FORMULA Version 3.4 Reference Manual

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ABSTRACT

FORMULA is a Forth-based programming environment for computer music, and can be used for algorithmic composition, interactive systems, or programmed score interpretation. It provides a programming model in which separate lightweight processes are used to generate musical parameters such as pitch, rhythm, volume, articulation, and tempo. FORMULA runs on personal computers (Macintosh and Atari ST) and is typically used to control MIDI synthesizers. This manual describes the features of FORMULA and briefly discusses its implementation.

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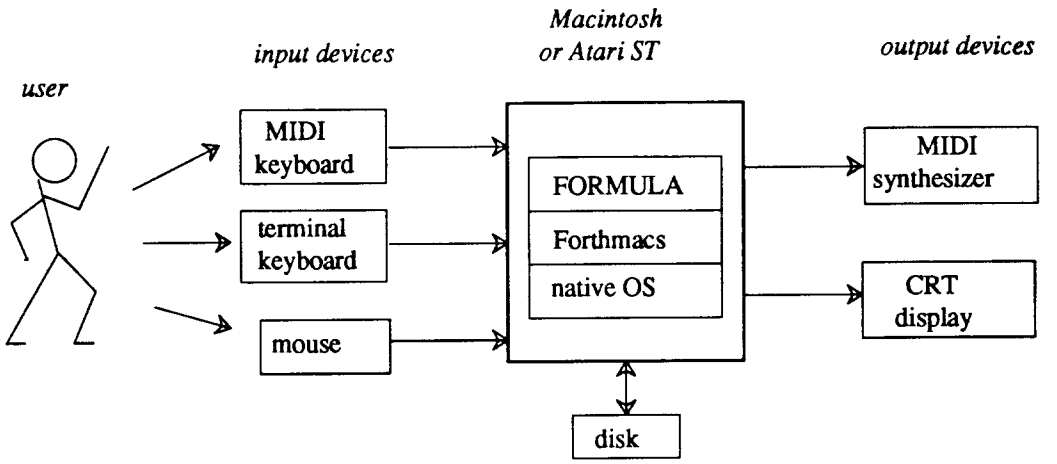
1. INTRODUCTION

FORMULA (*For*th *Mu*sic *La*nguage) is a programming environment for computer music. It runs on the Atari ST and is based on **Forthmacs**, a Forth system developed by Mitch Bradley. Distribution and copying policies for FORMULA and Forthmacs are given in Appendix A. A brief summary of Forth and Forthmacs is given in Appendix B.

FORMULA is intended for musicians who are also programmers. It emphasizes *algorithms* rather than static scores. FORMULA is not a sequencer or score editor, and currently has no graphical interface. However, using FORMULA you can write programs that:

- represent and perform "interpretations" of existing music;
- compose complex music using deterministic or random rules, and play it as they compose;
- interact with a human performer.

FORMULA programs produce sound by controlling an external synthesizer. Normally the connection to the synthesizer is made through MIDI (Musical Instrument Digital Interface; described in Appendix C). Programs can respond to input from various devices. On the Atari ST, these include the typewriter keyboard, the mouse, the joystick, and MIDI keyboards connected to the Atari's MIDI input port, as shown below.



1.1. Getting Started

The FORMULA Version 3.4 release is one double-sided 3.5" disk. The disk contains the source code for FORMULA (in the directory *formula.dir*), for synthesizer-specific configuration words (in *synths.dir*), and for various FORMULA programs (in *pieces.dir*). It also contains binaries for Forthmacs (*forth.tos*) and Emacs (*emacs.tos*), and a quick reference for Emacs (*emacs.ref*). Make a backup copy of the disk.

1.1.1. Compiling and Saving FORMULA

The FORMULA binary is not relocatable, so you must compile and save it on your own "working" disk (this disk must have at least 200K bytes free). To do this, first boot from the working disk. Then insert the FORMULA release disk, and run Forthmacs by double-clicking on *forth.tos*. When you get Forth's `OK` prompt, type

```
cd formula.dir
fload load
```

FORMULA takes about two minutes to compile. When it's done, type

```
cd ..\synths.dir
fload config.gen
```

This loads a *synthesizer configuration file* (§7.2); `config.gen` is for a "generic" MIDI synthesizer with 8 voices on MIDI channel one. This can be customized to your own synthesizer configuration; see §7.

Now insert your working disk and type

```
cd ..
ls
"" formula.tos save-rel
```

This saves the FORMULA binary on disk as *formula.tos*.[1] Henceforth you can load FORMULA directly from the working disk by double-clicking on *formula.tos*. You may also want to copy *emacs.tos* and the *pieces.dir* directory to the working disk.

1.1.2. Running FORMULA

Once FORMULA is loaded, you can start and stop it using

```
formula     ( --- ; start FORMULA )
restore     ( --- ; stop FORMULA )
```

Make sure your MIDI synthesizer is connected, and configure it to receive on MIDI channel one. You can now play a note by typing

```
50 $
```

If this doesn't work, something is wrong. Jiggle the cables, reboot, and try again.

The directory *pieces.dir* contains various FORMULA programs. Type

```
cd pieces.dir
fload demo
rnd-notes
```

and you will hear a stream of random notes. When you get tired of this, type

```
kill-all
```

to stop it[2]. The other files in the *pieces.dir* directory contain FORMULA programs in a variety of musical styles. Try compiling and running some of these (for fun, try running several at once). To hear a lengthy FORMULA sampler, type

```
fload concert       \ this will take a while
concert
```

1.1.3. Panic Buttons

If things go wrong and you lose control of the computer, press the **undo** key to abort FORMULA, and type `formula` again to continue. If this fails, press the Atari's reset button and start over.

---

[1] For obscure reasons, Emacs must not be loaded when you save FORMULA. Also, you can make an auto-booting version of FORMULA as follows: 1) create a directory named *auto*; 2) copy *forth.tos* into *auto*, renaming it *auto.prg*; 3) reboot from this disk; 4) load FORMULA and save it as *auto.prg* within *auto*.

[2] If notes continue to sound indefinitely after `kill-all`, it is because one of the programs had a "sustain pedal" down. Type `pedoff` to release it.

2. BASIC FEATURES

2.1. Playing Notes

Commands can be sent from the Atari's MIDI output port using the following words[3]:

```
mku    ( velocity key-no channel --- ; key-up command )
mkd    ( velocity key-no channel --- ; key-down command )
mpp    ( pressure key-no channel --- ; polyphonic pressure )
mcc    ( value control-no channel --- ; controller change )
mpc    ( patch-no channel --- ; patch change )
mat    ( aftertouch channel --- ; aftertouch )
mpb    ( bendhi bendlo channel --- ; pitchbend )
```

Type

```
127 60 0 mkd
```

to play a middle C (key number 60) on MIDI channel one[4], with a velocity of 127. To release the key, type

```
0 60 0 mkd
```

(a velocity of zero means "release the key").

Let's play a note that lasts exactly ½ second. The word

```
time-advance    ( delay --- ; )
```

pauses for the specified delay. The argument to `time-advance` is in units called *system virtual time* (SVT) whose default length is one millisecond[5]. Type the following on a single line:

```
127 60 0 mkd  500 time-advance  0 60 0 mkd
```

When you hit carriage return, you will hear a middle C sound for 500 milliseconds (½ second).

FORMULA also provides *$-words*, a more compact notation for playing notes. For example, try

```
c $
```

The word `c` pushes the number 60, and the word `$` plays (and releases) a note of the given pitch. In general, the $-words should be used in preference to the MIDI primitives given above.

2.2. Defining New Words

You can define note-playing words in FORMULA as follows:

---

[3] A "word" is the Forth equivalent of a function or program. If you are not familiar with Forth, see Appendix B.

[4] The number 0-15 are used to represent MIDI channels 1-16.

[5] The length of an SVT unit can be changed using

```
usecs-per-SVT    ( n --- set the length of an SVT unit to n microseconds ).
```

For example,

```
500 usecs-per-SVT
```

sets the SVT unit to 500 microseconds (½ millisecond), halving all durations and doubling the tempo. However, there are usually better ways to change tempo; alternatives are discussed in §3.5 and §5.4.

```
:ap word-name
  definition
;ap
```

Definitions can be typed in directly or loaded from a disk file (see Appendix B). `:ap` and `;ap` are exactly like `:` and `;` except that they make an additional "vocabulary" visible within the definition (§11.1). The "ap" stands for *active process*, explained below.

For example, type the following:

```
:ap devil
  c $ f+ $
;ap
```

You have defined a word named `devil` that plays a "devil's interval", C to F#. Type `devil` to hear it.

Once you have defined a word, you can use it in other words. For example:

```
:ap devils
  5 0 do devil loop
;ap
```

produces five `devils` in a row. This ability to define new words out of previously defined words can be used to build phrases out of motives, sections out of phrases, and so on.

Like all Forth words, note-playing words can be passed arguments on the stack. Suppose you would like to hear 7 `devils` in a row, transposed by the notes in a whole tone scale (i.e., C, D, E, F#, G#, A#, C). This can be done most easily by defining a `transposed-devil` that takes a transposition argument:

```
:ap transposed-devil     ( transposition --- ; )
  dup c + $
  f+ + $
;ap
```

We then call `transposed-devil` at each transposition desired:

```
:ap whole-devil
  12 0 do
    i transposed-devil
  2 +loop
;ap
```

2.3. Processes

While trying the above examples, you might notice that there is no response to terminal keyboard input while music is playing. To remove this limitation, FORMULA lets you execute multiple *processes* at the same time. This is done using a software technique called *multiprogramming* in which the CPU switches rapidly between processes to provide the illusion of simultaneous execution.

A *process* is a sequential "thread of control". Don't confuse processes and words; several processes can be executing within a single word (perhaps at different points within it) at once. FORMULA uses processes for various purposes (see Figure 1):

- *Note-playing* (or *active*) processes generate streams of notes. You can have several running at once, and you can type Forth commands or edit files with *emacs* while they run.
- *Auxiliary* processes can be used by note-playing processes to generate rhythms, volume changes, tempo changes, and articulation (§5).

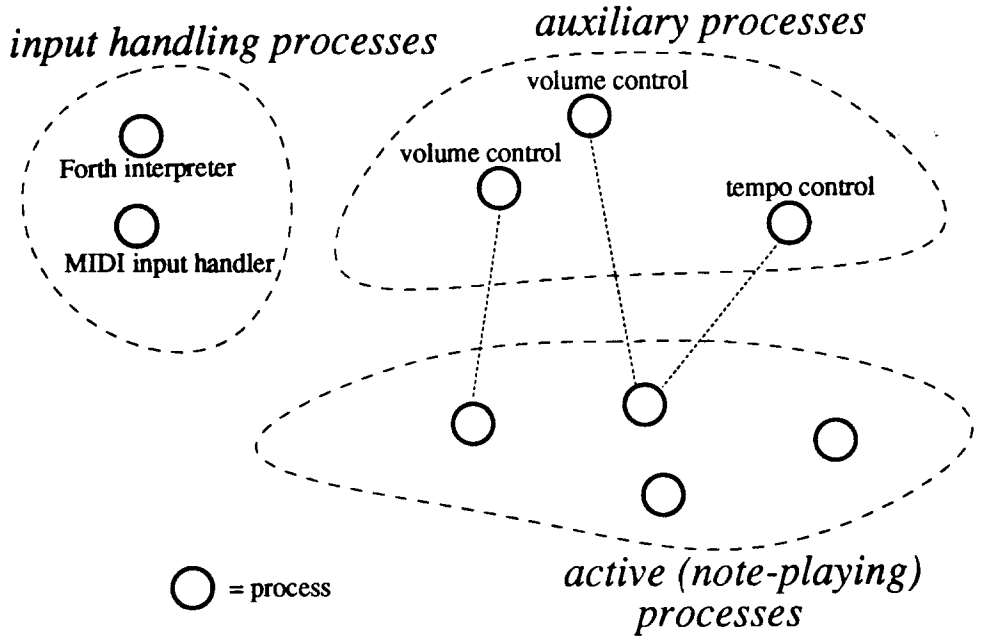


Figure 1: Multiple Process Types.

- *Input-handling* processes deal with input devices such as the terminal keyboard, the mouse, and MIDI keyboards (§8). The process that handles keyboard input is called the *Forth interpreter.*

  The following word is like `whole-devil`, but runs as a separate process:

```
:ap holy-devil
  ::ap whole-devil ;;ap
;ap
```

`::ap` and `;;ap` bracket the code to be executed by the new process. In this case the process will execute `whole-devil`, then exit.

Type `holy-devil`, and you will hear music. You can continue to type while it is playing. By running `holy-devil` a few times,[6] you can get several copies of `holy-devil` to run simultaneously.

This construct works as follows: the *parent process* (the Forth interpreter, in this case) executes `::ap`, which creates a new process (the *child* process) and skips to just past `;;ap`. The child process begins executing the code after `::ap`. When it reaches `;;ap`, it exits and goes away.

Every process has its own *data stack* for parameter passing and *return stack* for return addresses. Since a parent process and its child have separate stacks, parameters cannot be passed between them in the same way that parameters are passed between words. Instead, the number of

[6] Use **<control>p** or the ↑ key to do this with minimal typing; see Appendix B.

parameters to be transferred to a new process must be declared within the child process using:

```
[ n params ]
```

where `n` is the number of parameters needed. This instructs `::ap` to copy *n* words from the parent's stack to the child's stack. For example, the word:

```
:ap tardy-devil     ( delay --- )
  ::ap
    [ 1 params ]
    time-advance whole-devil
  ;;ap
;ap
```

will create a process that waits a while before playing.

2.4. Non-Standard Number Formats

Since the Atari ST can't do floating-point arithmetic efficiently, FORMULA uses other representations for fractional quantities, and provides the following notations for these forms:

- Expressions of the form `A.B` are converted to their equivalent 8-bit fixed-point values. For example, `1.0` is converted to 256 and `0.5` is converted to 128. This is used to specify fractional pitch values (§6.1) and tempos (§5.4).
- Expressions of the form `A|B` and `A(B` represent *rational numbers* (§3.5) that are used to specify time intervals.

These can be used in both interactive commands and word definitions.

3. MORE FEATURES

3.1. Process Groups

Note-playing processes can be collected into *groups*. A group can be controlled (suspended, resumed, or killed) as a single unit (§3.3). You can also control the tempo or volume of the notes played by the processes within a group (§5.3 and §5.4). Groups may also contain other groups as elements.

A group is created using the following construct:

```
::gp
  \ ... code for the group's initial process
;;gp
\ the original process resumes here when group processes exit
```

This can be used only within an active process definition. It works as follows: when a process *P* executes `::gp`, it becomes a group. A new process *Q* is created, executing the code following the `::gp`, and becomes the sole member of the new group. *Q* may create additional processes in the group using `::ap`. When all the processes in the group have exited, *P* becomes a process again and resumes execution after the `;;gp`.

For example:

```
:ap (trio
  ::gp                  \ create a group
    ::ap soprano ;;ap   \ create more processes within the group
    ::ap alto ;;ap
    bass
  ;;gp
;ap

:ap trio                \ non-blocking version of (trio
  ::ap (trio ;;ap
;ap
```

The word `(trio` makes the calling process into a group containing three processes (two of these are created by `::ap` to run `soprano` and `alto`; the third, created by `::gp`, runs `bass`). The calling process resumes only when all three processes have finished. Therefore if you call `(trio` from the Forth interpreter, keyboard input will be ignored until the piece is over. `trio` is a non-blocking version of `(trio`. If called from the interpreter, it creates a new top-level process in which `(trio` is executed.

The `::gp` construct also provides a convenient way to wait for a process to finish. Namely, the process that calls `::gp` waits for the processes created within the group to finish (there is no easy way to do this using `::ap`). In `concert`, for example, this is used to play a sequence of pieces.

3.2. Process Naming

Each process has a corresponding data structure called a *context block* (CB), which contains its stacks and other private data. Internal to FORMULA, a process is identified by the address of its CB. However, since CB addresses are typically 6-digit numbers, this is not convenient at the user-interface level. Instead, a process can have a *small integer identifier* (ID). These ID's are used by words that are *interactive* (i.e., intended to be typed by the user) to refer to processes. By default, a process has no ID; it can request one using

```
assign-proc-ID    ( --- ; assign an ID to this process )
```

In addition, processes can be given symbolic names:

```
proc-name" <string>"    ( --- ; assign a name to the calling process )
```

These symbolic names are not used directly to refer to processes, but are printed by `.all` (see below) to let you associate ID's and processes.

Many FORMULA programs begin by making themselves into a group with a name and ID, as follows:

```
:ap toccata
  ::ap                          \ make a new process
    assign-proc-ID              \ give it an ID
    proc-name" toccata"         \ and a name
    ::gp                        \ make it into a group

\ create more processes, play music, etc.

    ;;gp
  ;;ap
;ap
```

By making itself into a separate group, the program is "insulated" from other concurrent activities.

3.3. Process Display and Control

The word

```
.all      ( --- ; list all processes that have ID's)
```

shows a summary of the existing processes that have been assigned ID's; other processes are not shown. The following words can then be used to obtain more information about a particular process:

```
.gp       ( ID --- ; list all descendants of a process group )
.cb       ( ID --- ; print the contents of a process's context block )
.aux      ( ID --- ; list a process' auxiliary processes)
id->cb    ( ID --- CB ; convert an ID to the corresponding CB )
(.gp      ( CB --- ; list all members of a process group and its descendants)
(.cb      ( CB --- ; print the contents of a process's context block )
(.aux     ( CB --- ; print a process' auxiliary processes)
```

The following words manipulate note-playing processes and groups. They can be applied only to "top-level" objects, not to elements of groups.

```
suspend   ( ID --- ; suspend a process or group )
resume    ( ID --- ; resume a suspended process or group )
(suspend  ( CB --- ; suspend a process or group )
(resume   ( CB --- ; resume a suspended process )
kill-all  ( --- ; kill all processes and groups )
kill      ( ID --- ; kill a process or group )
(kill     ( CB --- ; kill a process or group )
immortal  ( --- ; make the calling process immune to kill-all )
```

3.4. Per-Process Storage

FORMULA provides a `quan` construct for defining named variables:

```
quan      ( name ; --- ; define a quan )
          ( name ; --- n ; a quan returns its value )
to        ( name ; n --- ; store to a quan )
addr      ( name ; --- address ; find address of quan )
```

For example:

```
quan counter        \ declare a quan named "counter"
11 to counter       \ store a value in it
counter .           \ get and print the current value
```

A *per-process variable* has a different copy for each process (a quan has only one copy, shared by all processes). Since each process has its own stack, data stored on the stack is automatically per-process. However, it is not always convenient to refer to stack locations, especially when they belong to other processes.

FORMULA supports *per-process quans*, or *pquans*.

```
pquan     ( name ; --- ; define a pquan )
pallot    ( n --- ; allocate n additional bytes to the last defined pquan )
poffset   ( name ; --- n ; find CB offset of pquan )
```

The `to` and `addr` operations for pquans are the same as those for quans; they refer to the calling process's copy of the pquan. Likewise, a pquan name by itself returns the value of the calling process's copy of the pquan. Other words are provided for accessing other process's copies of pquans (see below).

For example:

```
pquan offset            \ declare a pquan

:ap shifty-devil        ( transposition --- ; )
  ::ap
    [ 1 params ]
    to offset           \ store the transposition in the pquan
    3 0 do
      offset transposed-devil
    loop
  ;;ap
;ap
```

If several processes execute `shifty-devil` at once, each will have a separate copy of `offset`, and will therefore have an independent transposition.

The following words manipulate the pquans of other processes:

```
pget      ( name ; CB --- n ; get the value of another process's pquan )
ipget     ( name ; ID --- n ; get the value of another process's pquan )
pto       ( name ; n CB --- ; store into another process's pquan )
ipto      ( name ; n ID --- ; store into another process's pquan )
paddr     ( name ; CB --- address ; find address of another process's pquan )
ipaddr    ( name ; ID --- address ; find address of another process's pquan )
```

For example, if 3 is the ID of a process executing `shifty-devil`, the command

```
7 3 ipto offset
```

will change its `offset` to 7.

The pquans used internally by FORMULA are initialized at process creation; in most cases they are inherited from the parent process. User-defined pquans, however, are not automatically initialized in new processes.

3.5. Specifying Rational Time Intervals

Most musical time intervals can be expressed as a *rational number* (i.e., ratio of integers) of whole notes. For example, a quarter note is 1/4 of a whole note, and a half note triplet is 1/3. FORMULA lets you specify time intervals as rational numbers. The word `r>i` converts from rational form to integer (SVT) form. For example:

```
:ap quarter-C
  127 60 0 mkd              \ key down
  1 4 r>i time-advance      \ wait a quarter note
  0 60 0 mkd                \ key up
;ap
```

FORMULA converts expressions of the form `A|B` to `A B r>i`. Hence the above example could be written

```
:ap quarter-C
  127 60 0 mkd          \ key down
  1|4 time-advance      \ wait a quarter note
  0 60 0 mkd            \ key up
;ap
```

The conversion performed by `r>i` involves an integer computation of the form

*(num*rscale)/denom*

where `rscale` is a pquan representing the SVT duration of a whole note. The default value of `rscale` is 2000, giving a quarter note the duration

(1 * 2000) / 4 = 500 SVT units.

With the default SVT unit of one millisecond, this would be .5 second (i.e., 120 beats per minute).

Modifying `rscale` can be used for per-process tempo control for processes that use rational time specification. It can be done by a statement of the form

```
1500 to rscale
```

in the note-playing word, or by an interactive command of the form

```
1500 3 ipto rscale
```

where 3 is the ID of an existing note-playing process. Alternatively, the word

```
beats-per-minute    ( n --- ; set rscale to give n beats per minute )
```

sets `rscale` to the value that, at the default SVT unit of 1 millisecond, will produce *n* quarter-note beats per minute.

3.5.1. Round-off Accumulation

`r>i` accumulates round-off[7] on a per-process basis. If round-off were ignored, timing errors could occur after repeated rational-to-integer conversions. For example, a sequence of three 1/3-note triplets would be converted to

```
(2000*1)/3 = 666
(2000*1)/3 = 666
(2000*1)/3 = 666
```

yielding a total time advance of 1998 instead of 2000. With round-off accumulation, each division produces a fractional remainder of 2/3, yielding the sequence (666, 667, 667).

---

[7] "Truncation" is a more accurate term, since `r>i` rounds downwards.

Round-off accumulation is appropriate when the rational numbers represent a sequence of concatenated time intervals (e.g., time advances). In some cases, however, a process may want to do conversions that do *not* represent time advances, and whose round-off should not be accumulated (§5.4 and §5.5). In such cases, the following should be used:

```
(r>i    ( n d --- i ; rational conversion with no error accumulation )
A(B     ( --- ; equivalent to A B (r>i )
```

3.6. Vocabularies

FORMULA uses multiple vocabularies to hide words that are of interest only in certain contexts. These vocabularies are:

```
internals       ( words not intended for direct user access )
loaded          ( per-file compilation words -- used for recompile )
ap-defs         ( words relevant to note-playing process definitions )
sh-defs         ( words relevant to shape definitions )
td-defs         ( words relevant to time deformation definitions )
sg-defs         ( words relevant to sequence generator definitions )
```

Forthmacs maintains a *search list* of vocabularies to be scanned during word lookup. Words such as `:ap` add the relevant vocabulary to the search list. The following

```
only forth also definitions
```

restores the search list to its default state (`forth` is Forthmac's main vocabulary). This is often done at the start of source files, and it's often necessary to do it manually after a compilation error.

Beware of the following mistake: if you redefine a word defined in, say, `ap-defs`, and mistakenly put the definition in the `forth` vocabulary, subsequently definitions using `:ap` see the old definition of the word since `ap-defs` precedes `forth` in the search list.

4. $-WORDS: A HIGH-LEVEL NOTE-PLAYING FACILITY

As described in §2.1, notes can be played using MIDI primitives and `time-advance`, or using a higher-level interface called the *$-words*. The latter facility has several advantages:

- A single word plays a note or group of notes. The word arranges for the note-start command, the `time-advance`, and the note-end command.
- The specification of volume, tempo and articulation is "factored out" of the note-playing process. Note parameters are obtained from a combination of pquans (see below) and auxiliary processes (§5).
- The $-words indirectly call lower-level words to start and end notes. Because of this indirection, programs using the $-words can be synthesizer-independent.

As a preview of the $-words, try running the following:

```
:ap cadence
  g r a r b r 6$
  c e g +c $4
;ap
```

4.1. Simple $-Words

A note-playing process can play notes and rests using

```
$       ( pitch --- ; play a note )
rest    ( --- ; play a rest )
z$      ( pitch --- ; play a note but don't time-advance )
c$      ( pitch --- ; play an attenuated note, no time-advance )
$$      ( pitch --- ; play a note and its octave )
fe$     ( pitch delay --- ; play a note in the future )
fa$     ( pitch delay --- ; play a note in the future )
```

`$` plays a note. `Pitch` can be specified in a variety of ways (§6). By default, it is a MIDI pitch number (60 = middle C). If `pitch` is zero a rest occurs; `rest` is defined as `0 $`. The *duration* of the note or rest is obtained from an auxiliary process called a *timing sequence generator* (TSG). `$` does a `time-advance` by this amount.

`z$` is like `$`, but the process does not advance in time. Thus a process can play a chord by calling `z$` several times, followed by `$`. `c$` is like `z$`, but the volume is attenuated (§4.4). `$$` is like `$`, but plays the lower octave as well.

`fe$` arranges for a note to be played `delay` time in the future, using the parameters (volume, etc.) in effect now. `fa$` arranges for a note to be played `delay` time in the future, using the parameters in effect then.

4.2. Sustain Pedal

Notes can be controlled by a *sustain pedal*. If a note is released while its sustain pedal is down, it continues to sound until the pedal is released. The following words manipulate sustain pedals:

```
pedon    ( --- ; lower sustain pedal )
pedoff   ( --- ; raise sustain pedal )
ped      ( --- ; instantaneously raise and lower sustain pedal )
pedon$   ( --- ; lower sustain pedal and time-advance )
pedoff$  ( --- ; raise sustain pedal and time-advance )
ped$     ( --- ; raise and lower sustain pedal, then time-advance )
```

4.3. Synthesizer Output Paradigms

To produce synthesizer output, the $-words indirectly call lower-level *output paradigm* routines. Different output paradigms can be selected. There are currently three paradigms:

- The *synthesizer manager* (SM) allocates synthesizer voices based on user-specified *note priorities*, and uses *synthesizer drivers* for device independence. Non-standard MIDI (and non-MIDI) synthesizers can be accommodated this way.
- The *dumb synthesizer manager* (DSM) also uses synthesizer drivers, but does no voice allocation.
- *Direct MIDI output* (DMO) can be used only for standard MIDI synthesizers.

These paradigms are discussed in more detail in §7.

4.4. Pquans Used by the $-Words

The $-words use several quans and pquans to obtain note parameters. In some cases, their meanings depend on which output paradigm is used. The pquans are all inherited on process creation.

`$gtranspose` (quan) is added to all pitches. It is in 1/256-semitone units. For example, to transpose all processes by an octave, type:

```
12.0 to $gtranspose
```

`$transpose` (pquan) is added to the pitches of notes played by this process. It is in 1/256-semitone units.

`$volume` (pquan) is added to the volume of notes played by this process (volumes are in the range -127 to 128). Its intended use is to compensate for the particular patch being used, and to balance the volume of different processes.

`$cvolume` (pquan) is added to the volume of "chord" notes played by this process.

`$channel` (pquan) is used to decide which synthesizer channel(s) are used for notes played by this process. With DMO, it contains a MIDI channel number (0-15). With DSM, it points to a *channel descriptor* (§7.2). With SM, it points to a *synthesizer descriptor* (§7.2).

`$patch` (pquan) determines the patch (instrument sound) of notes played by this process. It is used only with SM and DSM, and its meaning depends on the synthesizer type being used. Processes that use DMO must change patches explicitly using `$DMO-change-patch` (§7.3).

`$location` (pquan) determines the spatial location of notes played by this process. It is used only with SM and DSM, and its meaning is synthesizer-dependent. By convention, 0 = left, 64 = center, and 127 = right.

`$priority` (pquan) is the priority of notes played by this process. It is used only with SM (§7.5). This priority determines which notes to preempt when all voices are used.

`$pedal` (pquan) selects a *logical sustain pedals* to be used for notes played by this process. It is used only with SM (§7.5).

4.5. Compound $-Words

To simplify notation, FORMULA allows pitches indices to be grouped together into *lists* (sequences) and *groups* (chords) that can then be played with the following *compound $-words*:

```
m$      ( pitch-list x --- ; play a sequence of x notes )
$n      ( pitch-group x --- ; play a chord with x notes )
m$n     ( pitch-group-list x y --- ; play a sequence of x y-note chords )
m$$     ( pitch-list n --- ; play n notes with lower octaves )
```

In each case, the process does a `time-advance` by the TSG amount after each chord or note is played. For example,

```
c e g +c  4 m$      ( plays a C major arpeggio )
c e g +c  4 $n      ( plays a C major chord )
c e g +c  f a +c +f  c e g +c 3 4 m$n     ( plays a C-F-C chord sequence )
```

The $-words `$`, `m$`, `$n` and `m$n` have "iterator" versions formed by appending `*k` to the word, and supplying the iteration count as the final argument. For example,

```
c e g +c  f a +c +f  c e g +c 3 4 5 m$n*k
```

plays the C-F-C sequence 5 times. This is equivalent to enclosing the whole thing in a do loop, except that pitches are computed just once.

It is convenient to define special versions of the compound $-words with built-in constants. `$4` is defined as `4 $n`, `8$` as `8 m$`, and `4$3*6` as `4 3 6 m$n*k`. `4$3*6`, for example plays a sequence of 4 3-note chords 6 times. Many commonly-occurring abbreviations of this sort are available (see the files *notation* and *notate2*), and others can be defined as needed.

Rolled chords can be played using

```
$nroll      ( pitch-group dt n --- ; play n notes spread over time dt )
```

This advances the process by TSG amount, NOT by *dt*. Hence the notes in the rolled chord can overlap with the subsequent notes generated by the process.

5. AUXILIARY PROCESSES

5.1. Introduction

The $-words take only pitch arguments. Other parameters (such as volume and duration) are obtained from pquans (§4.4) and from *auxiliary processes*. Auxiliary processes can also be used to change the tempo of note-playing process. An auxiliary process can be *attached* to either a process or a group. In the latter case, it affects all processes in group and its descendants. Auxiliary processes allow you to separate musical "interpretation" from the musical "score".

Auxiliary processes can be created using *embedded* process definitions. Here is an example, taken from the file *pieces/demo*:

```
:ap (demo
  ::gp
    92 beats-per-minute
    ::gsh1                          \ volume control process
      begin p f 3|4 oseg  f p 1|1 oseg again
    ;;sh
    ::gtd1                          \ tempo control process
      begin 0.8 1.2 1|1 seg 1|16 1pause 1.2 0.8 5|4 seg again
    ;;td
    ::ap                            \ first note-playing process
      begin
        /16 20 irnd 50 +            \ play a random note a random number of times
        brnd 1+ 4 * 0 do dup $ loop drop
        /1 rest
      again
    ;;ap
    ::tsg                           \ rhythm generator for 2nd process
      begin /8+ /4-3 again
    ;;sg
    0 begin                         \ second note-playing process
      20 irnd swap                  \ uses random/cyclic algorithm
      20 0 do
        over + 40 mod dup 40 + $
      loop
      drop
    again
  ;;gp
;ap

:ap demo
  ::ap
    assign-proc-ID proc-name" demo"
    (demo
  ;;ap
;ap
```

Auxiliary processes can also be created from the interpreter and attached to existing note-playing processes or groups.

5.1.1. Embedded Auxiliary Process Definitions

A note-playing process has *local* and *global* contexts, each of which is either the process itself or a group that contains it. By default, a process's local context is itself, and its global context is the top-level group containing it (or, if the process is top-level, the process itself). The following words can be used to change the contexts:

```
raise-local-context      ( --- ; move local context up one level )
lower-global-context     ( --- ; note global context down one level )
```

Each object contains *slots* for auxiliary processes. A slot is a pquan that is either zero or points to the CB of an auxiliary process. A note-playing word can contain *embedded auxiliary process definitions* that create new processes in its slots or those of its local or global contexts. For example:

```
:ap foo
  ::sh1                  \ install new volume shape in local context
    p f d/1 oseg         \ code of volume shape process
  ;;sh
  c e d f 4$             \ play some notes
;ap
```

The semantics are as follows: when a note-playing process reaches the start of the definition (`::sh1` in this case) the auxiliary process currently in the *sh1* slot of its local context is killed. A new process is created executing the embedded code, and is installed in the *sh1* slot of its local context. If desired, parameters can be passed to the new process using `[ n params ]`.

The constructs for embedded auxiliary process definitions are:

syntax	*location*	*purpose*	*process type*
`::tsg ... ;;sg`	self	note duration	sequence generator
`::sh1 ... ;;sh`	local context	volume control	shape
`::sh2 ... ;;sh`	local context	volume control	shape
`::gsh1 ... ;;sh`	global context	volume control	shape
`::gsh2 ... ;;sh`	global context	volume control	shape
`::ash ... ;;sh`	local context	articulation	shape
`::td1 ... ;;td`	local context	tempo control	time deformation
`::td2 ... ;;td`	local context	tempo control	time deformation
`::gtd1 ... ;;td`	global context	tempo control	time deformation
`::gtd2 ... ;;td`	global context	tempo control	time deformation

5.1.2. External Creation and Deletion of Auxiliary Processes

An auxiliary process can be attached to an existing object using

```
ish1     ( name ; ID --- ; )
ish2     ( name ; ID --- ; )
itd1     ( name ; ID --- ; )
itd2     ( name ; ID --- ; )
itsg     ( name ; ID --- ; )
iash     ( name ; ID --- ; )
```

For example

```
3 ish1 foo
```

creates a volume shape executing `foo` and installs it in the *sh1* slot of the object with ID 3 (it is attached to the object itself, not to its local or global context). If *name* is `noop` then the slot is cleared. Parameters cannot be passed to the shape.

The auxiliary processes attached to a process can be removed using

```
clear-aux        ( ID --- ; )
(clear-aux       ( CB --- ; )
```

5.2. Using Processes to Define Functions of Time

Shapes and time deformations define functions of time. Instead of defining functions in the usual way (by taking a time argument and returning a value) they use *procedural concatenation.* In this style of definition, a function is generated by a process. The process invokes a series of *primitives* (procedures representing a function defined on an interval) and thereby defines a function that is the concatenation of the primitives. The process may take parameters, and may execute arbitrary code between invocations of primitives.

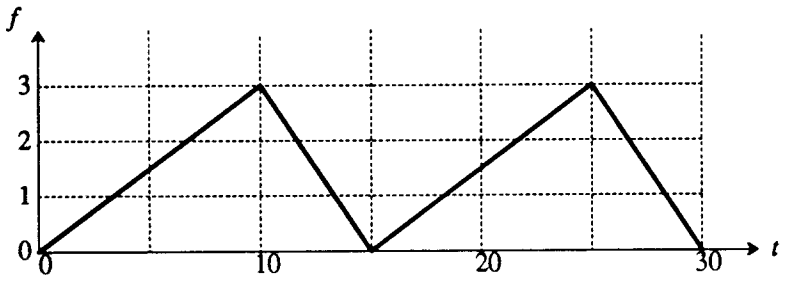
As an example of procedural concatenation, suppose

```
oseg      ( y1 y2 dt --- ; )
```

is a primitive representing a linear function varying from `y1` to `y2` over a time span of `dt`. The following function could then be defined:

```
: sawtooth      ( n --- ; sawtooth with n skewed teeth )
   0 do
      0 3 10 oseg
      3 0 5 oseg
   loop
;
```

The word `sawtooth` invoked at time zero with argument 2 defines the function shown below:



5.3. Volume Control

Shapes are functions, defined by procedural concatenation, used to control volume and articulation. Their definitions are delimited by `:sh` and `;sh`. The following primitives are currently available:

```
oseg     ( y1 y2 dt --- ; linear segment open on right )
cseg     ( y1 y2 dt --- ; linear segment closed on right )
ocon     ( y dt --- ; constant segment open on right )
ccon     ( y dt --- ; constant segment closed on right )
inf-con  ( y --- ; infinite constant-valued segment )
```

The closure is relevant for discontinuous functions; it determines the function value at the points of discontinuity. A primitive's closure on the left is determined by the right closure of the preceding primitive.

The volume of a note is represented by a number in the range -128 to 127. The volume of notes played using $-words is the sum of several components:

- Up to two *local* volume shapes.
- Up to two *global* volume shapes.

- The contents of a per-process variable `$volume`.
- If the note is played with `c$`, the contents of a per-process variable `$cvolume`.

To avoid overflow, it is useful to limit the contribution that each component can make. The convention is that the sum of all four shapes must lie between -96 and 95, `$volume` must lie between 0 and 32, and `$cvolume` must lie between -32 and 0.

Shape definitions may use the words `ppp`, `pp`, `p`, `mp`, `mf`, `f`, `ff`, and `fff`. Because the corresponding values are synthesizer-dependent, these words are defined in a synthesizer-specific configuration file (§7.2).

As an example, a shape definition such as:

```
:sh ramp                ( 1-measure crescendo )
  p f 1|1 oseg
;sh
```

could be used in another shape definition:

```
:sh 10ramps
  10 0 do ramp loop
;sh
```

or attached to a running note-playing process (process 2 in this example):

```
2 ish1 ramp
```

or invoked from a note-playing process

```
:ap foo                 ( n --- ; play 100 notes with n crescendi )
  ::sh1
    [ 1 params ]
    0 do ramp loop
  ;;sh
  100 0 do c $ loop
;ap
```

The last example could also be written as:

```
:ap foo                 ( n --- ; play 100 notes with n crescendi )
  ::sh1
    [ 1 params ]
    0 do
      p f 1|1 oseg
    loop
  ;;sh
  100 0 do c $ loop
;ap
```

5.4. Tempo and Rubato Control using Time Deformations

Continuous tempo fluctuations (e.g., for rubato) are done using *time deformations* (TD's). A TD defines a *tempo function*[8] by procedural concatenation. A TD is applied to a time interval by integrating the tempo function over the interval, starting from its current time position. For example, if the tempo varies linearly from 1 to 2 over an interval of duration 1, the interval is mapped by the TD to a duration of 1.5 (see Figure 2).

---

[8] "Inverse tempo functions" might be a better term, since a larger value means a slower tempo.

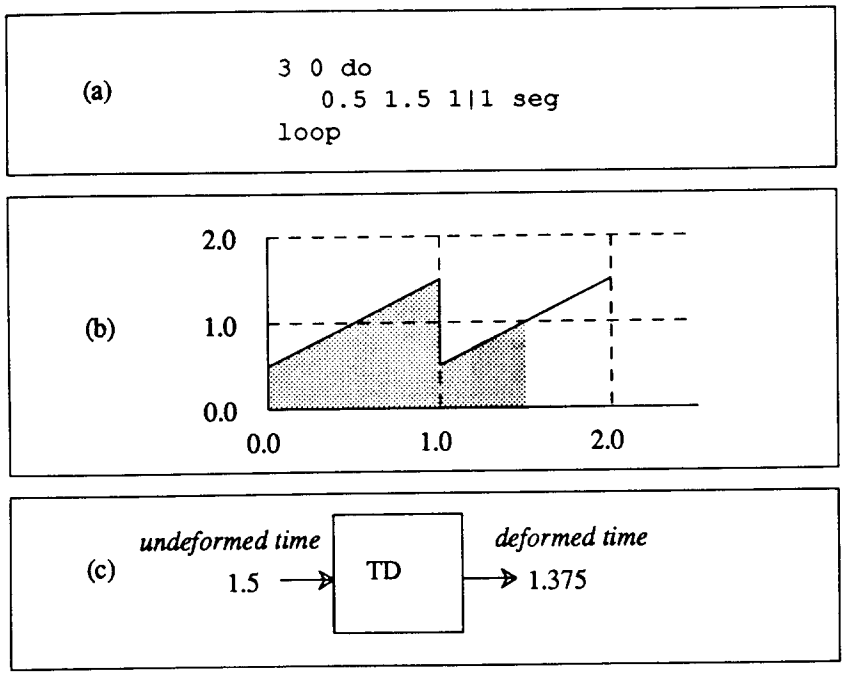


Figure 2: A time deformation (TD) viewed as (a) a procedural definition, (b) a tempo function that is integrated over its domain, and (c) a process that deforms time intervals.

The following TD primitives exist:

```
seg        ( r1 r2 dt --- ; linear tempo change from r1 to r2 over time dt )
con        ( r dt --- ; constant tempo of r over time dt)
inf-con    ( r --- ; infinite constant segment )
lpause     ( t --- ; pause of t before events )
rpause     ( t --- ; pause of t after events )
con.outer  ( r dt --- ; like con, but dt is in deformed units )
seg.outer  ( r1 r2 dt --- ; like seg, but dt is in deformed units )
```

`seg` and `con` represent linear and constant tempo functions. `lpause` and `rpause` insert a "pause" in the tempo function. Events scheduled for this instant occur after the pause with `lpause`, before it with `rpause`. FORMULA represents tempi using fixed-point numbers with an 8-bit fractional part; 256 is unity tempo. This allows `A.B` notation to be used (§2.4).

For example, the following TD does an accelerando over each 4-beat measure, and inserts a slight pause before the start of the next measure:

```
:td foo
  begin
    1.3 .9 1|1 seg
    1|32 lpause
  again
;td
```

It can then be attached to the note-playing process with ID 2:

```
2 itdl foo
```

or written as an embedded definition:

```
:ap blah
  ::tdl
    begin
      1.7 .9 1|1 seg
      1|32 lpause
    again
  ;;td
  100 0 do c $ loop
;ap
```

If two TD's are attached to the same object, their effects are multiplied. If TD's are attached to an object and its parent, they are combined in series: the output of one becomes the input of the other.

5.5. Articulation Control

In general the "delay until release" of a note (denoted *D(r)*) can differ from its "delay until next note" (denoted *D(n)*). *D(r)* may be longer (causing note overlap or *legato*) or shorter (*portamento* or *staccato*) than *D(n)*. This timing relationship will be called *articulation*. In FORMULA, the articulation for each note-playing process is controlled by an *articulation shape* that determines *D(r)* as a function of *D(n)*.

Articulation shapes define both a numeric value and a *mode*: absolute, relative, or ratio. The mode and the value *X* determine *D(r)* as a function of *D(n)*, as follows:

absolute:	$D(r) = X$
relative:	$D(r) = max(0, D(n) + X)$
ratio:	$D(r) = (D(n) * X)/256$

In other words, the value of an articulation gives either the release time of notes, the release time relative to the start of the next note, or the release time as a multiple (with 8-bit fractional part) of the time until the next note, depending on the mode.

Articulation shapes use the shape primitives (§5.3) to define their numeric value, and the words `absolute`, `relative` and `ratio` to set their mode. For example, the following articulation shape varies continuously from staccato to legato every 4 beats:

```
:sh art-shape
  ratio
  begin
    .1 1.2 1|1 oseg
  again
;sh
```

It can be attached to a running process:

```
2 art-shape iash
```

or written as an embedded process:

```
:ap blah
  ::ash
    ratio
    begin
      .1 1.2 1|1 oseg
    again
  ;;sh
  100 0 do c $ loop
;ap
```

5.6. Timing Sequence Generators

A *timing sequence generator* (TSG) is a process that generates a sequence of note durations for a note-playing process. The $-words get note durations from TSG's.

TSG word definitions are delimited by `:sg` and `;sg`. Embedded definitions are delimited by `::sg` and `;;sg`. A TSG generates a single sequence element using

```
&    ( n --- ; return a sequence element )
```

The value returned by `&` may be generated using any of the time specifications described in the previous section. A set of commonly occurring rhythmic patterns are defined using the following naming conventions:

name	*definition*	*meaning*
`/1`	`1|1 &`	whole note
`/4.`	`3|8 &`	dotted quarter
`/4..`	`7|16 &`	double dotted quarter
`/4,,`	`5|16 &`	quarter plus a 16th
`/4,,,`	`9|32 &`	quarter plus a 32nd
`/8.` *etc.*		
`2/8`	`/8 /8`	two eighths
`16/32` *etc.*		
`/4.8`	`/4. /8`	dotted quarter and eighth
`/2.4` *etc.*		
`/2-3`	`/2/3 /2/3 /2/3`	triplet half
`/4-3` *etc.*		
`/8+`	`/8 /16 /16`	eighth and two 16ths
`/4+` *etc.*		

The above words are in the *sg-defs* vocabulary since they are called only from TSG definitions. The names `/1`, `/2`, `/4`, `/8`, `/16`, `/32`, `/4.8`, `/2.4`, `/2+`, `/4+`, `/8+`, `/4-3`, and `/8-3` are also used in the *ap-defs* vocabulary for words that install a TSG that generates an infinite sequence of the given durations. This allows the following convenient notation in note-playing processes:

```
:ap foo
  /4 c d e 3$      \ play some quarter notes
  /8 f g a 3$      \ now play some eighth notes
;ap
```

An example of a TSG definition:

```
:sg funky
  2/4 /4+                    \ three quarters and two eighths
  5 0 do 8/8 /2-3 loop       \ eight eighths and a triplet half,
                             \ repeated five times
;sg
```

`funky` could be used in another TSG definition:

```
:sg blah
  funky 4/8 funky
;sg
```

This defines a sequence composed of 2 copies of the `funky` sequence with 4 eighths interposed. `funky` could be used in a note-playing process:

```
:ap player
  ::tsg funky ;;sg           \ start out in funky rhythm
  8 0 do c $ d $ loop        \ play some notes
  /16
  8 0 do c $ loop            \ switch to sixteenths and play more notes
;ap
```

This example could be rewritten as an embedded TSG definition:

```
:ap player
  ::tsg                       \ define funky rhythm
    2/4 /4+
    5 0 do 8/8 /2-3 loop
  ;;sg
  8 0 do c $ d $ loop         \ play some notes using funky rhythm
  /16
  8 0 do c $ loop             \ switch to sixteenths and play more notes
;ap
```

6. PITCH SPECIFICATION

6.1. Pitch Values and Pitch Indices

FORMULA provides several ways of specifying pitches. Two numeric representations are used:

- A *pitch value* is a fixed-point number with 8 fractional bits, representing a number of semitones[9]. 57.0 (represented as 57*256) is 440 Hz.
- A *pitch index* is an integer used to represent an element of a discrete scale.

The $-words normally take a pitch index as an argument. FORMULA provides two high-level mechanisms for specifying pitch indices: *symbolic pitch names* (`a, b, ...`) and *pitch sets* for specifying scales or chords. Both are described later in this section.

A pquan `$pitch-convert` points to a word, called automatically by the $-words, that converts from pitch index to pitch value. FORMULA supplies several alternative conversion words:

- `shift-convert` multiplies its argument by 256. Pitch indices then refer to the 12-tone equal tempered scale (this is the default.)
- `null-convert` is a no-op; this lets you pass pitch values directly to the $-words.
- `tuning-convert` maps the pitch index into an element of a scale defined by the *tuning system* facility described below.

For example:

```
' null-convert to $pitch-convert        \ play a quartertone above middle C
60.5 $

' shift-convert to $pitch-convert       \ back to equal temperament
60 $                                    \ play middle C
```

6.2. Symbolic Pitch Names

The words `a, b, ..., g` push a pitch index on the stack. The octave is not explicitly given with the pitch name. Instead, each process has a *current octave*, and `a, b, ..., g` refer to the note instance in this octave. Octaves range from C flat up to B sharp. Middle C is in octave 3, which is the initial octave of all processes. The current octave can be changed using

```
oct     ( n --- ; set current octave to n )
+oct    ( --- ; increment current octave )
-oct    ( --- ; decrement current octave )
```

Sharps and flats are denoted by appending `+` or `-` suffix (`f+, b-` etc.). Prepending a `+` or `-` to selects a pitch one octave above or below normal. A number (zero) representing a rest is pushed by the word `r`.

6.3. Tuning Systems

FORMULA includes a facility for defining and using nonstandard tuning systems (just-intoned scales, stretched tunings, etc). The facility is set up to be used with the $-words and the synthesizer manager; with a little work it could also be used independently. When used, each key-down command that the SM dispatches to a synthesizer driver includes a pitch value expressed as a multiple of 1/256 of a semitone. Synthesizer drivers use the fractional part if they

[9] Of course, the fractional bits are relevant only for synthesizers with microtonal capabilities.

can[10].

An example of a tuning system definition:

```
\ make an array of pitch value offsets

create (just 70 p, 182 p, 275 p, 386 p, 498 p, 569 p,
            702 p, 773 p, 884 p, 996 p, 1088 p,

\ declare a scale named "just" using these offsets

scale: just
  12 , 1206 p, (just ,
```

The first part creates a list named `(just` of fractional pitch offsets. The word `p,` converts an offset expressed in cents (1/100 of a semitone) into an offset in 1/256 of a semitone[11]. The second part defines a tuning system named `just`. It repeats every 12 pitches, and it ascends an octave plus 6 cents every period.

The word `just` is called with a pitch index *n* as an argument. This causes the scale to be used in the calling process. The "origin" of the scale is *n*: the pitch index *n* is mapped to its equal-tempered pitch value, and other pitch indices are mapped according to the tuning system. For example,

```
c just
```

causes the calling process to play in a just-intoned scale starting at C. Other processes can use different tuning systems.

The following tuning systems are predefined (see the file *scales*)[12]:

```
stretch
just
pent
pelog-barang
```

`stretch` is 12-tone equal temperament with each octave stretched by 8 cents. `just` is a 12-tone just-intoned scale. `pent` is a just-intoned pentatonic scale. It has been defined as a 12-note scale where groups of 2 and 3 indices map to the same pitch. `pelog-barang` is a 5-note Gamelan scale.

6.4. Pitch Sets

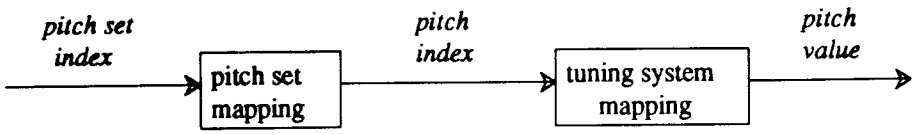
FORMULA provides a *pitch set* facility for defining scales, chords, and other arbitrary ordered groups of pitch indices. As shown below, this facility maps a *pitch set index* (i.e., scale degree) into a pitch index, which may then be mapped to a pitch value by the tuning-system mechanism described earlier.

---

[10] The facility is geared towards synthesizers that can be sent an independent pitch per note (such as the Yamaha FB-01) rather than those that require tunings to be downloaded into the synthesizer (such as the Yamaha DX7-II and TX81Z).

[11] The pitch offset in cents corresponding to a frequence ratio of *n/m* is *1200*log(n/m)/log(2)*. This formula can be used to enter a scale defined in terms of rational intervals.

[12] The manual for the "Tune Up" program (written by Tim Perkis, published by Antelope Engineering, 1048 Neilson St., Albany, CA 94706) is a rich source of data for nonstandard scales.



A pitch set may consist of separate *ascending* and *descending* sets of pitch indices. Each of these has an associated *pitch offset table*, a list of pitch-index offsets of the elements of the set. Each set is invariant under translation by a *pitch set period* (usually 12). A pitch set is described by a *pitch set template* and an *origin*. A pitch set template has four items:

The number of entires in each pitch offset table.
The pitch set period.
A pointer to the pitch offset table for the ascending group.
A pointer to the pitch offset table for the descending group.

Elements of the (ascending) pitch set consist of the origin, plus an element of the (ascending) pitch offset table, plus an integral multiple of the pitch set period.

The file *pitchset* contains definitions of several popular chords and scales. For example, here is the definition and use of a melodic minor scale:

```
\ first define pitch offset tables
create ascmin 0 , 2 , 3 , 5 , 7 , 9 , 11 ,
create descmin 0 , 2 , 3 , 5 , 7 , 8 , 10 ,

\ now define pitch set template
create minorscale 7 , 12 , ascmin , descmin ,

:ap foo         \ play ascending and descending minor scales
   g minorscale set-ps
   20 0 do +ps $ loop
   20 0 do -ps $ loop
;ap
```

For each process, the *current PS* and *position within PS* are maintained. The following words initialize pitch set use and convert pitch set indices to pitch indices.

```
set-ps    ( origin template-addr --- ; switch to new PS with the given )
            ( origin and template )
+ps       ( --- pitch ; next note up in ascending PS )
-ps       ( --- pitch ; next note down in descending PS )
+nps      ( n --- pitch ; n steps up in ascending PS )
-nps      ( n --- pitch ; n steps down in descending PS )
aps       ( n --- pitch ; nth element of ascending PS relative to origin )
dps       ( n --- pitch ; nth element of descending PS relative to origin )
psind     ( --- n ; a pquan that stores last PS index used )
pslast    ( --- pitch ; a pquan that stores last pitch returned )
```

7. SYNTHESIZER OUTPUT

7.1. Output Paradigms

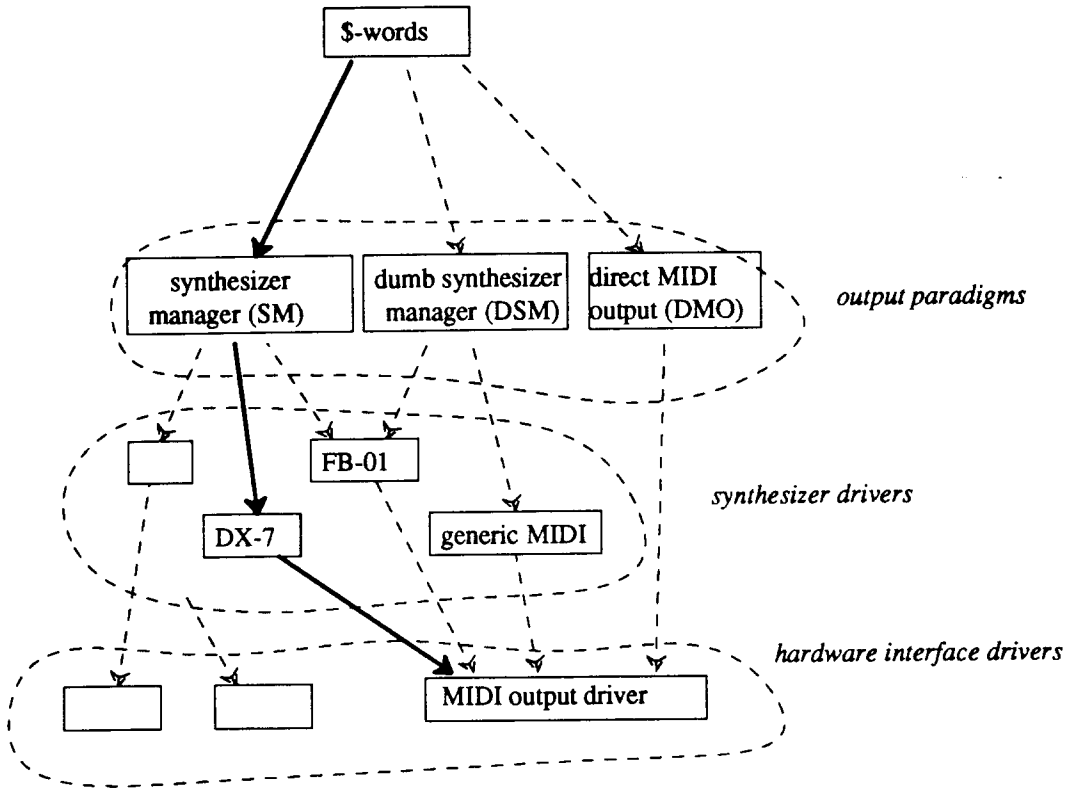
The capabilities of the synthesizers FORMULA controls will vary from user to user. For example, some synthesizers can play several notes at once, but are controlled using a single MIDI channel; we call these *1-channel synthesizers*. Others can receive commands on multiple MIDI channels simultaneously, and can play at most one note on a channel at once; we call these *n-channel synthesizers* (they are also called *multitimbral* because each channel can produce a different instrument sound). A user may have several synthesizers of different types, or may have synthesizers with non-MIDI interfaces (e.g., using the Atari's parallel port). A *synthesizer configuration* is the complete set of synthesizers being controlled by FORMULA.

After a $-word obtains a note's pitch, volume, and other parameters, how does it actually play the note? The answer is supplied by an *output paradigm*, a software layer interposed between $-words and synthesizers[13]. FORMULA provides three output paradigms:

- *Direct MIDI output* (DMO) directly generates MIDI commands. The program must specify which MIDI channel(s) to use.
- The *dumb synthesizer manager* (DSM) provides *synthesizer independence*. Instead of generating output directly, it calls *synthesizer drivers* to do the actual output (these drivers are supplied as part of the description of the configuration). This lets you use non-standard features of MIDI synthesizers (and non-MIDI synthesizers) with no program modifications. Programs still must specify the "channel" (not necessarily a MIDI channel) to be used.
- The *synthesizer manager* (SM) provides device independence and also does *synthesizer voice allocation*. Programs don't tell it which channel to use. Instead, the SM allocates channels (and voices within channels) dynamically, based on *note priorities* supplied by the program. For example, this can be used to ensure that melody notes are not preempted by the accompaniment.

The following diagram shows the various software components involved with synthesizer output:

[13] Processes may also access output paradigms directly, without using $-words. This interface is not described here, but can be found in the source code.



7.2. Synthesizer Configuration

Both the SM and the DSM need to be told about your synthesizer configuration: how many channels of each synthesizer type, and how many voices per channel. This is done using

```
declare-synth      ( --- synth-desc ; declare a synthesizer type )
declare-channel    ( channel-no synth-desc driver-addr nvoices
                       --- channel-desc ; declare a synthesizer channel )
```

`declare-synth` returns a *synthesizer descriptor* that identifies a synthesizer type[14]. The arguments to `declare-channel` are as follows. `synth-desc` is the synthesizer type of the channel, and `driver-addr` is the address of a synthesizer driver routine (see below). When the driver is called, `channel-no` is passed to identify the channel; for MIDI, this is the MIDI channel number. `nvoices` is the number of voices (i.e., maximum number of simultaneous notes) on the channel.

For example, here's a configuration routine for two MIDI synthesizers, a Yamaha with 1 voice each on MIDI channels 1-8, and a Roland with 16 voices on channel 10.

[14] A "synthesizer type" is really just the set of channels of that type.

```
quan yamaha-sd    \ points to synthesizer descriptor for Yamaha
quan roland-sd    \ points to synthesizer descriptor for Roland

: my-synth-config
 declare-synth to yamaha-sd      \ create a synthesizer descriptor for Yamaha
 declare-synth to roland-sd      \ create a synthesizer descriptor for Roland

\ declare the 8 Yamaha channels
 8 0 do
  i yamaha-sd [']  generic-MIDI-driver 1 declare-channel
  drop            \ the SM doesn't need the channel descriptor, so drop it
 loop

\ declare the one Roland channel
 9 roland-sd [']  generic-MIDI-driver 16 declare-channel
 drop
;
```

In this example, `generic-MIDI-driver` is a synthesizer driver routine that generates standard MIDI commands[15].

7.2.1. Selecting an Output Paradigm

A process "selects" an output paradigm by setting a pair of pquans (`$note-routine` and `$pedal-routine`) to point to routines provided by the paradigm. The words `$SM`, `$DSM` and `$DMO` set up these pquans for the paradigms described above. Because pquans are used, different processes may use different output paradigms[16]. A process inherits these pquans from its parent, as well as the other pquans used by the $-words (`$channel`, `$patch`, `$priority`, etc.).

For example, the following routine selects the SM output paradigm and arranges to use the Yamaha synthesizer (as declared above) with patch zero.

```
: my-select-paradigm
 $SM
 yamaha-sd to $channel
 0 to $patch              \ initial patch (Brass?)
 64 to $location          \ initial stereo location (center)
\ other pquans ($priority, $pedal, etc.) are initially zero
;
```

7.2.2. Initialization

The initialization word `formula` calls two deferred words:

- `set-synth-config` declares your synthesizer configuration to the SM.
- `select-paradigm` connects the $-words to an output paradigm. This involves initializing the pquans `$note-routine` and `$pedal-routine` and initializing other pquans (such as `$channel`) used by the paradigm.

You can redefine these; for example,

---

[15] FORMULA also includes a driver `fb01-driver` for the Yamaha FB-01 that supports microtonality using the FB-01's system exclusive messages.

[16] However, unexpected results may occur if a particular synthesizer is accessed via two different paradigms.

```
' my-synth-config is set-synth-config
' my-select-paradigm is select-paradigm
```

causes `formula` to select the SM and declare the synthesizer configuration given above. If this is done in a configuration file that is loaded prior to saving *formula.tos*, then this will be done automatically each time you run `formula`.

The default version of `select-paradigm` selects DMO, and the default version of `set-synth-config` is a no-op.

7.3. Direct MIDI Output

When direct MIDI output (DMO) is used, notes played with the $-words are translated directly into standard MIDI commands. There is no voice allocation, and no synthesizer drivers.

A configuration file for using DMO looks like this:

```
: select-DMO
  $DMO                  \ initialize $note-routine, $pedal-routine
  0 to $channel ;       \ use MIDI channel zero

' select-DMO is select-paradigm
```

DMO uses the `$channel` pquan to hold a MIDI channel number, which is included in all commands sent. DMO does not use the `$patch` pquan to select a patch. Instead, note-playing processes must use an explicit command:

```
DMO-change-patch     ( new-patch --- ; )
```

Therefore an instrument definition word for DMO might look like

```
:ap piano
  4 DMO-change-patch
  10 to $volume
  12.0 to $transpose
;ap
```

7.4. The Dumb Synthesizer Manager

The DSM provides synthesizer independence. The pquan `$channel` must be set to the channel descriptor of the synthesizer channel to be used. Therefore configuration routines must put channel descriptors in well-known places (e.g., quans). For example, the following configuration file is for a Yamaha FB-01 set up as 8 voices on channel 0, to be accessed via the DSM:

```
quan fb01-sd            \ synth descriptor for FB-01
quan fb01-cd            \ channel descriptor for FB-01's channel zero

: fb01-config-synth
  declare-synth to fb01-sd
  0 fb01-sd ['] fb01-driver 8 declare-channel to fb01-cd ;

: fb01-select-DSM
  $DSM
  fb01-cd to $channel
  0 to $patch
  64 to $location ;

' fb01-config-synth is config-synth
' fb01-select-DSM is select-paradigm
```

A process that uses DSM does not schedule an event to change instruments; it merely changes its `$patch` and `$location` pquans (unlike DMO, no explicit call is needed). Hence one might define words like

```
:ap piano
  th 304 to $patch
  10 to $volume              \ compensate for soft patch
  12.0 to $transpose         \ compensate for low patch (units are 1/256 semitone)
;ap

:ap $center
  64 to $location
;ap
```

When invoked from a process, `piano` will cause subsequent notes to be played using those parameters. The contents of `$patch` depend on the synthesizer type; they are interpreted by the synthesizer driver. In this case (for the FB-01) they include a bank number (3) and a patch number in that bank (4).

Using DSM with the generic MIDI driver is similar to using DMO, but there is one major difference. Suppose two processes use the same MIDI channel and change patches periodically. With DMO, each process will (perhaps unwantedly) be affected by the change-patch commands generated by the other. With DSM, change-patch commands are automatically generated for each note, as needed; all notes will be played with the correct patch.

7.5. The Synthesizer Manager

When using the SM, the pquan `$channel` must point to the descriptor for the synthesizer type to be used[17]. The `$priority` pquan specifies a *priority* for notes played by the process. The SM chooses the "best" channel to use for each note, and decides which existing note(s) to preempt. The SM uses the channel for which the priority of preempted notes is lowest. Processes that are playing crucial parts (e.g., melodies) should store a high value in `$priority`.

In addition, each note is assigned a *pedal group*, numbered 0 through 15, using the `$pedal` pquan. These "logical sustain pedals" can be manipulated independently; the pedal-manipulation words (§4.2) affect only the pedal specified by `$pedal`. When a logical sustain pedal is raised or lowered, all the notes using that pedal are affected. These notes may be distributed over several channels, and even over different synthesizer types.

As with the DSM, instrument parameters are controlled by changing the `$patch` and `$location` pquans.

7.6. The MIDI Output Driver

FORMULA's *MIDI output driver* is a collection of words, assembly language macros, and interrupt handlers. To improve performance, the driver eliminates redundant command bytes. It remembers the current "MIDI state", i.e., the last command byte output on the MIDI line. If the next command has the same command byte, the command byte is suppressed and only the data bytes are sent. For robustness, this mechanism is overridden (i.e., the command byte is sent regardless of the MIDI state) if no command byte has been sent in the last 1/2 second.

This concept is extended further to accommodate synthesizers with a *system-exclusive event*

---

[17] The `$channel` pquan is slightly overloaded; it points to a synthesizer descriptor in this case, *not* a channel descriptor.

state[18]. Such states are entered by a multi-byte system exclusive command, and exited by a `f7` byte. FORMULA's MIDI output driver represents each system-exclusive state by an index into an array `sysexcl-table`. Each element of this array points to a MIDI string (starting with a 32-bit length field) used to enter the corresponding state. A synthesizer driver that uses system-exclusive states must allocate an entry in this array at compile time (using `next-sysexcl-index`) and must pass the index to the MIDI output driver as the "command byte" of commands in its system-exclusive state.

MIDI channel states are encoded as follows: values from 128 to 257 represent standard MIDI command states, and values from 1 to 127 represent system-exclusive states corresponding to the entries in `sysexcl-table`. 0 represents no state (i.e., the state initially or immediately after a system-exclusive command).

The MIDI output driver can be accessed in several ways:

```
MIDI-command          ( Dn ... D2 command n --- ; output a MIDI command )
MIDI-output           ( Dn ... D1 n --- ; output raw MIDI bytes )
MIDI-command-event    ( machine-code event routine version of MIDI-command )
MIDI-output-event     ( machine-code event routine version of MIDI-output )
(MIDI-command)        ( assembler macro version of MIDI-command )
(MIDI-output)         ( assembler macro version of MIDI-output )
```

`MIDI-command` and `MIDI-output` are high-level words, and may be called only within `::ev` and `;;ev`[19]. Both words take an argument count *n* and a sequence of *n* bytes (unpacked, 1 per 32-bit stack entry). `MIDI-command` interprets the bottom byte as a MIDI command state, as described above, and suppresses it if possible. `MIDI-output` simply outputs the bytes without interpretation.

`MIDI-command-event` and `MIDI-output-event` are machine-code event routines with the same arguments, to be scheduled using `event` or `future-event`. `(MIDI-command)` and `(MIDI-output)` are assembly-language macros, to be used in synthesizer driver routines. They expect a pointer to an event record (§10.1) in A1. The `nargs` and `args` field of the event record contain the MIDI command. They do not free the event record; hence synthesizer drivers can use a statically-allocated record.

7.7. How to Write a Synthesizer Driver

A *synthesizer driver* is a machine-code word for controlling a particular type of synthesizer. The driver is passed detailed information about notes: stereo location, microtonality, and so on. It uses as much of the information as it can, given the capabilities of the synthesizer.

A synthesizer driver is called by `jsr` from the SM or DSM, and must return by `rts`. Its arguments are passed in registers:

```
d0: command code (see below)
a4: pointer to a channel descriptor (all commands)
a3: pointer to a note descriptor (key up/down command only)
d3: additional argument (all commands except key up/down)
```

The routine is allowed to change only d0-d2 and a0-a2. The command codes are:

0 = key up/down (the note and channel descriptors contain the pitch, volume, channel number, etc.).

---

[18] For example, the Yamaha FB-01 has a system-exclusive state in which key-down commands specify fractional pitches.

[19] `MIDI-command` and `MIDI-output` don't mask interrupts, so there are potential synchronization problems if you call them directly. Event performance, however, is automatically sequential.

1 = change patch (the new patch number is passed in d3).

2 = sustain pedal (an up/down flag is passed in d3; pedal down if nonzero).

3 = parameter change (the index of the parameter is passed in the high word of d3, and its value is passed in the low word of d3). Parameter indices are synthesizer-dependent, except that 256 (for aftertouch) and 257 (for pitch bend) are reserved values.

Data is passed to synthesizer drivers in channel and note descriptors. The following offsets are used to extract this data.

```
\ offsets into channel descriptors
15 constant cd-channel          \ channel number (8 bits)
16 constant cd-patch            \ current physical patch (low 16 bits)
                                \ and location (high 16 bits)

\ offsets into note descriptors
28 constant nd-pitch            \ 16-bit pitch (8 fractional bits)
32 constant nd-volume           \ 0 .. 127
```

The following is a fragment of the generic MIDI synthesizer driver. The complete code is in *sm-drvr0*.

```
create drvr0-buf                \ static event record for (MIDI-command)
action-rec-size 24 + allot

code generic-MIDI-driver
  drvr0-buf 1# a1 move
  nargs-offset a1 d) a0 lea             \ a0 points to buffer
  1 d0 subq
  0< wif                                \ handle key up/down command
    3 d0 moveq                          \ it's a 3-byte MIDI command
    d0 a0 )+ move                       \ fill in nargs field
    th 90 d0 moveq                      \ build MIDI command byte
    cd-channel a4 d) d0 byte or long
    d0 a0 )+ move                       \ and fill it in
    nd-pitch 2 + a3 d) d0 bmove         \ use integer part of pitch only
    th 7f # d0 byte and long
    d0 a0 )+ move
    nd-volume a3 d) a0 )+ move          \ volume
    ' (MIDI-command 1#) jmp             \ invoke MIDI output driver
  wthen

\ ... handle change-patch and other command codes
\ omitted here for brevity

end-code
```

8. INPUT HANDLING

FORMULA provides interfaces to mouse, keyboard and MIDI input. There is a single *handler process* for each type of input. Keyboard input is handled by the FORTH interpreter process. For the other input sources, you can write your own handler process or use a FORMULA default handler. Handlers are created by deferred words called from `formula`. You can redefine these words to install your own handlers.

A handler process executes an infinite loop, reading and handling input. Whenever there is no input it sleeps, to be later awakened by the corresponding input interrupt routine. If the response to an input event is instantaneous, it can be done by the handler process itself. Otherwise, the input handler should create a separate process to generate the response, thereby freeing itself to handle further input.

8.1. MIDI Input Handling

A MIDI input handler process calls

```
get-MIDI-command   ( --- data1 data0 command time | data0 command time ; )
```

to get the next MIDI command (if necessary, the process will sleep until the complete command has been received). The SVT time at which the command arrived is also returned; normally the handler stores this in its `time-position`.

The deferred word `create-MIDI-handler` creates the MIDI handler. A MIDI handler can be installed as follows (this must be loaded before running `formula`):

```
:ap my-MIDI-handler
  ::ap
    assign-proc-ID proc-name" MIDI handler"
    immortal
    begin
      get-MIDI-command
      to time-position
      ( ... handle the command )
    again
  ;;ap
;ap

' my-MIDI-handler is create-MIDI-handler
```

FORMULA's default MIDI handler maintains a table of *handler routines*, one for each type of MIDI command. When a MIDI command is received, the corresponding word is executed. The following table shows which entry corresponds to which MIDI control byte:

index	*meaning*	*data bytes*
0	keyup	velocity, key-number
1	keydown	velocity, key-number
2	polyphonic pressure	pressure, key-number
3	control change	value, control-number
4	patch change	patch-number
5	mono pressure	pressure
6	pitch bend	bend-lo, bend-hi
7	system command	none; this command is ignored

The MIDI action word is passed the one or two data bytes associated with the MIDI command each time it is executed. You can write your own MIDI action words and store them in this table. MIDI action words may create note-playing processes, but they themselves should not generate time advances as this will interfere with response to subsequent MIDI commands.

As an example, the following program provides a "MIDI delay line" with user specifiable decay rate, repetition speed, and number of repetitions:

```
quan repno 2 to repno           \ number of times to repeat each note
quan reprate 400 to reprate     \ SVT delay between repetitions

:ap rnote       ( vel keynumber --- ; repeat note with decay )
  ::ap
    [ 2 params ]
    repno 0 do
      2dup mkd                  \ play the note
      swap                      \ s: key-no vel
      2 3 */                    \ decay velocity a little
      swap                      \ s: vel key-no
      reprate time-advance      \ wait for delay time
    loop
    2drop
  ;;ap
;ap

' rnote 1 MIDI-action !       \ install handler for key down
```

FORMULA also provides routines that allow MIDI channel patch commands to automatically reconfigure the `MIDI-action` table. For each of the system non-system MIDI commands, a table of CFA pointers, indexed by patch number, is maintained. When a command to change to channel-patch *N* is received, `default-cp` examines the *N*th entry in each of these arrays and, if it is non-zero, stores it in the appropriate entry of the `MIDI-action` table. The syntax for assigning an action to a MIDI channel patch number is:

```
n ku-action: <name>     ( key up action for patch N )
n kd-action: <name>     ( key down action for patch N )
n pp-action: <name>     ( polyphonic pressure action for patch N )
n cc-action: <name>     ( continuous controller action for patch N )
n cp-action: <name>     ( channel patch action when CP N is received )
n at-action: <name>     ( aftertouch action for patch N )
n pb-action: <name>     ( pitch bend action for patch N )
```

For this system to work, every `cp-action` must call `default-cp`.

8.2. Mouse Input Handling

FORMULA's mouse interrupt handler is installed by calling `+mouse`. After this is done, the mouse position and the state of the left and right mouse buttons is maintained in the following quans:

```
mouse-x         \ mouse x coordinate
mouse-y         \ mouse y coordinate
left-button     \ left button down
right-button    \ right button down
```

`mouse-x` and `mouse-y` can be set to any initial value; mouse motions are handled by making incremental changes to them.

These quans can be "polled" by any process. You may instead want to have a process that sleeps until there is mouse input. FORMULA provides a default mouse handler process is started

by calling `mouse-hnd` (which in turn calls `+mouse`). Whenever a mouse event occurs, this process calls the deferred word `mouse-routine`, which you can define to do whatever you want. In the following example, a pair of notes is played on each mouse event, with pitches corresponding to the x and y positions of the mouse.

```
:ap foo
  ::ap
    mouse-x 8 / 50 + z$
    mouse-y 8 / 50 + $
  ;;ap
;ap

' foo is mouse-routine

mouse-hnd
```

8.3. Function Key Handling

The Atari's function keys and shifted function keys can be assigned FORMULA words to be executed when the key is pressed. Indices from 0 to 9 select function keys 1 to 10 while indices from 10 to 19 select shifted function keys.

```
FK-table     ( name ; --- ; create a function key action table )
FK-action:   ( name ; n --- ; insert entry in a function key action table )
default-FK-table     ( predefined default function key action table )
```

`FK-table` defines a function key action table (initially all entries are `noop`). Invoking `name` activates the table. `FK-action:` makes *name* the nth entry of the currently active table.

For example:

```
default-FK-table
11 FK-action: foo
```

will activate the default function key table and cause `foo` to be executed whenever you press the shift key and function key 2 simultaneously.

9. STILL MORE FEATURES

9.1. Random Number Generators

FORMULA provides the following words for generating random numbers:

```
rnd          ( --- n )
irnd         ( m --- n )
brnd         ( --- flag )
rndinit      ( n --- )
grnd         ( m --- n )
frnd2        ( m --- n )
frnd2-init   ( --- )
frnd3        ( old n --- new )
trand        ( table-addr --- n )
```

`rnd` returns a 32-bit random integer from the uniform distribution. `irnd` returns a random integer from the uniform distribution from 0 to *n-1*. `brnd` returns a random 0 or 1 (it's faster than `2 irnd`). `rndinit` initializes, based on the seed `n`, the table used by used by `rnd`, `irnd` and `brnd`. `grnd` returns a random number from the Gaussian distribution with mean zero and standard deviation *m*, rounded to the nearest integer. `frnd2` returns a number from an integer sequence on *(0, ..., m-1)* with (roughly) *1/f* frequency content. The underlying distribution is uniform. The sequence's "state" is per-process; `frnd2-init` must be called to initialize this state by each process using `frnd2`. `frnd3` is another *1/f* random number generator; its state consists simply of its previous value, which is passed as the *old* argument. `trand` returns a random number from a distribution on *(0, ..., n-1)* described by a table whose first entry is the sum of weights, and whose remaining *n* entries are weights on each integer in *(0, ..., n-1)*.

9.2. Time Control Structures

FORMULA has three *time control structures*:

```
maxtime ( n --- )
 ...
maxend

mintime ( n --- )
 ...
minend

mintime ( n --- )
 ...
minloop
```

`maxtime ... maxend` specifies that the enclosed code is to consume at most *n* units of time (in the process's units). If this limit is exceeded, control is transferred to the statement following `maxend` and the stacks are restored to their level at `maxtime`. For example,

```
:ap foo
  ::tsg begin 1|4 irnd & again
  8|1 maxtime
    begin c $ again
  maxend
;ap
```

plays a sequence of random-length notes lasting exactly 8 measures.

`mintime(n) ... minend` specifies that the code block is to be extended by a `time-advance`, if necessary, so that it consumes at least *n* units of virtual time.

`mintime(n) ... minloop` specifies that the code block is to be iterated, if necessary, so that it consumes at least *n* time units.

These structures can be nested; outermost structures have priority. Future actions scheduled within a `maxtime` construct will be performed even if they lie outside the bound. In the example given above, this means that the end times of the notes generated by `foo` may lie beyond the 8-beat limit.

9.3. Memory Allocation

Most of FORMULA's internal data structures are dynamically allocated. The memory allocation facility may be useful to user programmers as well.

```
malloc      ( n --- addr ; allocate a block of n bytes )
free        ( addr --- ; free an allocated block )
```

Memory is allocated from an area that starts at `default-free-mem` and grows downwards as needed. If FORMULA runs out of memory, it panics (i.e., process scheduling is disabled and interrupt vectors are restored to their original state).

10. EVENT BUFFERING AND PROCESS SCHEDULING

10.1. Event Scheduling

The *computation* of a note (i.e., its pitch, volume etc.) can be distinguished from its *performance* (sending the MIDI commands to start and stop the note). FORMULA exploits this distinction to increase timing accuracy by using a technique called *event buffering*. An *event* is an output action whose computation can be separated from its performance. Processes are allowed to compute events slightly ahead of time. Event descriptors are kept in an *event buffer*, and performed when their time arrives. Each descriptor contains the address of a *performance routine* and a set of parameters to pass to that routine.

The use of event buffering requires that a process wanting to generate an output (e.g., to start a note) does not do it directly, but rather *schedules an event* to do it. For example, the word `mkd` (§2.1) does not directly generate MIDI output; it schedules an event that will generate the output. Most FORMULA programmers will never have to schedule events directly, since it is done for them by higher-level words such as `mkd` and `$`. This section explains the event-scheduling interface, for those who are interested.

Event performance routines may be either high-level Forth, or (for efficiency) machine-code routines[20]. The following constructs are used to schedule Forth events:

```
::ev
  ( Forth code for event routine )
;;ev

n ::fev
  ( Forth code for event routine )
;;ev
```

The first construct schedules an event for the current time position of the process; the second schedules an event for `n` units later. In both cases, `[ n params ]` can be used to pass parameters to the event routine. For example, the following program prints 0 through 9, one number per second:

```
:ap
  10 0 do
    i
    ::ev
      [ 1 params ]
      .
    ;;ev
    1000 time-advance
  loop cr
;ap
```

The following words are used to schedule machine-code events:

```
event             ( args nargs CFA --- ; schedule an event )
event-rec         ( args nargs CFA --- rec ; schedule an event )
future-event      ( args nargs CFA delay --- ; schedule event after delay )
```

`CFA` is the address of a machine-code event performance routine. `args` is a set of parameters to be passed to that routine. The routine will be called with a pointer to an "event record" in the A1 register; it may modify A0-A2 and D0-D3. An event descriptor has several fields; the ones relevant to event performance routines are the number of arguments and the argument block. The

[20] Event routines are executed at interrupt level and they cannot call TOS routines (e.g., terminal and disk I/O).

offsets of these fields are stored in the constants `nargs-offset` and `args-offset` respectively. The order of arguments is the same as their stack order. The word must return with an `rts` instruction. In addition, it normally must free the event record using the `(free)` macro, which expects the record pointer to still be in A1.

`event-rec` is like `event` but returns a pointer to the event record[21]. `future-event` is like `event`, but causes the event to be scheduled *delay* units in the future.

As an example, `mkd` is defined as

```
:ap mkd
  th 90 or 3 ' MIDI-command event
;ap
```

where `MIDI-command` is a machine-code routine, written according to the above rules, that outputs a MIDI command.

10.2. Synchronization

Processes may be interrupted by I/O and clock interrupts. In addition, a process may *preempt* another process. Hence any data structures that are shared between a process and an interrupt handler, or between two processes, need a *synchronization* mechanism. FORMULA provides several synchronization mechanisms.

10.2.1. Mutual Exclusion Between Processes

Mutual exclusion is needed for "critical sections" of code in which at most one process can be allowed to execute at once. Since process preemption is done using a "software interrupt" mechanism (§11.1.3), mutual exclusion between processes can be achieved by masking software interrupts:

```
mask-softint        ( --- ; raise software interrupt mask level )
unmask-softint      ( --- ; lower software interrupt mask level )
```

These must always occur in matched pairs, which can be nested. This method should be used only for fairly short critical sections.

For potentially time-consuming critical sections, *real-time semaphores* should be used. A process holding a semaphore can be preempted (in contrast with software interrupt masking, which disables preemption). If a process *A* tries to acquire a semaphore held by a preempted process *B*, *B* is temporarily "promoted" to the deadline of *A*, allowing it to run until it releases the semaphore. The operations are:

```
semaphore:    ( name ; --- ; declare a semaphore )
init-sema     ( semaphore-addr --- ; initialize a semaphore )
P             ( semaphore-addr --- ; acquire the lock )
V             ( semaphore-addr --- ; release the lock )
```

`semaphore:` creates a named semaphore. The resulting word, when invoked, returns the semaphore address. The semaphore must be initialized (at runtime) before it is used.

10.2.2. Synchronizing with Input Sources

The above mechanisms cannot be used to synchronize with interrupt handlers. The following words provide a synchronization mechanism for interrupt-driven input with a single handler process (these are used in the FORMULA implementation of keyboard, MIDI and mouse input,

---

[21] This is used by the SM, for which the argument to the note-end event is a pointer to the event record for the note-start event.

and can be used for other I/O devices):

```
input-handler          ( name ; --- ; declare an input handler structure )
wait-for-input         ( handler-structure --- ; )
(wake-input-handler)   ( assembly language macro )
```

`input-handler` allocates a *handler structure* that maintains a pointer to the handler process and a counter for the amount of data available. `wait-for-input` is called from the handler process; if no input is available, the process sleeps. `(wake-input-handler)` is used in the input interrupt handler whenever new input has been received. It wakes up the handler process if necessary.

10.2.3. Interrupt Masking

The synchronization mechanism of last resort is to mask hardware interrupts:

```
set-mask        ( --- old-mask ; mask interrupts )
(set-mask)      ( assembly language macro version )
restore-mask    ( old-mask --- ; restore old mask )
(restore-mask)  ( assembly language macro version )
```

Interrupts (and therefore preemptions) cannot occur between `set-mask` and `restore-mask`. Interrupt-masking should be used only for short critical sections (100 instructions or less) because of the possibility of lost interrupts, especially from MIDI input.

10.3. Process Scheduling Parameters

Each top-level process has several "scheduling parameters", stored in the following pquans (all times are in SVT units):

- `time-position` is the time for which the process is currently computing events.
- `deadline` determines the order of process execution: the executing process is that with the earliest deadline (§11.3.2).
- `maxdel` determines how far ahead of the current SVT the process is allowed to compute. If the process advances to a time position such that

  time-position > (current SVT) + maxdel

  then the process is suspended, and remains *dormant* until the condition no longer holds. `maxdel` must be nonnegative.
- `mindel` determines the process's deadline as a function of its time position:

  deadline = time-position - mindel

  A process's `mindel` must be strictly less than its `maxdel`, and can be negative.

A quan `system-mindel` stores the maximum amount by which processes are allowed to fall "behind schedule" before the advance of system virtual time is stopped to allow them to catch up. Specifically, SVT is not advanced if

earliest deadline + system-mindel < current SVT

The `maxdel` and `mindel` parameters of top-level processes can be adjusted to obtain a "scheduling policy" that is optimized for your particular application. (A process belonging to a group is governed by the parameters of its top-level ancestor group.)

- The relative values of `mindel` can be used to "prioritize" input-handling processes. Suppose response to MIDI input is more time-critical than response to mouse input. By giving the MIDI input handler process a larger (more positive) `mindel` than the mouse handler, the MIDI handler will have an earlier deadline (and will therefore run first) whenever MIDI and mouse events occur at about the same time.

- The value of `maxdel` is a tradeoff between timing accuracy and response latency. If `maxdel` is small, the process will respond quickly to input but may experience event timing errors if system load is heavy or its own computations are long. If `maxdel` is large, the process will be more immune to timing errors, at the expense of increased input response time.

By changing `system-mindel` you can determine what happens when the system falls behind schedule. If `system-mindel` is nonnegative, then SVT stops advancing whenever the system falls behind schedule (i.e., when SVT exceeds the earliest process deadline). All subsequent events are uniformly shifted in time, but the system loses synchronization with external timing sources. If you need such synchronization, `system-mindel` should be given a large negative value. This may cause short-term compression of events if lateness occurs.

`maxdel` and `mindel` can be changed at any time. For example, the `maxdel` of a process can be temporarily reduced during a period of frequent user interaction with the process. A process must call

```
0 time-advance
```

to have these changes take effect (that is, to change its `deadline` and perhaps become dormant).

10.4. Background Processes

FORMULA's deadline scheduling mechanism is designed for processes that schedule output events for specific times, using relatively small amounts of CPU time to compute the events. Unfortunately, not all processes conform to this model. For example, the Forth interpreter process, while it is executing `words` (which prints the contents of a vocabulary) uses large amounts of CPU time and has no particular output timing requirements.

Such processes can be accommodated by making them into *background* processes:

```
background    ( --- ; make caller into a background process )
foreground    ( --- ; make caller into a foreground process )
```

The deadline of a background process is always "infinite"; the range `0x7fffff00` to `0x7fffffff` is reserved for background processes. The time position of a background process is initially less than current SVT. When a background process does something of a real-time nature (scheduling an event, calling `time-advance`, or creating a group) its time position is set to the maximum of its current value and the current SVT. This arrangement allows background processes to generate real-time output; e.g., you can play music in the Forth interpreter. The computation of the music, however, is done with an infinite deadline so it may potentially be "starved" by other processes.

11. FORMULA IMPLEMENTATION

11.1. Scheduling and Event Performance

This section briefly describes FORMULA's implementation of process and event scheduling. Three "global" time systems are used:

Real time (or "wall clock" time) is maintained by a 200 Hz periodic clock interrupt.

System time (ST) normally advances at the same rate as real time. However, when a process has fallen behind schedule (that is, when the current ST exceeds the "deadline" of the process), ST stops advancing to allow the process to catch up.

System virtual time (SVT) advances with ST, but with a scaling factor `tempo` (units of SVT per unit of ST). `tempo` provides a high-resolution global tempo control. It can be set directly (it is a quan) or using `usecs-per-SVT` (§2.1).

11.1.1. Data Structures

FORMULA uses the following record types. The pquan mechanism (§3.4) is used to access the fields of these records.

- *Context blocks*: each stores the state of a process, including its stacks and pquans.
- *Event records*: each describes a pending event, including its parameters and a pointer to its performance routine.

These records are organized in the following structures:

- The *execution queue* is a list of context blocks of executable processes, sorted by increasing value of `deadline`. The executing process (the *execution queue head*) is always that with the earliest deadline.
- The *wakeup buffer* stores event records and context blocks of dormant processes. It is implemented as an array of lists of entries. Each entry has a `wakeup-time` field storing the SVT when the event is to be performed or the process is to be made executable. The array position of an entry is given by the low order bits of its wakeup time.

11.1.2. Time-Advance and Event Scheduling

FORMULA's time-related primitives are implemented as follows. First, `time-advance` stores its argument in the `delay` pquan, applies the caller's TD's to `delay` and adds the result to its `time-position`. If the caller is in a group, the delay until the new earliest member of the group is propagated to the group's context block; this recurses up the tree. At the top level, the assignments

```
deadline = time-position - mindel;
wakeup-time = time-position - maxdel;
```

are done. If `wakeup-time` is greater than the current SVT, the object is moved to the wakeup buffer; otherwise the object is reinserted in the execution queue. In either case, a context switch is done to the new execution queue head.

`event` allocates an event record and moves its arguments to the record. The wakeup time of the event record is set to the maximum of the caller's time position and the current SVT. The event record is then inserted in the wakeup buffer.

11.1.3. Event Performance and Preemption

The FORMULA scheduler executes processes in order of increasing deadline, and a process is preempted if one with an earlier deadline becomes runnable. Action performance and process

preemption are done jointly by the clock interrupt handler and the software interrupt handler[22]. On each clock interrupt, the handler sees if the current SVT is less than the earliest process deadline. If so, it adds `tempo` to the current SVT, and checks if any entries in the wakeup buffer array for times between the previous and current SVT's are non-empty, and requests a software interrupt if so.

The software interrupt handler processes lists of records from the wakeup buffer. It moves dormant processes to the execution queue and executes event performance routines. The software interrupt routine continues to process lists from successive entries of the wakeup buffer until its index exceeds the current SVT. If, on completion of the software interrupt handler, there is a new execution queue head, then the old execution queue head is preempted and a context switch is done.

When a process is awakened by an interrupt routine, it is moved to the wakeup buffer rather than directly to the execution queue. Its wakeup time is assigned so that it will be awakened on the next clock tick.

`kill` and `suspend` set flags in the context block. These flags are checked, and the appropriate action taken, the next time the object is removed from the wakeup buffer.

11.2. The Accuracy and Range of Time Specification

The timing accuracy of events is limited by the 5 millisecond resolution of the Atari's interrupt clock. Forthmacs uses 32-bit integers, producing the following limitations:

- Time positions are integers, so SVT wraps around (producing indeterminate results) every 2^{32} SVT units, roughly 1000 hours if SVT unit = 1 ms.
- In rational conversion by `r>i`, the term *numerator*rscale* must fit in 32 bits, and the denominator must fit in 16 bits.
- Time deformations use 8-bit fixed-point multipliers. Therefore time intervals passed through TD's must fit in about 23 bits (depending on the magnitude of the tempo functions).

The following table shows representative time interval representations for `rscale` = 2000 and SVT unit = 1000 microseconds (the defaults).

	whole note	64th note
rational	1|1	1|64
SVT	2000	~31
real-time	2 sec.	~.03 sec.

With these parameters, the largest usable interval is about 4000 whole notes if time deformations are used (because of the 23-bit limitation).

There are several sources of round-off error in FORMULA:

- The round-off accumulated by `r>i` is 16 bits, leaving uncompensated error up to 2^{-16} of an SVT unit.
- TD's accumulate only 8 bits of error. This is a problem only when multiple processes use different TD's that should synchronize periodically.

---

[22] A *software interrupt* is requested in software, and has lower priority than any hardware interrupt. On the Atari ST, this is done using the horizontal retrace interrupt, which is normally not used, has lower priority than any other interrupt, and is triggered at a very high rate.

APPENDIX A: DISTRIBUTION AND COPYING

The current release of FORMULA is available from the authors. The copying policies for FORMULA and Forthmacs are described in the file *copying.txt*. Both packages are copyrighted, but the respective authors have granted permission for the release disks to be freely used, copied, and given away. However, they may not be sold.

APPENDIX B: FORTH AND FORTHMACS

1. Forth

FORMULA is an extension of the programming language Forth. You can use FORMULA without knowing Forth, but you will be somewhat limited. A good introductory book on Forth is *Mastering FORTH* by Anita Anderson and Martin Tracy, published by Prentice Hall.

Forth is a very simple programming language. Forth's program unit is the *word*. Words communicate using a *data stack*; most words take their arguments from the stack and leave their result on the stack. Return addresses are kept on a separate *return stack*.

The documentation of a word often includes a 1-line summary:

```
name    ( old --- new ; comments )
```

Old and *new* represent the stack contents before and after executing the word. For example, the summary of the words + and `over` are:

```
+       ( n m --- sum ; replace top 2 stack elements by their sum )
over    ( n m --- n m n ; duplicate 2nd-to-top stack element )
```

Some words take a text argument (usually the name of a word or a file) that follows them in the command or source file. For example, the word `array` is used as follows:

```
10 array foo        ( declare an array of 10 words )
```

The 1-line summary of `array` is:

```
array   ( name ; nwords --- ; declare an array )
```

Forth systems are interactive, and include an *interpreter* that processes your keyboard input. The interpreter lets you invoke a word simply by typing its name. It also lets you enter word definitions via the keyboard. Most Forth systems also include built-in words that let you create and edit disk files, and load word definitions from disk files.

2. Forthmacs [23]

Forthmacs is an implementation of the Forth-83 standard with many enhancements, and includes a version of the Emacs text editor. **Forthmacs** has many features that set it apart from other Forth implementations:

- **File system interface**

  Forthmacs uses named files instead of disk blocks, and provides the following file commands:

```
fload   ( file-name ; --- ; load (interpret) a file )
ed      ( --- ; invoke the Emacs text editor )[24]
more    ( file-name ; --- ; view a file w/ pagination )
cd      ( directory-name ; --- ; enter a subdirectory )
rm      ( file-name ; --- ; delete a file )
mv      ( oldname newname ; --- ; rename a file )
ls      ( --- ; list directory contents )
```

  You can use absolute and relative pathnames as in UNIX, except that \ rather than / separates components.

---

[23] This section is to help you get started with Forthmacs; you should buy the complete documentation if you plan on using FORMULA a lot.

[24] Emacs documentation is included in the Forthmacs documentation.

- **Command completion**

  If you type the start of a word name, **<control><space>** will extend it to a complete name if possible. This saves typing when using long names. **<control>?** prints the names that extend the current word fragment.

- **Command history**

  <control>p and **<control>n** cycle back and forth through a list of recent command lines; this can be used to avoid retyping long commands.

- **Command-line editing**

  Command lines (including those resurrected by **<control>p**) may be edited with intra-line Emacs commands; **<return>** causes the entire line to be executed, regardless of cursor position.

- **Decompilation and On-Line Documentation**

  The following words facilitate on-line source code browsing:

```
see         ( name ; --- ; decompile a word )
.calls    ( CFA --- ; )
whatis      ( name ; --- ; print 1-line summary )
```

  `See` can, in most cases, completely reconstruct a word's definition from its compiled form. This allows you to conveniently peruse the source code of Forthmacs and FORMULA. `.calls` lists all words that call a given word. `whatis` prints a 1-line summary of a word (this uses the files *whatis.doc* and *whatis.ind* on the release disk; it does not work for FORMULA words).

- **Deferred Words**

  Forthmacs allows a form of forward reference using *deferred words*. Such a word is declared by

```
defer foo
```

  It may then be used in other word definitions. It must later be bound to an actual definition (say `blah`) using

```
' blah is foo
```

- **Structured 68000 Assembler**

  Forthmacs provides a 68000 assembler that uses Forth-like control structures for generating conditional branches. The assembler uses 8-bit branch offsets. This is inadequate for control structures in large words, so FORMULA provides a set of structures using 16-bit offsets; see the file *lbranch*.

APPENDIX C: THE MIDI STANDARD

MIDI (Musical Instrument Digital Interface) is an industry standard for connecting devices such as synthesizers, keyboards and computers. Connecting the *MIDI out* socket of one device to the *MIDI in* socket of another establishes a MIDI connection. Additional instruments can be "daisy-chained" by connecting the *MIDI thru* socket of one to the *MIDI in* socket of the next.

Information is transmitted between devices in the form of *MIDI commands*. Each command is a sequence of 8-bit bytes. MIDI provides 16 distinct *channels* that allow commands to be directed to specific synthesizers in a chain. Commands consist of an ID for the type of command being delivered, a MIDI channel number, and whatever parameters are required to describe the command. For example, a MIDI "key down" command contains the command ID, the MIDI channel number, the pitch to be played, and the "velocity" with which it should be played (this normally determines the volume of the note).

Each MIDI command is encoded by a *command* byte (always with the high-order bit set, and therefore in the range 128-255) followed by some *data bytes* (always in the range 0-127). The following table shows the format of standard MIDI commands. The low-order 4 bits of a command byte are the number of the channel to which the command applies.

command byte (x = channel number)	*meaning*	*data bytes*
8x	keyup	velocity, key-number
9x	keydown	velocity, key-number
ax	polyphonic pressure	pressure, key-number
bx	control change	value, control-number
cx	patch change	patch-number
dx	mono pressure	pressure
ex	pitch bend	bend-lo, bend-hi
fx	system command	varies

In the MIDI numbering scheme, 60 is middle C.

APPENDIX D: FORMULA SOURCE FILES

The directory *formula.dir* contains the following files:

```
patches     bug fixes for Forthmacs
features    words of general (non-FORMULA-specific) utility
lbranch     assembler words to use 16-bit branch offsets
while       multi-exit ''while'' statements
pquan       quans and pquans
decls       declarations of deferred and aliased words
interupt    interrupt masking, etc.
panic       handler for undo key, out-of-memory panic, etc.
malloc      memory allocation
flags      declarations of compile-time flags
proc-cb     basic context block format
stack       words to copy between stacks and memory blocks
process     context-switching primitives
queue       manipulation of various types of queues
aux         definitions of auxiliary-process pquans
tempo       SVT-related stuff
execute     execution queue
wakeup      wakeup buffer
schedint    scheduling interrupt handlers (clock, software interrupt)
rt-sched    basic process scheduling
backgrnd    background processes
event       event scheduling and ::ev
gp-sched    group scheduling
gp-creat    group creation
procuser    process/group naming, ID's, pquan manipulation, listing
jobcntrl    suspend, resume, kill
define     :ap, ::ap and params
faq         future action queue
fevent      ::fev
timebnd     time control structures
handler     synchronization primitives for input handlers
midi-in     low-level MIDI input
midiout1    MIDI output driver
midiout2    interfaces to MIDI output driver (events, macros etc.)
6850-int    6850 interrupt handler
midi-hnd    high-level MIDI input
semaphor    real-time semaphores
tty-out     terminal output with semaphore protection
tty-in      terminal input handling
func-key    function key handling
airshaft    crude windowing facility
mouse       mouse handling
rational    rational to SVT conversion
fraction    A|B, A(B, A.B notation
ptchname    symbolic pitch names
slots       auxiliary process stuff
```

sg	sequence generators
sg-set	install sequence generators
shape	shapes
sh-set	install shapes
td	time deformations
td-set	install time deformations
dlr-quan	quans and pquans used by $-words
dollar	the $-words
dlr-dmo	interface of $-words to DMO
notation	more $-words
sm-data	SM data structures and configuration words
sm-drvr0	generic MIDI synthesizer driver
sm-event	SM event routines
dlr-sm	interface of $-words to SM and DSM
generic	default SM initialization words
tuning	tuning systems
scales	definitions of some tuning systems
pitchset	pitch-set words
debug	debugging words
decomp	decompiler ("see") extensions
random	random number generators
formula	system initialization
init-def	context block initialization

APPENDIX E: DEBUGGING FORMULA PROGRAMS

1. Crash Analysis

Debugging FORMULA programs can be difficult because of multiple processes, asynchrony, and preemption. With experience, it's not much harder than debugging single-process programs. The following is a brief list of suggestions.

- Many bugs result in stack overflow or underflow. This can often be detected using `.cb` (§3.3), or by printing the stack pointer values (returned by `sp@` and `rp@`) within a process.
- If the computer "goes dead" (i.e., stops responding to input) but the cursor is still blinking, the likely causes are 1) an infinite loop in a process or an event routine, and 2) a `mask-softint` without a corresponding `unmask-softint`. The undo key should work in this case.
- If the undo key fails, the likely causes are 1) an infinite loop in an interrupt handler or in a section of code that masks interrupts, and 2) a `set-mask` without a corresponding `restore-mask`. In this case all you can do is reboot.
- The quan `who` points to the currently executing process, and the quan `execution-queue-head` points to the top-level object containing this process (perhaps the process itself). It is often helpful to examine these context blocks after an exception.

Many bugs result in hardware exceptions (bus error, illegal instruction). Forthmacs handles these exceptions and saves the machine state, allowing it to be examined later (even after a reboot[25]) using

```
showcrash    ( --- ; print hex dump of 68000 state at last exception )
```

This shows the values of the 68000 registers and stacks at the time of the exception. The registers of greatest interest are the program counter (PC), and Forth's "virtual PC" (the A5 register). These PC points into the code word being executed at time of the crash, and A5 points into the high-level Forth word from which it was called. The easiest way to figure out the words involved is to use

```
dump      ( start-addr nbytes --- ; print hex/ASCII memory dump )
```

to survey the relevant areas of memory, looking for dictionary headers (which contain the ASCII word names). You'll want to use `hex` to switch to hexadecimal mode. Once you've found out exactly where your program was when it crashed, and you've examined the contents of the registers and stacks at that point, it's usually easy to figure out what went wrong.

During debugging it is helpful to know the internals of Forthmacs (i.e., the structure of its dictionary and its register usage). This information is in the Forthmacs manual (see Appendix A).

2. Recompiling FORMULA

The FORMULA source is divided into many files (see Appendix D). Each file *foo* begins by creating a symbol `_foo` in the `loaded` vocabulary. Typing

```
recompile _foo
```

will `forget` back to that point in the dictionary, and will recompile that part of FORMULA. It also calls `restore`, so you must run `formula` again after recompiling.

---

[25] Stack dumps may be meaningless after a reboot, because memory has been zeroed.

You can generate stripped-down versions of FORMULA by editing the file *flags*. This file contains compile flags whose presence enables the compilation of a particular feature. For example, the $-words are compiled only if `_DOLLAR_` is defined.

Compile errors may leave the Forth interpreter with an undesired vocabulary search list (§3.6). You can examine the search list using `order`. You can restore it to the standard state by typing

```
only forth also definitions
```

APPENDIX F: FORMULA GLOSSARY

The following is a list of the words defined by FORMULA. Each word name is followed by the name of the source file in which it is defined.

$	dollar	((pent1	scales
$$	dollar	((pent2	scales
$*k	dollar	((stretch	scales
$2	notation	(.aux	slots
$5	notation	(.cb	procuser
$8	notation	(.cb-summary	procuser
$DMO	dlr-dmo	(.def-class	patches
$DSM	dlr-sm	(.exec-class	patches
$SM	dlr-sm	(.gp	procuser
$channel	dlr-quan	(::-docol	define
$cvolume	dollar	(::ap	define
$gtranspose	dlr-quan	(::ev	event
$location	dlr-quan	(::fev	fevent
$n	dollar	(::gp	define
$n*k	dollar	(::sh	sh-set
$note-routine	dlr-quan	(::td	td-set
$nroll	dollar	(::tsg	decomp
$patch	dlr-quan	(::tsg	sg-set
$pedal	dlr-quan	(DSM-config	generic
$pedal-routine	dlr-quan	(DSM-paradigm	generic
$pitch-convert	dlr-sm	(M-command)	midiout1
$priority	dlr-quan	(M-out)	midiout1
$transpose	dlr-quan	(MIDI-command	midiout1
$volume	dlr-quan	(MIDI-output	midiout1
&	sg	(P	semaphor
(#keys-in-buffer)	tty-in	(RT-active-exit	rt-sched
(#newkeys-in-buffer)	tty-in	(SM-config	generic
($n	dollar	(SM-paradigm	generic
((.gp*	procuser	(V	semaphor
((::sh	decomp	([	patches
((::sh	sh-set	(]	patches
((::td	decomp	(add-empty-multi)	sm-event
((::td	td-set	(add-multi)	sm-event
(([	patches	(add-single)	sm-event
((]	patches	(adr	pquan
((bye	formula	(arouse-process)	wakeup
((cr	patches	(ascmin	pitchset
((cursor-off	patches	(assign-ID	procuser
((cursor-on	patches	(at	patches
((esc	patches	(blues	pitchset
((init-active	initdef	(clear-aux	slots
((just	scales	(create-MIDI-handler	midi-hnd
((just1	scales	(def-class	patches
((lf	patches	(descmin	pitchset
((pelog-barang	scales	(dispose)	sm-event
((pent	scales	(do-scan	patches

(exec-class	patches	(save-forth-state*)	process
(fifo-append)	queue	(scale	random
(fifo-get)	queue	(set-all-mask)	interupt
(fin-active	initdef	(set-complex-state)	midiout1
(forth-context)	panic	(set-default-mask)	interupt
(frac-literal?	fraction	(set-mask)	interupt
(free)	malloc	(set-state)	midiout1
(frnd2	random	(stack->record)	stack
(iadr	pquan	(suspend	jobcntrl
(init-active	initdef	(switch-to-XQ*	execute
(init-passive	initdef	(switch-to-XQ*)	execute
(init-process)	initdef	(switch-within-tree)	process
(insert-deadline)	queue	(switch-within-tree*	process
(insert-time-position)	queue	(to	pquan
(invmajsc	pitchset	(unlink-multi)	sm-event
(ito	pquan	(unlink-single)	sm-event
(key-down)	sm-event	(unmask-softint)	interupt
(key-up)	sm-event	(unmask-sysclock)	interupt
(kill	jobcntrl	(update-SVT)	tempo
(link-multi)	sm-event	(update-cur-offset)	wakeup
(major	pitchset	(wake-input-handler)	handler
(majsc	pitchset	(wake-process)	wakeup
(make-action-rec)	stack	(wakeup-call)	wakeup
(malloc)	malloc	(wakeup-check)	wakeup
(mask-softint)	interupt	+MIDI	6850-int
(mask-sysclock)	interupt	+PVemit	airshaft
(maxtime	timebnd	+a-	ptchname
(minend	timebnd	+b-	ptchname
(minloop	timebnd	+c-	ptchname
(minor	pitchset	+clock	schedint
(mintime	timebnd	+d-	ptchname
(next	jobcntrl	+e-	ptchname
(null	pitchset	+f-	ptchname
(paddr	pquan	+fraction	fraction
(panic	panic	+g-	ptchname
(pget	pquan	+mouse	mouse
(pn")	procuser	+n	ptchname
(poffset	pquan	+nps	pitchset
(pto	pquan	+oct	ptchname
(r>i	rational	+perf	schedint
(r>i)	rational	+ps	pitchset
(rec->XQ*)	execute	+semaphore	semaphor
(rec->wakeup)	wakeup	+shaft	airshaft
(recompute-prior)	sm-event	+tty	func-key
(record->stack)	stack	-MIDI	interupt
(restore	formula	-PVemit	airshaft
(restore-forth-state*)	process	-a-	ptchname
(restore-machine-state*)	process	-b-	ptchname
(restore-mask)	interupt	-c-	ptchname
(resume	jobcntrl	-clock	interupt
(rts	event	-d-	ptchname

-e-	ptchname	/2	notation
-f-	ptchname	/2+	notation
-fraction	fraction	/2+	notation
-g-	ptchname	/2,,,	notation
-mouse	mouse	/2.	notation
-n	ptchname	/2.4	notation
-nps	pitchset	/32	notation
-oct	ptchname	/4	notation
-perf	interupt	/4+	notation
-ps	pitchset	/4-3	notation
-semaphore	semaphor	/4-3	notation
-shaft	airshaft	/4..	notation
-tty	tty-in	/4.8	notation
.::ap	decomp	/4.8	notation
.::ev	decomp	/64	notation
.::gp	decomp	/8	notation
.::sh	decomp	/8	notation
.::sh	decomp	/8+	notation
.::td	decomp	/8-3	notation
.::td	decomp	/8-3	notation
.::tsg	decomp	10/16	notation
.::tsg	decomp	11$	notation
.;;ap	decomp	12/16	notation
.;;ev	decomp	16/32	notation
.;;gp	decomp	16/8	notation
.;;sh	decomp	2$	notation
.;;td	decomp	2/16	notation
.;;tsg	decomp	2/2	notation
.adr	decomp	2/32	notation
.all	procuser	2/4	notation
.aux	slots	2/8	notation
.cb	procuser	32/16	notation
.eq	debug	4/32	notation
.gp	procuser	4/4	notation
.iadr	decomp	5$	notation
.ito	decomp	5/8	notation
.padr	decomp	6/16	notation
.pget	decomp	6850-handler	6850-int
.poffset	decomp	7/8	notation
.pquan	decomp	8$	notation
.ps	pitchset	8/16	notation
.pto	decomp	8<<	features
.quan	decomp	8>>	features
.stack	procuser	:-)	features
.to	decomp	::ap	define
.wq	debug	::ap-init-active	define
/1	notation	::ash	sh-set
/1	notation	::ev	event
/1,,	notation	::fev	fevent
/16	notation	::gp	define
/16.	notation	::gp-init-active	define

::gsh1	sh-set	P	semaphor
::gsh2	sh-set	PV#line	airshaft
::gtd1	td-set	PV#out	airshaft
::gtd2	td-set	PV(emit	airshaft
::sh	sh-set	PV(esc	tty-out
::sh1	sh-set	PVat	airshaft
::sh2	sh-set	Pemit	tty-out
::td1	td-set	RT-active-exit	rt-sched
::td2	td-set	RT-awaken	rt-sched
::tsg	sg-set	RT-sleep	rt-sched
:ap	define	RT-time-advance	rt-sched
:sg	sg	SM-$note-routine	dlr-sm
:sh	shape	SM-$pedal-routine	dlr-sm
:td	td	SM-note-end	sm-event
;;ap	define	SM-note-prep	dlr-sm
;;ev	event	SM-note-start	sm-event
;;gp	define	SM-param-change	sm-event
;;sg	sg-set	SM-pedal-down	sm-event
;;sh	sh-set	SM-pedal-up	sm-event
;;td	td-set	V	semaphor
;ap	define	Vemit	tty-out
;sg	sg	a-	ptchname
;sh	shape	absolute	shape
;td	td	active-FK-table	func-key
BP-deadline	backgrnd	active-create	rt-sched
DMO-change-patch	dlr-dmo	active-exit	decls
DMO-note	dlr-dmo	addr	pquan
DMO-note-prep	dlr-dmo	adr	pquan
DMO-pedal	dlr-dmo	aps	pitchset
DSM-$note-routine	dlr-sm	arg0	proc-cb
DSM-$pedal-routine	dlr-sm	arg1	proc-cb
DSM-note-end	sm-event	arg2	proc-cb
DSM-note-prep	dlr-sm	args	proc-cb
DSM-note-start	sm-event	array	features
DSM-pedal-event	sm-event	ash-setup	sh-set
FAQ-active-exit	faq	ashcb	slots
FAQ-future-event	faq	assign-proc-ID	procuser
FAQ-time-advance	faq	awaken	decls
FK-action:	func-key	b-	ptchname
FK-routine	func-key	background	backgrnd
FK-table	func-key	beats-per-minute	rational
MIDI-command	midiout2	bitmask	random
MIDI-command-event	midiout2	bitprob	random
MIDI-handler	midi-hnd	block-key?	tty-in
MIDI-inbuf	midi-in	blues	pitchset
MIDI-input	midi-in	branch-addr	timebnd
MIDI-outbuf	midiout1	brnd	random
MIDI-output	midiout2	c$	dollar
MIDI-output-event	midiout2	c-	ptchname
MIDI-time-tag	midi-hnd	carray	features
MIDI-transmit	midiout1	cbsize	pquan

iadr
id
id->cb
idle-process
immortal
inf-con
inf-con
init-$
init-MIDI-input
init-MIDI-output
init-SM
init-active
init-globals
init-ids
init-main-process
init-mem-alloc
init-mouse
init-passive
init-sema
init-wakeup
input
input-handler
insert-deadline
insert-time-position
interpret-frax
invmajsc
ip-save
ipget
ipto
irnd
itd1
itd2
ito
itsg
key-handler
kill
kill-all
latest-ap
left-button
lex-level
limit
limited-line-feed
local-ptr
lpause
m$
m$$
m$*k
m$n
m$n*k
main-process
major

pquan
procuser
procuser
formula
jobcntrl
shape
td
dlr-quan
midi-in
midiout1
sm-data
decls
formula
procuser
formula
malloc
mouse
decls
semaphor
wakeup
aux
handler
queue
queue
fraction
pitchset
proc-cb
procuser
procuser
random
td-set
td-set
pquan
sg-set
schedint
jobcntrl
jobcntrl
rt-sched
mouse
timebnd
random
airshaft
aux
td
dollar
dollar
dollar
dollar
dollar
decls
pitchset

majorscale
make-XQ-head*
make-action-rec
malloc
mask-softint
mask-sysclock
mask-userclock
mat
max-stack
maxdel
maxend
maxtime
mcc
mcount
mhead
min-stack
mindel
minend
minloop
minor
minorscale
mintime
mkd
mku
mouse-active
mouse-handler
mouse-hnd
mouse-in-process
mouse-routine
mpb
mpc
mpp
mtail
mouse-x
mouse-y
my-#line
my-#out
my-bot
my-top
n#
n>ps
nada
name
nargs
ndup
needparams
nest-level
new-.inline
next-proc
next-sysexcl-index
not-now

pitchset
semaphor
stack
malloc
interupt
interupt
interupt
midiout2
timebnd
proc-cb
timebnd
timebnd
midiout2
midiout1
midiout1
timebnd
proc-cb
timebnd
timebnd
pitchset
pitchset
timebnd
midiout2
midiout2
mouse
mouse
mouse
mouse
mouse
midiout2
midiout2
midiout2
midiout1
mouse
mouse
airshaft
airshaft
airshaft
airshaft
ptchname
pitchset
decls
procuser
proc-cb
stack
dollar
timebnd
decomp
proc-cb
midiout1
wakeup

notquan	pquan	psind	pitchset
nps	pitchset	pslast	pitchset
num-type	fraction	psmod	pitchset
ocon	shape	psptr	pitchset
oct	ptchname	pssize	pitchset
octave-offset	ptchname	psup	pitchset
oseg	shape	pto	pquan
our-(esc	patches	pvalue	aux
our-at	patches	quan	pquan
our-skey	patches	quan?	pquan
p,	tuning	quick-key?	tty-in
paddr	pquan	r	ptchname
pallot	pquan	r$	dollar
panic	panic	r>i	rational
params	define	ratio	shape
params-OK?	decls	raw-future-event	fevent
params-addr	decls	right-button	mouse
parent	proc-cb	realias	features
patch-emacs	patches	rec->wakeup	wakeup
patch-erase	patches	recompile	decls
patch-iftrue	patches	record->cbstack	stack
pcall	aux	record->stack	stack
ped	dollar	relative	shape
ped$	dollar	relmous	mouse
pedals	sm-data	repeat	while
pedoff	dollar	repeat	while
pedoff$	dollar	rest	dollar
pedon	dollar	restore	decls
pedon$	dollar	restore-TOS-intvecs	interupt
perform-all	faq	restore-kbd-routines	interupt
pget	pquan	restore-main-cursor	airshaft
poffset	pquan	restore-mask	interupt
pquan	pquan	resume	jobcntrl
pquan0	proc-cb	retadr	aux
pquan1	proc-cb	reverse	stack
pquan2	proc-cb	revive-group	gp-creat
pquan3	proc-cb	rnd	random
pquan4	proc-cb	rndind	random
pquan5	proc-cb	rndinit	random
pquan?	pquan	rp-save	proc-cb
pquanlist	pquan	rpause	td
pquans	pquan	rs-level	timebnd
preempted-CB	proc-cb	rscale	rational
pret	aux	rscale-ptr	rational
proc-name"	procuser	rstack	proc-cb
process-XQH-delay*	rt-sched	save-TOS-intvecs	interupt
process-delay	gp-sched	save-main-cursor	airshaft
propagate-delay	gp-sched	savel	sm-event
psbase	pitchset	scale:	tuning
psdown	pitchset	scan-::ap	decomp
psget	pitchset	scan-::ev	decomp

scan-::gp	decomp	tcenter	tuning
scan-::sh	decomp	td-create	td
scan-::sh	decomp	td-fin	td
scan-::td	decomp	td-init	td
scan-::td	decomp	td-return	td
scan-::tsg	decomp	td-value	td
scan-::tsg	decomp	td1-setup	td-set
seg	td	td1cb	slots
seg.outer	td	td2-setup	td-set
select-paradigm	dlr-quan	td2cb	slots
semaphore:	semaphor	temp-stack	panic
seqno>prior	dlr-sm	tempo	tempo
set-deadline*	execute	test-flag	proc-cb
set-default-mask	interupt	time-advance	decls
set-flag	proc-cb	time-position	proc-cb
set-mask	interupt	timebnd-time-advance	timebnd
set-ps	pitchset	to	pquan
set-shaft	airshaft	tod	stack
set-synth-config	sm-data	tor	stack
set-userclock-freq	interupt	trand	random
setup	timebnd	transpose	stack
sg-fin	sg	tsgcb	slots
sg-value	sg	tsptr	tuning
sh-create	shape	tto	pquan
sh-fin	shape	tuning-convert	tuning
sh-setup	sh-set	unalias	features
sh-value	shape	undo-handler	tty-in
sh1-setup	sh-set	unlink-non-singleton	gp-creat
sh1cb	slots	unmask-softint	interupt
sh2-setup	sh-set	unmask-sysclock	interupt
sh2cb	slots	unmask-userclock	interupt
shaft(emit	airshaft	usec-per-SVT	tempo
shemit	tty-out	value	aux
shift-convert	dlr-sm	value2	aux
shuffle-down	patches	vol	dollar
sleep	decls	wagain	lbranch
softint-handler	schedint	wait-for-input	handler
softint-mask-level	interupt	wakeup-immortal-process	jobcntrl
softint-request	interupt	wakeup-process	jobcntrl
sp-save	proc-cb	wakeup-routine	proc-cb
stack->cbstack	stack	wakeup-time	proc-cb
start-group	gp-creat	wbegin	lbranch
startup	decls	wbrif	lbranch
suicide	jobcntrl	welse	lbranch
suspend	jobcntrl	while	while
switch-to-XQ*	execute	while	while
sysclock-handler	schedint	who	pquan
sysexcl-index	midiout1	wholetone	pitchset
system-mindel	schedint	wif	lbranch
tbase	tuning	woffset	lbranch
tcall	aux	wrepeat	lbranch

```
wrepeat         while
wthen           lbranch
wuntil          lbranch
wwhile          lbranch
wwhile          while
z$              dollar
```

APPENDIX G: DIFFERENCES BETWEEN VERSION 3.4 AND PREVIOUS VERSIONS

If you have written programs under an earlier version of FORMULA you will have to change them somewhat for version 3.4. The following are some of the major differences:

(1) All process creation is done using `::` constructs. Executing a `:ap` word from the interpreter no longer causes it to run as a separate process. `[ n params ]` is relevant only within a `::` construct.

(2) The `shl foo` notation for installing auxiliary processes no longer exists. You must use `::shl`, etc.

(3) A TSG word cannot be directly called within an active process definitions. It can be called only within `::tsg ... ;sg` or `:sg ... ;sg`.

(4) `create-group` no longer exists. Use `::gp`.

(5) Timing sequence generators no longer have an implicit infinite loop around them. If a TSG reach the end of its definition, it exits and quarter-note durations are used.

(6) A volume shape or TD disappears (and ceases to have an effect) when the end of its definition is reached.

(7) Symbolic pitch names no long refer to the "closest instance" of the named pitch; they now refer to the instance within the current octave.

(8) Instead of directly assigning to `rscale` and `tempo`, you should use `beats-per-minute` and `usecs-per-SVT`.

(9) Words like `d/8` no longer exist. Use `1|8` instead.

(10) Use `1|8` instead of `1 8 r>i`.

(11) Many words relating to `$` have been renamed; for example, `volume` becomes `$volume`, `patch` becomes `$patch`, etc.

(12) `+double` and `-double` went away; use `$$` instead.