (nfc)(TAKF)</td>
<td>15.8</td>
</tr>
<tr>
<td>Dolphin in InterLisp Nov 1981 (tr)</td>
<td>11.195</td>
</tr>
<tr>
<td>11/780 in Franz (nfc)</td>
<td>8.4</td>
</tr>
<tr>
<td>11/780 in Franz (nfc)</td>
<td>8.35</td>
</tr>
<tr>
<td>11/780 in Franz with (nfc)(TAKF)</td>
<td>7.5</td>
</tr>
<tr>
<td>11/750 in PSL, generic arith</td>
<td>7.1</td>
</tr>
<tr>
<td>MC (KL) in MacLisp (TAKF)</td>
<td>5.9</td>
</tr>
<tr>
<td>Dolphin in InterLisp Jan 1982 (tr)</td>
<td>5.71</td>
</tr>
<tr>
<td>Dual (MC68000) in Franz(lfc)</td>
<td>5.38</td>
</tr>
<tr>
<td>Vax 11/780 in InterLisp (load = 0)</td>
<td>4.24</td>
</tr>
<tr>
<td>Foonly F2 in MacLisp</td>
<td>4.1</td>
</tr>
<tr>
<td>Apollo (MC68000) Pascal</td>
<td>3.8</td>
</tr>
<tr>
<td>11/750 in Franz, Fixnum arith</td>
<td>3.6</td>
</tr>
<tr>
<td>(Projected) on RISC in Franz (lfc, tr)</td>
<td>3.52</td>
</tr>
<tr>
<td>(Projected) on RISC in Franz (lfc, tr)</td>
<td>3.51</td>
</tr>
<tr>
<td>MIT CADR in ZetaLisp</td>
<td>3.16</td>
</tr>
<tr>
<td>MIT CADR in ZetaLisp</td>
<td>3.1</td>
</tr>
<tr>
<td>MIT CADR in ZetaLisp</td>
<td>3.1</td>
</tr>
<tr>
<td>Apollo (MC68000) PSL SYSLISP</td>
<td>2.93</td>
</tr>
<tr>
<td>11/780 in NIL (TAKF)</td>
<td>2.8</td>
</tr>
<tr>
<td>11/780 in NIL</td>
<td>2.7</td>
</tr>
<tr>
<td>11/750 in C</td>
<td>2.4</td>
</tr>
<tr>
<td>(Projected) RISC PSL/Franz (lfc, tr)</td>
<td>2.23</td>
</tr>
<tr>
<td>11/780 in Franz (nfc)</td>
<td>2.13</td>
</tr>
<tr>
<td>11/780 (Diablo) in Franz (nfc)</td>
<td>2.1</td>
</tr>
<tr>
<td>11/780 in Franz (nfc)</td>
<td>2.1</td>
</tr>
<tr>
<td>(Projected) RISC PSL/Franz (lfc, tr)</td>
<td>2.04</td>
</tr>
<tr>
<td>68000 in C</td>
<td>1.9</td>
</tr>
<tr>
<td>Utah-20 in PSL Generic arith</td>
<td>1.872</td>
</tr>
<tr>
<td>11/750 in PSL INUM arith</td>
<td>1.4</td>
</tr>
<tr>
<td>11/780 (Diablo in C</td>
<td>1.35</td>
</tr>
<tr>
<td>11/780 in Franz (lfc)</td>
<td>1.13</td>
</tr>
<tr>
<td>UTAH-20 in Lisp 1.6</td>
<td>1.1</td>
</tr>
<tr>
<td>UTAH-20 in PSL inum arith</td>
<td>1.077</td>
</tr>
<tr>
<td>MC (KL) in MacLisp</td>
<td>.93</td>
</tr>
<tr>
<td>SAIL (KL) in MacLisp</td>
<td>.83</td>
</tr>
<tr>
<td>SAIL in bumbled MacLisp</td>
<td>.79</td>
</tr>
<tr>
<td>68000 in machine language</td>
<td>.7</td>
</tr>
<tr>
<td>RISC in C</td>
<td>.66</td>
</tr>
<tr>
<td>Dorado in InterLisp Jan 1982 (tr)</td>
<td>.53</td>
</tr>
<tr>
<td>UTAH-20 in SYSLISP arith</td>
<td>.526</td>
</tr>
<tr>
<td>SAIL in machine language</td>
<td>.255</td>
</tr>
<tr>
<td>SAIL in machine language</td>
<td>.184</td>
</tr>
<tr>
<td>SCORE (2080) in machine language</td>
<td>.162</td>
</tr>
<tr>
<td>S-1 Mark I in machine language</td>
<td>.114</td>
</tr>
</tbody>
</table>
47707 function calls  
max recursion depth is 18  
average recursion depth is 15.4  

notes:  
All cases running compiled  
(tr) means Tail Recursion Removal  
(nfc) means 'normal function call' in Franz  
(ffc) means 'fast function call' in Franz  
(lfc) means 'local function call' in Franz (function call directly to an  
entry point using knowledge of the internals of the function by the  
compiler).  
On the 68000 Franz, np & ibot are in registers rather than the standard  
memory locations.

The PSL compiler generated the VAX assembly code, which was again  
expanded into the equivalent RISC instructions. Under a naive association of  
registers, the result was surprisingly good. The current RISC standard (chosen  
by Jim Miro) is to pass the result of a procedure call back in the same register  
as the first parameter; the construction of the TAK function saves 3 register  
move per call. A second kernel function, "sub1", had to be introduced, since the  
PSL compiler did not expand it in-line. An in-line expansion would have sped up  
the benchmark somewhat. This process is shown in appendix II.

The result is the faster PSL/Franz entry for RISC; it outran the 11/750 in C,  
the 11/780 in NIL (a statically scoped Lisp), and the MC68000 running PSL SYS-  
LISP. The PSL SYSLISP is a Lisp-structured language for systems programming;  
no other Lisp should run much faster.

The PSL Lisp was still a far cry from the C performance. With INUM arithmetic, it should be much faster. The simplicity of the benchmark leaves little  
room for optimizations, although the following are possible:

1. the 4 NOP's can be eliminated; some data flow analysis would be required to  
keep the operations correct. This appears as the "NOP's removed" entry  
which outruns the 11/780 Franz.

2. the branch to the return statement might be replaced by the the return  
statement itself; this requires simple control flow analysis in the optimizer.

I feel this is an encouraging result. Although not outrageously fast, we can,  
at worst, expect better performance than the VAX 11/750 or the MC68000. A  
real Lisp system, with a sophisticated compiler, would gain some edge on the  
11/780. With Inum arithmetic, for example, the benchmark should beat the  
speed of C on the RISC. The Inum arithmetic would use the same hardware arithmetic as C, and removal of tail-recursion would eliminate extra procedure calls.
5. Ups and Downs with the Lisp runtime stack

I was at first worried about the performance of the RISC window file. The window file is an array of eight frames of local registers; procedure calls and returns cause the active frame to shift. In C, most of the stack motion is contained by the window file. Occasionally the file overflows or underflows, and windows have to be moved in or out of memory. The memory traffic due to procedure calls and returns is greatly reduced.

Textbook Lisp programs tend to be highly recursive functions such as factorials or linear list traversals. Such functions would generate long, monotonic rises and falls in the stack height; these would negate the advantages of the window file, as opposed to a standard register saving mechanism. To test the validity of this assumption, a special compiler and interpreter were constructed.

The Lisp compiler, LISZT, was modified to interject a call statement before and after each original call and jsb. These extra calls invoke the tracing procedures “upstack” and “downstack”, which put tracing codes into an output file for later analysis.

The Lisp interpreter was rebuilt to trace its own internal calls and jsb’s, and the “upstack” and “downstack” procedures are included in the kernel. When Lisp functions were compiled with the tracing compiler, and loaded into the tracing interpreter, all stack movement is monitored, except for system calls and calls to the tracing functions themselves.

The usage of exotic returns was handled separately. Franz Lisp keeps a linked list threaded through the execution stack, and the links are followed in the event of an abnormal return. Eventually a frame in the execution stack is found, which is capable of catching the exception. I had intended to handle this on RISC by directly writing over the window file, and restoring execution from the correct frame. This requires about the same amount of work as processing a file overflow. To account for the occurrence of such returns in the stack simulation, they were replaced by a sequence of eight stack rises. Rises were used, as opposed to falls, to prevent the stack from falling into negative space; the effect on file performance should be the same. Interestingly, no abnormal returns occurred in any of the test cases.

Six test cases were used, four real and two contrived. The real examples are PHRAN, the PHRAsal ANalyser; LISZT, the Franz Lisp compiler; the Lisp-coded portion of LIKZT; and GLEAN, a system for performing static analyses of Lisp programs. The two contrived cases are the compiled and interpreted versions of a function which copies a list; it is used to measure the effect of linear stack behavior.

Figure 4 shows the stack behavior of the interpreted copy function copying a list. The intermediate calls in the interpreter obscure the overall rise/fall pattern, so [2,2] replacement is optimal (as in most C programs). Under [2,2] replacement, two windows are copied to memory each time the file overflows, and two are restored from memory each time the file underflows. Figure 5 shows the operation of LISZT as it compiles itself. The monotonic rises and falls tend to be shallow.

Table 7 shows the frequency of the various length rises and falls. Over 80% in each case were of length two or less. Over 80% of all calls & returns were contained in these shallow moves. Table 8 shows the performance of the [2,2] replacement policy. In the case of LISZT [2,2] replacement came in third place to [2,1] and [1,2] replacement, but was within 3% of the first place policy. In the compiled copy case, [7,8] replacement is in first place. In this contrived example, the stack rises and falls 100 places, with a minor amount, of intermediate
Figure 4 - COPY stack behavior
1. Figure 5 - Liszt stack behavior
calls. [7,8] replacement is within 2% of optimal, while [2,2] replacement is consistent with the other measurements. In the other four cases, [2,2] replacement showed the best performance. This is the same best policy as for C.

<table>
<thead>
<tr>
<th>program</th>
<th>% of intervals length=1</th>
<th>% of calls/returns contained by intervals length=1</th>
<th>% of calls/returns length=2</th>
<th>maximum depth</th>
</tr>
</thead>
<tbody>
<tr>
<td>PHRAN</td>
<td>61%</td>
<td>36%</td>
<td>32%</td>
<td>38</td>
</tr>
<tr>
<td>LISZT</td>
<td>58%</td>
<td>33%</td>
<td>29%</td>
<td>43</td>
</tr>
<tr>
<td>LISZT (Lisp part)</td>
<td>64%</td>
<td>43%</td>
<td>36%</td>
<td>56</td>
</tr>
<tr>
<td>GLEAN</td>
<td>61%</td>
<td>37%</td>
<td>27%</td>
<td>26</td>
</tr>
</tbody>
</table>

Table 8 -- behavior of window file, under [2,2] replacement policy

<table>
<thead>
<tr>
<th>program</th>
<th>calls/returns</th>
<th>% memory traffic over optimal</th>
<th>% file dumps saved</th>
</tr>
</thead>
<tbody>
<tr>
<td>PHRAN</td>
<td>139484</td>
<td>49%</td>
<td>97%</td>
</tr>
<tr>
<td>LISZT</td>
<td>392384</td>
<td>63%</td>
<td>98%</td>
</tr>
<tr>
<td>LISZT (Lisp part)</td>
<td>141059</td>
<td>46%</td>
<td>98%</td>
</tr>
<tr>
<td>GLEAN</td>
<td>1649</td>
<td>40%</td>
<td>98%</td>
</tr>
<tr>
<td>COPY (interpreted)</td>
<td>2626</td>
<td>42%</td>
<td>89%</td>
</tr>
<tr>
<td>COPY (compiled)</td>
<td>612</td>
<td>51%</td>
<td>68%</td>
</tr>
</tbody>
</table>

Note also from table 8 that the register file was able to contain all but 3% of the procedure calls, saving ~85% of the procedure-call housekeeping. The register file is definitely a success for these cases, something I had not anticipated at the beginning of this project.

This unexpected pattern in stack behavior is probably due to:

1. a large percentage of the execution occurring in the C-coded kernel, which shows typical C-like behavior,
2. use of iterative control structures in Lisp, eliminating much need for recursion,
3. clever compilation frequently removing recursion, and
4. a large number of intermediate function calls masking out any long, monotonic rises and falls.

The frequency of execution in the Lisp kernel is mentioned in section 2. The shallow maximum depth in table 7 is attributable to the second and third reasons, and the fourth is demonstrated in the graph of figure 4.
6. RISC vs. CISC Lisp

Previously I mentioned execution of data in Lisp; this is commonly done by invoking an interpreter function, even from compiled code. An alternative is to interpret Lisp directly on the hardware or firmware. Some current Lisp machines interpret bytecodes, which are produced by preprocessing Lisp programs; one such is the CADR machine listed in table 6. Its performance is reasonable, although nothing spectacular. An important consideration is whether a machine is single-user or timeshared; the MC68000 shows reasonable performance in comparison with an overloaded pdp-11, so the cost per operation per user may favor the microprocessor.

The SCHEME chip is an attempt to execute Lisp directly in microcode [10]. Scheme [11] is a statically scoped dialect of Lisp. The order of parameter evaluation is unspecified, and all parameters are evaluated before calling. This makes the language well-adapted for compilation.

The projected performance of the scheme chip is good in comparison with interpreted Lisp, but shows poor performance compared with compiled Lisp. A LISP system would have to be largely interpreted to run as slow as the SCHEME chip.

Table 9 shows the comparison of times to compute the 20th Fibonacci number, using Peano arithmetic. The projected performance of SCHEME is twice as fast as the Franz Lisp interpreter, but is twenty times slower than compiled Franz Lisp. This is outrageously bad performance for Lisp applications such as Macsyma.

Figure 6 - The scheme benchmark

(defun fib (x)
  (cond ((zerop x) 0)
       ((zerop (sub1 x)) 1)
       (t (plus (fib (sub1 x))
                (fib (sub1 (sub1 x)))))))

(defun plus (x y)
  (cond ((zerop x) y)
        (t (plus (sub1 x)
                 (add1 y)))))

<table>
<thead>
<tr>
<th>Table 9 - performance of the scheme benchmark</th>
</tr>
</thead>
<tbody>
<tr>
<td>KA-10 scheme interpreter in MacLisp</td>
</tr>
<tr>
<td>VAX 11/780 Franz interpreter</td>
</tr>
<tr>
<td>scheme chip (projected)</td>
</tr>
<tr>
<td>VAX 11/780 Franz, compiled (normal funcall)</td>
</tr>
<tr>
<td>VAX 11/780 Franz, compiled (local funcall)</td>
</tr>
</tbody>
</table>
7. Conclusion

We find no reason to anticipate poor performance of Lisp running on RISC architecture. The memory speed is high enough for list processing, the instruction set has the most important features, and the register window file appears surprisingly successful. For good performance, a RISC Lisp system must be modeled after the C system; the language must be compiled and registers must be used as much as possible, resembling more the structure of PSL/SYSLISP.

Other general-purpose and CISC microprocessor systems, such as the MC68000 and scheme chips, are unlikely to deliver superior performance and may indeed perform a great deal worse.
8. References

4. Fateman, R.J., "Is a Lisp machine different from a Fortran machine?", ACM SIGSAM bulletin, vol. 12 no 3, August '78 (8-11).
11. Steele, G.L., and Sussman, G.J., "The revised report on SCHEME -- a dialect of Lisp", MIT AI memo #452
12 Gabriel, D., private communication from RPG@SU-AI
(defun tak (x y z)
  (cond ((not (lesseq y x)) z)
        (t (tak (tak (sub1 x) y z) (tak (sub1 x) z x) (tak (sub1 z) x y))))
)

(defun test ()
  (tak 13 12 6))

1.1. TAK in Franz
1.2. Vax output code from Liszt

.globl F00013  # (fcn lambda tak)
F00013:
.word 0x5c0
movab linker, r8
movl r7, r10
movab 12(r10), r6
L00014:
movl 4(r10), (r6)+  # (beginning cond)
   #(beginning not)
   #(calling lessp)
   #(from y to stack)
movl 0(r10), (r6)+  # (from x to stack)
movab -3(ro), r7
calls $0, *trantb+0
movl r7, r6
tstl r0
jneq L00016
movl 8(r10), r0  # (from z to reg)
jbr L00015
L00016:
cmpl 0(r10), $1024  # (calling tak)
   #(tail merging)
   #(calling tak)
jleq L00017
cmpl 0(r10), $9212
jleq L00013
L00017:
movl 0(r10), r0  # (from x to reg)
jsb _qoneminus
movl r0, (r6)+  # (from reg to stack)
jbr L00019
L00013:
subl3 $4, 0(r10), (r5)+
L00019:
movl 4(r10), (r0)+  # (from y to stack)
movl 8(r10), (r6)+  # (from z to stack)
movab -12(r6), r7
calls $0, *trantb+3
movl r7, r6
movl r3, (r6)+  # (from reg to stack)
cmpl 4(r10), $1024  # (calling tak)
jleq L00020
cmpl 4(r10), $9212
jleq L00021
L00020:
movl 4(r10), r0  # (from y to reg)
jsb _qoneminus
movl r0, (r6)+  # (from reg to stack)
jbr L00022
L00021:
subl3 $4, 4(r10), (r5)+
L00022:
movl 8(r10), (r6) +  #(from z to stack)
movl 0(r10), (r6) +  #(from x to stack)
movab -12(r6), r7
calls $0, *tranmb+8
movl r7, r6
movl r0, (r6) +  #(from reg to stack)
cmpl 8(r10), $1024  #(calling back)
jeq L00023
cmpl 8(r10), $9212
jeq L00024

L00023:
movl 8(r10), r0  #(from z to reg)
jsd -done minus
movl r6, (r6) +
jbr L00025

L00024:
subl 8, 8(r10), (r6) +

L00025:
movl 0(r10), (r6) +  #(from x to stack)
movl 4(r10), (r6) +  #(from y to stack)
movab -12(r6), r7
calls $0, *tranmb+8
movl r7, r6
movl r0, (r6) +  #(from reg to stack)
movl -12(r6), 0(r10)
movl -3(r6), 4(r10)
movl -4(r6), 8(r10)
movab 12(r10), r6
jbr L00014

L00015:
ret
.globl F00026  #(fcn lambda test)
F00026:
.word 0x5c0
movab linker, r6
movl r7, r10
movab 0(r10), r6

L00027:
movl $5192, (r6) +  #(calling back)
  #(from (fixnum 19) to stack)
movl $5169, (r6) +  #(from (fixnum 12) to stack)
movl $5144, (r6) +  #(from (fixnum 6) to stack)
movab -12(r6), r7
calls $0, *tranmb+8
movl r7, r6
ret
bind_org:
.set linker_size
.set trans_size

.long 0
.long 0
.long -1
lit_org:
.asciz "lessp"
.asciz "tak"
.asciz "tak"
.asciz "test"
lit_end:
.data # this is just for documentation
.asciz "@(#)Compiled by Liszt version 8.10 on Tue Sep 7 23:10:14 1982"
.asciz "@(#)decl.l  1.3  3/15/82"
.asciz "@(#)array.l  1.1  9/25/81"
.asciz "@(#)datab.l  1.3  5/27/82"
.asciz "@(#)expr.l  1.3  5/6/82"
.asciz "@(#)io.l  1.1  9/25/81"
.asciz "@(#)funal.l  1.3  2/10/82"
.asciz "@(#)funbl.l  1.11  7/21/82"
.asciz "@(#)func.l  1.4  5/7/82"
.asciz "@(#)tlev.l  1.17  3/24/82"
.asciz "@(#)fixnum.l  1.6  10/21/81"
.asciz "@(#)util.l  1.2  10/7/81"
1.3. Equivalent code for risc

.globl F00013
    ; (fcn lambda tak)
    F00013:
    add   r0, #0, r8 ; linker stub
    add   r30, #12, r29
    L00014:
    ldl   4(r30), r18 ; (beginning cond)
    stl   r13, C(r29) ; (beginning not)
    add   r29, #4, r29 ; (calling lessp)
    add   r29, r0, r13 ; (from y to stack)
    add   r29, #-3, r14 ; (from x to stack)
    ldl   trantb+3(r0), r18 ; calling lessp
    call  r15, _lessp(r0)
    add   r0, r1, r16
    add   r29, #-3, r29
    sub   r14, r0, r0, (c)
    jmp   near L00015(r0)
    nop
    ldl   8(r3C), r3C ; (returning z)
    jmp   none, L00015(r0) ; return
    nop
    L00016:
    ldl   0(r30), r18 ; (calling tak)
    sub   r13,#Fixzero+4596-4096,r0,(c) ; constant MAY be too big!
    ; (tail merging)
    ; (calling tak)
    jmp   1e, L00017(r0)
    nop
    ldl   0(r30), r19 ; constant MAY be too big!
    sub   r13,#Fixzero+4596+4096,r0,(c)
    jmp   1e, L00013(r0)
    nop
    L00017:
    ldl   0(r30), r14 ; (from x to reg)
    call  r15, _setout(r0) ; exit on overflow
    add   r0, r1, r16
    L00018:
    ldl   0(r30), r18
    sub   r13, #4, r18
    stl   r13, 0(r29)
    add   r29, #4, r29
L00019:

    ldl    4(r30), r18
    stl    r13, 0(r29)
    add    r29, #4, r29
    ldl    8(r30), r18
    stl    r13, 0(r29)
    add    r29, #4, r29
    add    r29, #-12, r14
    ldl    trantb+8(r0), r18
    call   r15, F00013(r0)
    add    r0, r1, r16
    add    r29, #-12, r29
    stl    r14, 0(r29)
    add    r29, #4, r29
    ldl    4(r33), r18
    sub    r13, #Fixzero+4596-4096, r0, (c) ; (calling tak)
    jmp    1a, L00020(r0)
    nop

    ldl    4(r30), r18
    sub    r13, #Fixzero+4596+4096, r0, (c) ; (calling tak)
    jmp    1a, L00021(r0)
    nop

L00020:

    ldl    4(r30), r14
    call   r15, _getout(r0)
    add    r0, r1, r16

L00021:

    ldl    4(r30), r18
    sub    r13, #4, r18
    stl    r13, 0(r29)
    add    r29, #4, r29

L00022:

    ldl    8(r30), r18
    stl    r13, 0(r29)
    add    r29, #4, r29
    ldl    0(r30), r18
    stl    r13, 0(r29)
    add    r29, #4, r29
    add    r29, #-12, r14
    ldl    trantb+8(r0), r18
    call   r15, F00013(r0)
    add    r0, r1, r16
    add    r29, #-12, r29
    stl    r14, 0(r29)
    add    r29, #4, r29
    ldl    8(r30), r18
    sub    r13, #Fixzero+4596-4096, r0, (c)
    jmp    1a, L00023(r0)
    nop
L00023:

ldl
sub
jmo
nop
8(r30), r18
r15, #Fixzero+4596+4096, r0, {c}
le, L00024(r0)
nop

L00024:

ldl
call
add
8(r30), r14
r15, _getout(r0)
r0, r1, r16

L00025:

ldl
stl
add
ldl
stl
add
add
ldl
call
add
add
stl
add
ldl
stl
ldl
stl
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add
stl
add
add
add
add
add
add
8(r30), r18
r13, 0(r29)
r29, #4, r29
4(r30), r18
r13, 0(r29)
r29, #4, r29
r29, #12, r14
tranb+8(r0), r13
r15, F00013(r0)
r0, r1, r16
r29, #12, r29
r14, 0(r29)
r29, #4, r29
-12(r29), r13
r13, 0(r30)
-3(r29), r18
r13, 4(r30)
-4(r29), r13
r13, 8(r30)
r30, #12, r29
le, L00024(r0)
nop

L00015:

rat
nop
r31
*globl  _test
*globl  F00026

; name visible from "C"
; (fcn lambda test)

_test:
F00028:
  add    r0, #0, r3
  add    r30, r0, r29

L00027:
  add    r0, #Fixzero+4596+72, r18
  add    r18, 0(r29)   ; (calling tek)
  add    r29, #4, r29
  add    r0, #Fixzero+4596+48, r18
  add    r18, 0(r29)
  add    r29, #4, r29
  add    r29, #-12, r14
  ldl     trantb+3(r3), r18
  call    r15, F00013(r3)
  add    r0, r1, r16
  add    r29, #-12, r29
  add    r14, r0, r30
  ret    r31

; pass result upward

; linkage stuff
trantb:
  .long   _lessp
  .long   F00013
  .long   F00013
  .long   F00026

; location of "lessp"
; "tek"
; "test"
Appendix II – coding TAK from PSL to rise

(da tak (x y z)
     (cond ((not (lessp y x)) z)
             (t (tak (sub1 x) y z)
                 (tak (sub1 y) z x)
                 (tak (sub1 z) x y)))))

tak test ()
    (tak 13 12 c))

2.1. TAK in PSL

(*ENTRY TAK EXP 3)
(SUBL2 27 (REG ST))

GO302
(MOVL (RES 1) (DEPENDED (REG ST))))
(MOVL (REG 2) (DISPLACEMENT (REG ST) 4))
(MOVL (REG 3) (DISPLACEMENT (REG ST) 8))
(MOVL (REG 1) (REG 2))
(MOVL (DISPLACEMENT (REG ST) 4) (REG 1))
(JSB (ENTRY LESSP))
(CMPL (REG 1) (REG NIL))
(JNEQ GO304)
(MOVL (DISPLACEMENT (REG ST) 8) (RES 1))
(JBR 50031)

GO304
(MOVL (DEPENDED (REG ST)) (REG 1))
(JSB (ENTRY SUP1))
(MOVL (DISPLACEMENT (REG ST) 8) (REG 3))
(MOVL (DISPLACEMENT (REG ST) 4) (REG 2))
(BSBNW (INTERNALENTRY TAK))
(MOVL (REG 1) (DISPLACEMENT (REG ST) 12))
(MOVL (DISPLACEMENT (REG ST) 4) (REG 1))
(JSB (ENTRY SUB1))
(MOVL (DEPENDED (REG ST)) (RES 3))
(MOVL (DISPLACEMENT (REG ST) 8) (REG 2))
(BSBNW (INTERNALENTRY TAK))
(MOVL (REG 1) (DISPLACEMENT (REG ST) 16))
(MOVL (DISPLACEMENT (REG ST) 8) (RES 1))
(JSB (ENTRY SUP1))
(MOVL (DISPLACEMENT (REG ST) 4) (REG 3))
(MOVL (DEPENDED (REG ST)) (REG 2))
(BSBNW (INTERNALENTRY TAK))
(MOVL (REG 1) (REG 3))
(MOVL (DISPLACEMENT (REG ST) 16) (REG 2))
(MOVL (DISPLACEMENT (REG ST) 12) (REG 1))
(JBR GO304)

GO301
(ADDL2 20 (REG ST))
(RS3)

*** (TAK): base 547366, length 123 bytes
TAK

(*ENTRY TEST EXP 3)
(MOVL 4 (REG 3))
(MOVL 12 (REG 2))
(MOVL 13 (REG 1))
(JMP (ENTRY TAK))

*** (TEST): base 547776, length 15 bytes

2.2. Intermediate code from compiler
2.3. VAX output code from compiler
2.4. Equivalent code for RISC