ProTem
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ProTem is a programming system that serves as both programming language and operating system, and includes a theorem prover to check each step of program composition. This document is an informal specification of ProTem. Formal specifications of the data types and program semantics can be found in the book *a Practical Theory of Programming* (with syntactic differences). “ProTem” also means “for now”, short for the Latin words “pro tempore”.

Programming languages and operating system languages have a lot of functionality in common, but differ greatly in syntax and terminology. These differences are historical, accidental, and unnecessary. They complicate a programmer's life with no benefit. For example, a file is just a variable; file update and storage are just assignment. By unifying the programming language and the operating system commands, both gain in functionality. Communication channels and file piping are as useful in programming as they are in operating systems. Directories and permissions are useful in large-scale multi-programmer programs. Conditional execution (*if*) and indexed loops (*for*) are useful operating system commands.

ProTem is also designed for easy proof of correctness, including functionality, time requirements, and space requirements. To that end, loops can be constructed by labeling any block of code with a specification, and then using the label within the block of code. For example,

\[
\langle n\geq 0 \Rightarrow n'=0 \rangle \text{ if } n>0 \langle n:=n-1. \text{ } n\geq 0 \Rightarrow n'=0 \rangle
\]

The proof methods are the subject of the book *a Practical Theory of Programming* and paper *Specified Blocks*. They do not require preconditions, postconditions, or invariants. If proof is not wanted, then an ordinary identifier can be used as label. For example,

\[
\text{loop if } n>0 \langle n:=n-1. \text{ } \text{loop} \rangle
\]

A primary design criterion is to make ProTem a small, easy-to-learn, easy-to-use language. The size of a language can be measured by the number of symbols and by the complexity of grammar structure, which can be measured by the number of nonterminals. ProTem has 8 keywords. (C has 28, Python has 35, Pascal has 36, Haskell has 37, Ada has 62, MS Basic has 205.) ProTem is presented by a Presentation Grammar, which has just the structure that a programmer needs to know, not all the structure that a compiler needs. It has 2 nonterminals (program and data) plus some informally defined kinds of names. (There is also an LL(1) grammar with 23 nonterminals and an LR(0) grammar with 13 nonterminals at the end of this document. For comparison, the Haskell grammar has 68 nonterminals, and the Python grammar has 87 nonterminals.) The design ethos demands an extremely good reason for adding a new feature to ProTem that requires a new keyword or syntax. That same design ethos will not tolerate any addition to the 2 nonterminals in the Presentation Grammar.

To judge ease of use, you need to use the language, but you may get a sense of the ease of use (and of the beauty of the language, if that is of interest) from reading example programs. For that purpose, there are example programs near the end of this document.

The design of ProTem is complete except for the following. We need to describe and compose picture and sound elements. We need to define touchpad and touchscreen gestures. We may need to define regions of documents and regions of the screen to be clickable links. An implementation is partly written.
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Symbols

ProTem has 8 keywords, plus 4 kinds of lexeme, and 70 other symbols; altogether they are:

```
case  else  for  if  new  old  plan  result
number  text  name  comment
  "  "  «  »  `  '  ,  ,..  ;  ;;  ;..  .  :  ::  :=  =
≠  <  >  ≤  ≥  !  !!  ?  ??  (  )  { }  \[  \]
\〈  \〉  \[|  \|
\in
∞  &  %  +  –  ×  /  _
→  ↔  \top  \bot  \land  \lor  \land^\land  @  *  ~
\notin
\in\in\in\in\in
\in\in\in\in\in
\in\in\in\in\in
\in\in\in\in\in
\in\in\in\in\in
```

Some of the ProTem symbols may not be on your keyboard. Here are the substitutes.

- for “ and ” use " for “ and ” use ", for « use \« for » use \>>
- for ‘ use ‘ for ≠ use /= for ≤ use <=
- for ⟨ use <: for ⟨ use >: for \[ use [l for \] use l]
- for – use - for × use >< for ↔ use <>
- for \ use /\ for v use \/ for \ use // for ∈ use :~
- for \ use \ for \ use <l for \ use >: for \ use \:
- for = use \l for \ use infinity for \ use true for \ use false

The names infinity, true, and false are predefined, and redefinable.

A number is formed as one or more decimal digits, with an optional decimal point between digits. A decimal point must have at least one digit on each side of it. Here are four examples.

```
0   275   27.5   0.21
```

A text begins with a left-double-quote, continues with any number of any characters (but a double-quote (left or right) within a text must be underlined), and concludes with a right-double-quote. Characters within a text are not limited to any alphabet. Here are five examples.

```
""          "abc"         "don’t"         "Just say "no"."         "♠♣♥♦"
```

A name is either simple or compound. A simple name is either plain or fancy. A plain simple name begins with a letter from an alphabet (this document uses the 26 small and 26 capital letters of the English alphabet), and continues with any number of letters and decimal digits, except that keywords cannot be names. A fancy simple name begins with «, and continues with any number of any characters not limited to any alphabet, except « and », and ends with ». A compound name is composed of two or more simple names joined with backslash \ characters. For examples:

plain simple names: x Al george refStack
fancy simple names: «Rick & Margaret» «x’ ≥ x»
compound names: ProTem\grammars\LL1 DCS«grad recruiting»\«2016-9-8»

A comment begins with ` and ends at the end of the line. Characters within a comment are not limited to any alphabet. For example: `I heart ProTem

At each point in a program, a name is one of

- newname: a simple name that is not defined in the current scope,
- or a compound name that is not defined in its dictionary
- oldname: a simple name that is defined in the current scope,
- or a compound name that is defined in its dictionary.

An oldname is defined as one of: variablename, constantname, dataname, programname, channelname, unitname, or dictionaryname.
**Presentation Grammar**

There are 35 ways of forming a program. There are a few words of explanation on the right side; full explanations come later.

- `new newname : data := data` define `newname` with type and initial value
- `new newname := data` define `newname` but do not evaluate data
- `new newname = data` define `newname` but do not execute program
- `new newname ![ program ]` define `newname` with type and initial value
- `new newname ? data ! data` define measuring unitname
- `new newname #1` define dictionaryname
- `new newname \ \ dictionaryname` define dictionaryname with definitions
- `new newname` forward definition of `newname` or `programname`
- `new newname oldname` remove or hide
- `variablename := data` assign variable to value
- `channelname ! data` to channel send output
- `channelname ? data` from channel receive input in this pattern
- `channelname ? ! data` from channel receive corrected input and echo
- `simplename [ program ]` define `simplename` and execute `program`
- `programname . program` sequential composition
- `program || program` concurrent composition, case separator
- `if data [ program ] if-program` if `data` then `if-program`
- `if data [ program ] else [ program ] if-else-program` if `data` then `if-program` else `if-else-program`
- `case data [ program ] case-program` case `data`
- `case data [ program ] else [ program ] case-else-program` case `data` else `case-else-program`
- `for simplename := data [ program ] for-program` for `simplename` := `data` do `for-program`
- `plan simplename := data [ program ] plan-program` plan `simplename` := `data` do `plan-program`
- `plan simplename : data [ program ] plan-program` plan `simplename` := `data` do `plan-program`
- `plan simplename ! data [ program ] plan-program` plan `simplename` := `data` do `plan-program`
- `plan simplename ? data [ program ] plan-program` plan `simplename` := `data` do `plan-program`
- `plan simplename \ [ program ] plan-program` plan `simplename` do `plan-program`
- `program data program brackets` `program` execute `data` enclosed in brackets
- `program variablename` `program` execute variable `variablename`
- `program channelname` `program` execute channel `channelname`
- `program dictionaryname` `program` execute dictionary `dictionaryname`

There are 59 ways of expressing data. Examples and pronunciations are shown on the right side.

- `number` 0 1.2
- `∞` infinity, the infinite number
- `data & data` complex number $x \& y = x + iy$
- `data %` percentage $x \% = x/100$
- `+ data` plus, identity
- `– data` minus, negation, not
- `data + data` plus, addition
- `data – data` minus, subtraction
- `data × data` times, multiplication
data / data         divided by, division
data ^ data         to the power, exponentiation
data ^^ data        scale, scientific notation \( x^{\text{^y}} = x \times 10^y \)
∀                     top, true
⊥                     bottom, false
data \ data         minimum, conjunction, and, set intersection
data v data         maximum, disjunction, or, set union
data = data          equals, equation
data ≠ data         not equals, differs from, exclusive or
data < data         less than, strict implication, strict subset
data > data         greater than, strict reverse implication, strict superset
data ≤ data         less than or equal to, implication, subset
data ≥ data         greater than or equal to, reverse implication, superset
bunch union
data , data        bunch from (including) to (excluding)
data ‘ data        bunch intersection
data : data         bunch inclusion  2, 3: 0, 2, 3, 5
data :: data       reverse bunch inclusion  (A::B) = (B:A)
ψ data             bunch size, bunch cardinality  ψ(3, 5) = 2
{ data }         set  {0, 2, 5}
~ data             contents of a set or list  ~{0, 2, 5} = 0, 2, 5
$ data             set size, set cardinality  ${0, 2, 5} = 3
 data ∈ data        elements of a set  2, 3 ∈ {0, 2, 3, 5}
\# data         power  \#(0, 1) = \{null\}, \{0\}, \{1\}, \{0, 1\}
"abc"             “abc”
\text{string join}
\text{string from (including) to (excluding)}
\text{string indexing}
\text{string modification}
\leftrightarrow(2; 3; 5; 7) = 4
\text{string length}
\text{definite repetition}
\text{indefinite repetition}  *x = nat*x
\text{list}
\text{list join}
\text{list length, function size}
\text{list index, function argument, composition}
\text{pointer indexing}
\langle \text{function, parameter is constantname} \rangle
\text{function, function space}  A→B = \langle x: A \rightarrow B \rangle
\text{domain of a list or function}
\text{selective union}
\text{variable name}
\text{constant name}
\text{data name and evaluate data}
\text{the most recent data read on the channel}
\text{test for written but unread data on the channel}
\text{unit name, positive finite real number constant}
\text{conditional data, if data then data else data}
result data := data [[ program ]] result-data, define variablename
( data ) data brackets
Precedence

Here is the precedence (order of execution) of the forms of program.

0  new  old  :=  !  ?  programname  plan  if  case  for  [  ]
1  plan argument  left-to-right
2  ||
3  .

Program brackets [ ] can always be used to change the order of execution.

Here is the precedence (order of evaluation) of the forms of data.

0  number  text  name  ⊤  ⊥  ∞  ??  !!  ( )  [ ]  { }  〈  〉
1  list index  function argument  postfix  %  ??  !!  infix  @  &
2  left-to-right
3  fi  x  %  ??  !!  in
4  left-to-right
5  fi  x  +  –  ¢  $  ↔  #  ~  ☐  *  in
6  left-to-right
7  fi  x  *  _  →  ^  ^^  right-to-left
8  in
9  fi  x  ×  /  ∧  ∨
10  left-to-right
11  in
12  fi  x  =  ≠  <  >  ≤  ≥  :  ::
13  left-to-right
14  in
15  fi  x  ⊨ ⫤
16  right-to-left
17  in
18  fi  x
19  ⊩ ⫤
20  left-to-right

The domain and the argument of a function, and the index of a list, must be on precedence level 0. Any data expression becomes precedence level 0 by putting it in data brackets ( ). On level 6, the operators are “continuing”. This means, for example, that \( a=b=c \) neither associates to the left \( (a=b)=c \) nor associates to the right \( a=(b=c) \), but means \( (a=b) \land (b=c) \). Similarly \( a<b=c\leq d \) means \( (a<b) \land (b=c) \land (c\leq d) \). Whenever “data” appears in an alternative for “program”, all forms of data are allowed, with this exception: the argument of a plan must be on precedence level 0. Only one alternative for “data” contains “program”, and there all forms of program are allowed.

Using ProTem

Following the prompt ➥, key in a program, and then, to cause execution, press [ctl x], which is the simultaneous combination of the control key and the letter x. For example, you can key in

\[ \textbf{! 2+2} \]

The ! means output to the screen (see Output and Input). Then press [ctl x], causing 4 to be printed on the screen. Thus ProTem can be used as a calculator.

As we will see in Constant Definition, the program

\[ \textbf{new temp := 2+2} \]
followed by [ctl x], saves the result of the calculation under the name temp, perhaps for use in further calculation. As we will see in Program Definition, the program

\[ \textbf{new myprogram [! “2+2=”; 2+2]} \]
followed by [ctl x], defines and saves a program named myprogram . The saved program is not immediately executed. To execute this saved program, key in

myprogram

followed by [ctl x].

A program may stretch over many lines. You may make changes to a program using the standard editing commands and delete (backspace) key anytime before you press [ctl x]. When you press [ctl x], keywords become bold, names become italic, and keyboard substitutes become the proper symbols. Then the program is checked for errors, and if none, it is executed. Saved programs and data can be edited using the command [ctl e] (see Edit).
**Data**

ProTem's basic data are numbers, characters, and binary values. ProTem's data structures are bunches, sets, strings, and lists. In addition, there are functions and **result-data**.

**Numbers**

Numbers are not divided into disjoint types. A natural number is an integer number; an integer number is a rational number; a rational number is a real number; a real number is a complex number. There is also an infinite number $\infty$ greater than all other numbers.

In addition to the number symbols, there are predefined names of numbers such as $\pi$ (the ratio of a circle's circumference to its diameter), $e$ (the base of the natural logarithms), and $i$ (the imaginary unit, a square root of $-1$). Predefined names can be redefined. The postfix operator % means division by 100; for examples, 99.9%, x% and (x+y)%. There are two 1-operand prefix operators + and -. There are nine 2-operand infix operators + – ×/ ^ ^^ ∧ ∨ & . There are predefined function names such as abs, arc, arccos, arcsin, arctan, ceil, cos, cosh, div, exp, floor, im, ln, log, mod, re, round, sin, sinh, sqrt, tan, and tanh (see **Predefined Names**). Division of integers, such as 1/2, may produce a noninteger. Exponentiation is 2-operand infix ^; for example, 1.2×10^3 (one point two times ten to the power three), which can be written more briefly as 1.2^^3, and in general, $x^{^y} = x \times 10^y$. The operator ^ is minimum (arms down, does not hold water; note that ^ and ∧ are different). The operator ∨ is maximum (arms up, holds water). The complex number $x + iy$ can be written more briefly as $x&y$.

**Characters**

A character is a text of length 1. We leave it to each implementation to list the characters, and to state their order. In addition to the character symbols such as “a” (small a) and “ ” (space), there are some predefined character names: delete (backspace), tab, nl (new line, next line, return, enter), click, doubleclick, and end (the end-of-file character). Predefined functions suc and pre give the successor and predecessor in the character order. Predefined functions charnat and natchar map between characters and their (possibly extended ASCII or unicode) numeric encodings. Some key combinations, for example, [ctl x] and [ctl c], are characters and have numeric encodings.

**Binary Values**

The two binary values are ⊤ and ⊥. Negation is ¬, conjunction (minimum) is ∧, disjunction (maximum) is ∨.

The infix 2-operand operators = and ≠ apply to all data in ProTem with a binary result; the two operands may even be of different types.

The order operators < > ≤ ≥ apply to real numbers (including rationals, integers, and naturals), to characters, to binary values, to sets (subset, superset), to strings of ordered items, and to lists of ordered items, with a binary result. In the number order, $\infty$ is smallest and $\infty$ is largest. In the character order, “ ” (space) comes first and end comes last. In the binary order, ⊥ is below ⊤, so ≤ is implication.

The postfix operator !! applies to channels, and has a binary result saying whether there is written but unread data on the channel.
Bunches

Any number, character, binary value, set, string of elements, and list of elements is an elementary bunch, or synonymously, an element. For example, the number 2 is an elementary bunch, or element. Every expression is a bunch expression, though not all are elementary.

Bunch union is denoted by a comma:

\[ A , B \]

For example,

\[ 2, 3, 5, 7 \]

is a bunch of four integers. There is also the notation

\[ x_{\ldots}y \]

where \( x \) and \( y \) are integers or \( \infty \) or \(-\infty\) or characters that satisfy \( x \leq y \). Note that \( x \) is included and \( y \) is excluded. For example, \( 0_{\ldots}10 \) is a bunch consisting of the first ten natural numbers, and \( 5_{\ldots}5 \) is the empty bunch \( \text{null} \).

For any \( A \) and \( B \),

\[ A : B \]
\[ A :: B \]

is binary. The size (or cardinality) of \( A \) is \( \mathcal{C} A \). For examples, \( \mathcal{C}(0, 1) = 2 \) and \( \mathcal{C}\text{null} = 0 \) and \( \mathcal{C}(a_{\ldots}b) = b - a \). The data brackets ( ) are sometimes needed due to operator precedence. Bunches are equal if and only if they include the same elements, ignoring order and multiplicity.

Bunches serve as a type structure in ProTem, as the contents of sets, and other uses. There are several predefined bunch names:

- \( \text{null} \) the empty bunch
- \( \text{nat} \) all natural numbers. Examples: 0, 1, 2
- \( \text{int} \) all integer numbers. Examples: \(-2, -1, 0, 1, 2\)
- \( \text{rat} \) all rational numbers. Examples: \(1/2, 3.4\)
- \( \text{real} \) all real numbers. Example: \(2^{\sqrt{2}}\)
- \( \text{com} \) all complex numbers. Examples: \((-1)^{\sqrt{2}}, 3 & 4\)
- \( \text{char} \) all characters. Examples: \(\text{“a”, “”, “,”}\)
- \( \text{bin} \) both binary values: \(\top, \bot\)
- \( \text{text} \) all texts (character strings). Examples: \(\text{“abc”, “Say “hi”,”}\)
- \( \text{ord} \) the ordered type for which \(\land, \lor, <, >, \leq, \geq\) are defined
- \( \text{all} \) all ProTem items

In ProTem, all operators whose precedence is before that of bunch union, except \( \mathcal{C} \) and \( \mathcal{S} \), distribute over bunch union. Infix \(*\) distributes in its left operand only. For examples,

\[ -(3, 5) = -3, -5 \]
\[ (2, 3) + (4, 5) = 6, 7, 8 \]

This makes it easy to express the plural naturals \(\text{nat} + 2\), the even naturals \(\text{nat} \times 2\), the square naturals \(\text{nat}^{\sqrt{2}}\), the natural powers of two \(2^{\text{nat}}\), and many other things.

Sets

A set is formed by enclosing a bunch in set brackets. For examples, \(\{0, 2, 5\}, \{0_{\ldots}100\}, \{\text{null}\}, \{\text{nat}\}\). The inverse of set formation is the content operator \(\sim\). For example, \(\sim\{0, 1\} = 0, 1\). The size (or cardinality) of a set, traditionally written \(|S|\), is \$S$ in ProTem. For examples, \$\{0, 1\} = 2$, \$\{\text{null}\} = 0$, and \$\{\text{nat}\} = \infty$. The element relation is \(x \in S\). For example, \(1, 2 \in \{0, 1, 2, 3\}\). The
union operator, traditionally $\cup$, is $\lor$ in ProTem. The intersection operator, traditionally $\cap$, is $\land$. Subset, traditionally $\subseteq$, is $\leq$; strict subset is $<$; superset is $\geq$; strict superset is $>$. The power operator $^*$ takes a bunch as operand and produces the bunch of all sets that contain only elements of the operand. For example, $^*\langle 0, 1 \rangle = \{\text{null}\}, \{0\}, \{1\}, \{0, 1\}$. In $^*\langle 0, 1 \rangle$, the data brackets ( ) are needed due to operator precedence.

**Strings**

There is a predefined string name:

$$\text{nil}$$  the empty string

Any number, character, binary value, list, and function is a one-item string, or synonymously, an item. For example, the number 2 is a one-item string, or item.

String join is denoted by a semi-colon:

$$S ; T \text{ join } T$$

For example,

$$2; 3; 5; 7$$

is a string of four integers. There is also the notation

$$x;..y \text{ to } y \text{ (same pronunciation as } x;..y \text{)}$$

where $x$ and $y$ are integers or characters that satisfy $x\leq y$. Again, $x$ is included and $y$ is excluded. For examples, 0;..10 is a string consisting of the first ten natural numbers, and 5;..5 = nil.

The length of a string is obtained by the $\leftrightarrow$ operator. For examples, $\leftrightarrow(2; 3; 5; 7) = 4$, and $\leftrightarrow(x;..y) = y-x$. The data brackets ( ) are needed due to operator precedence.

A string is indexed by the _ operator. Indexing is from 0. For example, $(2; 3; 5; 7)_{2} = 5$. A string can be indexed by a string. For example, $(3; 5; 7; 9)_{(2; 1; 2)} = 7;5;7$.

If $S$ is a string and $n$ is an index of $S$ and $i$ is any item, then $S<_{n=i}$ is a string like $S$ except that item $n$ is $i$. For example, $3; 5; 9 \leftarrow_{2=8} 3 = 3; 5; 8$. This operator associates from left to right, so $3; 5; 9 \leftarrow_{2=8} 3 = 3; 5; 8$. And $3; 5; 9 \leftarrow_{2=8} 3 = 3; 5; 8$. And $3; 5; 9 \leftarrow_{2=8} 3 = 3; 5; 8$.

A text is a more convenient notation for a string of characters.

"abc" = "a"; "b"; "c"

"He said "Hi",". = "H"; "e"; " "; "s"; "a"; "i"; "d"; " "; ""; "H"; "i"; ""; ""; ""

"abcdefgghij"_{(3;..6)} = "def"

Strings are equal if and only if they have the same length, and corresponding items are equal. They are ordered lexicographically. For examples,

$$3; 5 \prec 3; 5; 2 \prec 3; 6$$

$$(3; 5)\lor(3; 5; 2) = 3; 5; 2$$

A bunch of items is an item. Since string join precedes bunch union on the precedence table, we have $$(3, 4); (5, 6) = 3;5, 3;6, 4;5, 4;6$$

A string is an element (elementary bunch) if and only if all its items are elements.

If $S$ is a string and $n$ is a natural number, then

$$n * S \quad \text{n copies of } S \text{ or } n S's$$
is a string, and
* S strings of S or any number of S's
is a bunch of strings. For examples,
3*5 = 5;5;5
3*(4, 5) = 4;4;4, 4;4;5, 4;5;4, 4;5;5 5;4;4, 5;4;5, 5;5;4, 5;5;5
*5 = nil, 5, 5;5, 5;5;5, 5;5;5;5, and so on
The * operator distributes over bunch union in its left operand only.
null*5 = null
(2,3)*5 = 2*5, 3*5 = 5;5, 5;5;5
Using this semi-distributivity, we have
*a = nat*a

Lists

A list is a packaged string. It can be written as a string enclosed in list brackets. For example,
[0; 1; 2]

Let L and M be lists, let n be a natural number, and let p be a string of natural numbers. The list operators are:

☐ L domain of L
~ L content of L
# L length of L
L n L at n, L at index n
L @ p L at p, L at pointer p
L ; M L join M
L M L composed with M
L | M L otherwise M, the selective union of L and M
i → x L index i is item x and otherwise L

plus the operators L∧M, L∨M, L= M, L≤ M, L≥ M. For examples,

☐[10; 11; 12] = 0, 1, 2 the domain of a list
~[10; 11; 12] = 10; 11; 12 the content of a list
#[10; 11; 12] = 3 the length, or number of items, in a list
[10;..20] 5 = 15 indexing starts at zero
[[2; 3]; 4; [5; [6; 7]]] @ (2; 1; 0) = 6
[0;..10];[10;..20] = [0;..20] joining lists
[10;..20] [3; 6; 5] = [13; 16; 15] composition (L M)n = L(M n)

By using the @ operator, a string acts as a pointer to select an item from within an irregular structure. If the list L | M is indexed with n, the result is either L n or M n depending on whether n is in the domain (0..#L) of L. If it is, the result is L n, otherwise the result is M n.

[10; 11] | [0;..10] = [10; 11; 2;..10]
1→21 | [10; 11; 12] = [10; 21; 12]

The index can be a string, as in
(0;1) → 6 | [[0; 1; 2]; [3; 4; 5]] = [[0; 6; 2]; [3; 4; 5]]

When a string or list is indexed by a structure, the result has the same structure as the index.
(10;..20) _ [2; (3, 4); [5; [6; 7]]] = [12; (13, 14); [15; [16; 17]]]
[10;..20] [2; (3, 4); [5; [6; 7]]] = [12; (13, 14); [15; [16; 17]]]

Let S = 10; 11; 12. Then
\[ S_0(0, \{1, [2; 1]; 0\}) = S_0, \{S_1, [S_2; S_1]; S_0\} = 10, \{11, [12; 11]; 10\} \]

Let \( L = [10; 11; 12] \). Then
\[ L(0, \{1, [2; 1]; 0\}) = L_0, \{L_1, [L_2; L_1]; L_0\} = 10, \{11, [12; 11]; 10\} \]

Lists are equal if and only if they have the same length and corresponding items are equal. They are ordered lexicographically. For examples,
\[ [3; 5] < [3; 5; 2] < [3; 6] \]
\[ [3; 5] \lor [3; 5; 2] = [3; 5; 2] \]

The list brackets \([\ ]\) distribute over bunch union. For example,
\[ [0, 1] = [0], [1] \]

Thus \([10*\text{nat}]\) is all lists of length 10 whose items are natural, and \([4*[6*\text{real}]\) is all 4 by 6 arrays of reals.

**Conditional Data**

The 3-operand expression \( x \vdash y = z \), pronounced “if \( x \) then \( y \) else \( z \)”, has binary operand \( x \), but \( y \) and \( z \) are of arbitrary type. For example,
\[ y \neq 0 \vdash x/y = \text{“nan”} \]

If \( y \neq 0 \) has value \( \top \), then this data expression has number value \( x/y \). If \( y \neq 0 \) has value \( \bot \), then this data expression has text value “nan”. This operator associates from right to left so that it can be evaluated from left to right. For example,
\[ (a \vdash b = c \vdash d = e) = (a = b = (c = d = e)) \]

If \( a \) has value \( \top \), then this expression has value \( b \), with no need to evaluate \( c \), \( d \), or \( e \).

**Functions**

A function defines a parameter; that is its only job. Let \( p \) (parameter) be any simple name, let \( D \) (domain) be any expression (but not using \( p \)), and let \( B \) (body) be any expression (possibly using \( p \) as a constant name for an element of \( D \)). Then \( \langle p: D \rightarrow B \rangle \) is a function with parameter \( p \), domain \( D \), and body \( B \). For example,
\[ \langle n: \text{nat} \rightarrow n+1 \rangle \quad \text{map } n \text{ in } \text{nat} \text{ to } n+1 \]

is the successor function on the natural numbers. The parameter name begins its scope at the left function bracket \( \langle \) and ends its scope at the right function bracket \( \rangle \) (see **Scope**). The \( \square \) operator gives the domain of a function. For example,
\[ \square \langle n: \text{nat} \rightarrow n+1 \rangle = \text{nat} \]

The \# operator gives the size of the function, which is the size of its domain. For example,
\[ \# \langle n: (0..10) \rightarrow n+1 \rangle = 10 \]

A function of \( n+1 \) parameters is a function of 1 parameter whose body is a function of \( n \) parameters. For example, the average function
\[ \langle x: \text{rat} \rightarrow \langle y: \text{rat} \rightarrow (x+y)/2 \rangle \]

has two parameters. The notation for applying a function to an argument is the same as that for indexing a list: adjacency. If \( f \) is a function of two parameters, then \( f x y \) applies \( f \) to \( x \) and \( y \). Caution: in some languages, applying \( f \) to \( x \) and \( y \) is \( f(x, y) \). In ProTem, comma is bunch
union, and function application distributes over bunch union. So in ProTem, \( f(x, y) = fx, fy \).

The predefined function \( \text{form} \) has four parameters. The first three parameters say how to format a number, and the last is the number to be formatted. For example, \( \text{form} \, 4 \, 1 \, 10 \, \pi = "3.1416^{\times}0" \). We can define a new function

\[
\text{new myform} = \text{form} \, 4 \, 1 \, 10
\]

by supplying just three parameters, and then apply it to a number to be formatted:

\[
\text{myform} \, \pi = "3.1416^{\times}0"
\]

When the body of a function does not use its parameter, there is a syntax that omits the function brackets \( () \), unused name, and colon. For example, \( 2 \rightarrow 3 \) means \( \langle n : 2 \rightarrow 3 \rangle \) or choose any other parameter name. And \( \text{nat} \rightarrow \text{bin} \) means \( \langle n : \text{nat} \rightarrow \text{bin} \rangle \) or choose any other parameter name.

Argumentation comes before bunch union in precedence, and so it distributes over bunch union.

\[
(f, g) (x, y) = fx, fy, gx, gy
\]

If you want to apply a function to a bunch without distributing over the elements of the bunch, you must package the bunch as a set.

Allowing the body of a function to be a bunch generalizes the function to a relation. For example, \( \text{nat} \rightarrow \text{bin} \) can be viewed in either of the following two ways: it is a function (with unused and omitted parameter) that maps each natural to \( \text{bin} \); it is all functions with domain at least \( \text{nat} \) and range at most \( \text{bin} \). As an example of the latter view, we have

\[
\langle i : \text{int} \rightarrow \text{mod} \, i \, 2 = 0 \rangle : \text{nat} \rightarrow \text{bin}
\]

If \( f \) and \( g \) are functions, then

\[
f|g \quad \text{“f otherwise g”}, \text{“the selective union of } f \text{ and } g \text{”}
\]

is a function that behaves like \( f \) when applied to an argument in the domain of \( f \), and otherwise behaves like \( g \).

\[
\square (f|g) = \square f, \square g
\]

\[
(f|g) x = (x: \square f = fx \equiv g x)
\]

The function \( \langle f : (\text{nat} \rightarrow \text{rat}) \rightarrow f \, 2 \rangle \) is “higher order”, which means it has a function-valued parameter. It can be applied to any function with domain at least \( \text{nat} \) and range at most \( \text{rat} \).

Let \( f \) and \( g \) be functions such that \( \neg f : \square g \ (f \text{ is not in the domain of } g) \). Then \( gf \) is the composition of \( g \) and \( f \).

\[
(x: \square (g f)) = (x: \square f) \land (f x: \square g)
\]

\[
(gf) x = g (fx)
\]

result-Data

A result-data allows us to use a program to compute data. It has the form

\[
\text{result} \ \text{simplename} : \text{data} := \text{data} \ [\text{program}]
\]

A local variable is defined with a type and initial value. Then the program is executed. The result is the final value of the newly defined local variable. We have not yet presented programs, but the following example, which approximates the base of the natural logarithms \( e \), should give the idea.

\[
\text{result} \ \text{sum} : \text{rat} := 1
\]

\[
\text{new} \ \text{term} : \text{rat} := 1.
\]

\[
\text{for} \ i := 1;..15 \ [\text{term} := \text{term} \cdot i, \ \text{sum} := \text{sum} + \text{term}]
\]
There are no side effects. Nonlocal variables become constants within the program; their values may be used, but assigning them is not permitted. Input from and output to nonlocal channels are not permitted. Defining and undefining dictionaries and names within dictionaries are not permitted.

All the ways of expressing data can be combined arbitrarily, without restriction. Here is a function whose body is a \textit{result}-data. It expresses the number of times $2$ is a factor of $n$.

\begin{align*}
(n: (nat+1) \rightarrow \textbf{result} \ f: 0..n := 0 \\
\langle \textbf{new} m: 1..n+1 := n. \\
\textit{loop} \langle \textbf{if} \ \text{even} \ m \langle f := f + 1. \ m := m/2. \ \textit{loop} \rangle \rangle \rangle
\end{align*}

A \textit{result}-variable begins its scope at the left program bracket $\langle$ and ends its scope at the corresponding right program bracket $\rangle$ (see \textbf{Scope}). Consequently, the \textit{result}-variable can be any simple name, even one that has already been defined in the scope that encloses the \textit{result}-data. The type and initial value of the \textit{result}-variable cannot use the \textit{result}-variable.

\textbf{Quote and Unquote}

The predefined function \textit{quote} takes any data and produces a text representation of the data. Roughly speaking, it quotes its argument. For examples, \textit{quote} $123$ = “$123$” , \textit{quote} $\top$ = “$\top$” , \textit{quote} “abc” = ““abc”” , \textit{quote} $\{0, [1; 2] \} = \{0, [1; 2]\}$ . The argument is evaluated before quoting; for examples, \textit{quote} $(2\times3)$ = “$6$” , \textit{quote} $(0<1)$ = “$\top$” . In a context where $x=3$ , \textit{quote} $(x\times4)$ = “$12$”. Function \textit{quote} does not provide any control over the format of the resulting text. For numbers, fine control over the format of the resulting text is provided by the predefined function \textit{form}.

The predefined function \textit{unquote} is a kind of inverse of \textit{quote} . It applies to texts; roughly speaking, it unquotes its argument. For examples, \textit{unquote} “$123$” = $123$ , \textit{unquote} “$\top$” = $\top$ , \textit{unquote} ““abc”” = “abc” , \textit{unquote} “$\{0, [1; 2]\}$” = $\{0, [1; 2]\}$ . The argument is evaluated after unquoting; for examples, \textit{unquote} “$2\times3$” = $6$ , \textit{unquote} “$0<1$” = $\top$ . In a context where $x=3$ , \textit{unquote} “$x\times4$” = $12$ . In a context where $x$ is not defined , \textit{unquote} “$x\times4$” = “error” . If the argument does not represent a ProTem data expression, the result is “error”.

Whenever a data that is not a text is used in a context that requires a text, the \textit{quote} function is applied automatically. For example

“abc”; $123$

places a number where a text should be. So \textit{quote} is applied automatically ( “abc”; \textit{quote} $123$ ) resulting in a text ( “abc”; “$123$” ) as required for string join ( “abc123” ) . If \textit{quote} has been redefined (see \textbf{Scope}), the predefined \textit{quote} is used.

Whenever a text data is used in a context that requires a data that is not a text, the \textit{unquote} function is applied automatically. For example,

“$123$” + $1$ = \textit{unquote} “$123$” + $1$ = $123+1$ = $124$

If \textit{unquote} has been redefined (see \textbf{Scope}), the predefined \textit{unquote} is used. If the result is “error” , \textit{unquote} is not further applied.

\textbf{Scope}

A simple name is defined in these six ways: by the keyword \textit{new} , as a named program, as a function parameter, as a plan parameter, as a \textbf{for}-index, or as a \textit{result}-variable; we have already met function parameters and \textit{result}-variables; we shall meet the others shortly. The scope of a simple name is the part of a program in which the name is defined. The scope of a simple name is limited
by program brackets [ ] , except that the scope of a function parameter is limited by function brackets ⟨ ⟩ , and the scope of a dictionary definition is not limited by any brackets.

Except for dictionary definition, a simple name defined in a local scope using the keyword new must be new, not already defined since the most recent opening program bracket [ . Its scope extends from its definition through all following sequentially composed programs to the corresponding closing program bracket ] . But it may be covered by a redefinition in an inner scope. Using new x=2 and new x=3 as example definitions, and letting A , B , C , D , and E stand for arbitrary program forms (but not new or old ), in

[A. new x=2. B. [C. new x=3. D]. E]

the definition of x as the number 2 is not yet in effect in A , but it is in effect in B , C , and E . The definition that makes x the number 3 is in effect in D . None of A , B , C , D , or E can contain a redefinition of x unless it is within further scope limiters [ ] or ⟨ ⟩ .

A name defined by new can become undefined by the keyword old , ending its scope early. So in

new x=2. A. old x. B

the definition of x is in effect in A but not in B . Within B , the name x has the same meaning (if any) that it had before the definition new x=2 . After old x , the name x is again new and available for definition. However,

new x=2. [old x. A]

is not allowed; a scope cannot be ended by old within a subscope (except for dictionaries; see Dictionary Definition).

A scope can be nested inside another scope, which can be nested inside another, and so on. Outside all scope limiters, [ ] and ⟨ ⟩ , is the persistent scope. In the persistent scope, there is a dictionary named predefined that contains the predefined names.

When you define a new name in the persistent scope, the name must differ from all names already in the persistent scope. A name defined by new in the persistent scope is called a persistent name. Persistent names serve as “files”. The scope of a persistent name ends only with old . Its scope does not end with the end of a computing session (see Session), not even by switching off the power, which should not cut the power instantly, but should first cause the values of any variables in the persistent scope to be saved in nonvolatile memory.

Whenever a simple name is used, it is looked up as follows: first, look in the most local scope (innermost [ ] or ⟨ ⟩ ); then look in the next most local scope; then the next, and so on; when all local scopes have been searched, look in the persistent scope; then look in the predefined dictionary. The first occurrence found is the one that is used.

Whenever a compound name is used, the search for the leading name starts in the persistent scope, then continues if necessary in the predefined dictionary.

Programs

Some program constructs are concerned with names: defining a name ( new ), deleting a name ( old ). Other program constructs are variable assignment, input, output, and a variety of ways of combining programs to form larger programs. All programs, including those that define and delete names, are executed in their turn, just like variable assignments and input and output.
Variable Definition

Variable definition has the form

\[ \text{new } \text{newname} : \text{data} := \text{data} \]

The newname becomes a variablename. Here is an example variable definition.

\[ \text{new } x : \text{nat} := 5 \]

This defines \( x \) to be a variable assignable to any element in \( \text{nat} \), and initially assigned to 5. There is no such thing as an “uninitialized variable” nor the “undefined value” in ProTem. In a variable definition, the data after \( : \) is called the “type” of the variable, and the data after \( := \) is called the “initial value”. The type can be anything except the empty bunch, and the initial value must be an element of the type. The type and initial value can depend on previously defined names, including variables. For example,

\[ \text{new } y : 0,..2 \times x := x \]

defines \( y \) as a variable whose value can be any natural number from (including) 0 up to (excluding) twice the current value of \( x \) (the value of \( x \) at the time this definition is executed), with initial value equal to the current value of \( x \). But the type and initial value cannot make use of the variable being defined.

Here are three more examples.

\[ \text{new } s : [10*\text{int}] := [10*0] \]
\[ \text{new } t : \text{text} := "" \]
\[ \text{new } u : (0,..20)*\text{char} := \text{“abc”} \]

In the first example, \( s \) is defined as a variable that can be assigned to any list of ten integers, and is initially assigned to the list of ten zeroes. In the middle example, \( \text{text} \) is a predefined bunch equal to \( *\text{char} \), so \( t \) can be assigned to any text, and is initially assigned to the empty text. In the last example, \( u \) is defined as a variable that can be assigned to any text of length less than 20, and is initially assigned to the text “abc”.

Assignment

A variable can be reassigned by the assignment program. It has the form

\[ \text{variablename} := \text{data} \]

Here are two examples using the definitions of the previous subsection.

\[ x := x + 1 \]
\[ s := \text{3} \rightarrow \text{5} \mid s \]

The data on the right of \( := \) must be an element in the type (evaluated at definition) of the variable on the left of \( := \). As in the examples, the data on the right of \( := \) can make use of the variable on the left of \( := \).

Constant Definition

Constant definition has the form

\[ \text{new } \text{newname} := \text{data} \]

The newname becomes a constantname. The data on the right of \( := \) cannot make use of the name on the left of \( := \). The constantname cannot be reassigned. Here are three constant definitions.

\[ \text{new } \text{size} := 10. \]
\[ \text{new } \text{piBy2} := \frac{\pi}{2}. \]
\[ \text{new } \text{range} := 0,..\text{size} \]

where \( \pi \) is a predefined constant name.
A constant may use variables to express its value. For example

```
new xplus1 := x+1
```

The current value of variable $x$ is used to evaluate $x+1$, and $xplus1$ expresses that value. Variable $x$ may later be reassigned to another value, but that does not affect the value of $xplus1$. For example,

```
new x := nat := 3. `x has value 3
new xplus1 := x+1. `x has value 3 and xplus1 has value 4
x := 5 `x has value 5 and xplus1 has value 4
```

**Data Definition**

Data definition has the form

```
new newname = data
```

The newname becomes a dataname (note $=$ rather than $:=$ as in constant definitions).

```
new xplus2 = x+2
```

makes the value of $xplus2$ depend on the value of variable $x$. As $x$ changes value, $xplus2$ changes value so that $xplus2 = x+2$ is always $\top$. In the constant definition of $xplus1$ earlier, $x+1$ is evaluated once, at definition time. In the data definition of $xplus2$, $x+2$ is not evaluated at definition time; it is evaluated every time $xplus2$ is used in a context that requires its value.

```
new x := nat := 3. `assigns x to 3
new xplus2 := x+2. `assigns x to 5
x := xplus2 `assigns x to 7
```

A data definition can depend indirectly on a variable. For example,

```
new twoxplus4 = 2*xplus2
```

makes $twoxplus4$ depend indirectly on the value of variable $x$. In this definition, the value of $xplus2$ is not required, so it is not evaluated. If $x$ currently has value 3, then $x := twoxplus4$ assigns $x$ to 10. Then another $x := twoxplus4$ assigns $x$ to 24.

**Data Recursion**

In a variable definition, the type and initial value cannot depend on the variable being defined.

```
new bad: 0..2*bad := bad `illegal
```

is not allowed due to the two occurrences of $bad$ to the right of the colon. Likewise a constant definition cannot be recursive.

Data definition does allow recursion. The next two examples define $fact$ and $div$ to be the factorial function and integer division function for natural numbers.

```
new fact = 0 -> 1 | \langle n: (nat+1) -> n * fact (n-1) \rangle

new div = \langle a: nat -> \langle d: (nat+1) -> a<d 0 = even a 2 * div (a/2) d = 1 + div (a-d) d \rangle \rangle
```

Here is a bunch of texts (a grammar). This bunch includes the text “$a+b+a-a$” and many more.

```
new term = \langle a: term -> term; “+” term; “−” term \rangle
```

This recursive definition is equivalent to the nonrecursive definition

```
new term = \langle a: “a”, “b”: (\langle “+”, “−” \rangle; (“a”, “b”)) \rangle
```

Here is a function that eats arguments until it is fed argument 0.

```
new eat = \langle n: nat -> n=0 != \emptyset \langle eat \rangle \rangle
```

So $eat\ 5\ 2\ 0 = 0$, and $eat\ 4\ 7\ 3\ 8\ 0 = 0$, and $eat\ 1\ 2 = eat$ and $eat: nat -> (0, eat)$. The next example defines all binary trees with integer nodes.
new tree = [nil], [tree; int; tree]
Here is a pure, baseless recursion. If it is evaluated, its evaluation is nonterminating.
new rec = rec

**Constant versus Data Definition**

A constant definition evaluates its data once, at definition time, whereas a data definition evaluates its data each time its value is required. If the data is fully evaluated, there is no difference. For example, there is no difference between these two definitions:

```plaintext
new five := 5
new five = 5
```

When there are no variables used to express the value (neither directly nor indirectly), there is no semantic difference between data definition and constant definition, but there may be an efficiency difference. Compare these two definitions.

```plaintext
new six := 5+1
new six = 5+1
```

If the value of six is never required, the data definition (=) is more efficient. If the value of six is required once, they are equally efficient. If the value of six is required two or more times, the constant definition (:=) is more efficient. Here is a more interesting comparison.

```plaintext
new double := (n: (0,..10) \rightarrow 2×n)
new double = (n: (0,..10) \rightarrow 2×n)
```

The constant definition causes the function to be evaluated by applying it to all its arguments and storing the results. In effect, the function is evaluated to the list

```
[0; 2; 4; 6; 8; 10; 12; 14; 16; 18]
```

Then, when the value of double applied to an argument is required, that argument indexes the list. The data definition does not evaluate the function. Each time the value of double applied to an argument is required, the body of the function is evaluated. Which one is more efficient depends on the size of the domain, the complexity of the result, and the number of times the definition is used.

Here is a recursive data definition defining alla to be the infinite text that is all “a”.

```plaintext
new alla = “a”; alla
```

It is a data definition, evaluated as needed, so in alla_5 it is evaluated six times with result “a”.

**Output and Input**

Each channel is defined to transmit a specific type of value. The output channels screen, printer, and mail, and the input channels keys and mail are predefined to transmit text. The input channel microphone and the output channel speaker are predefined to transmit sound. We can define local channels to transmit any type of value (see Channel Definition).

Output has the form

```
channelname ! data
```

Channel screen accepts text, which is displayed on the screen. The program

```
screen! “Hi there.”
```

sends the text “Hi there.” to the screen. Output is buffered so it will be available when screen is ready to receive it. Texts can be joined and sent together.

```
screen! “Answer = “; quote x; nl
```

where quote is a predefined function that converts to a text, and nl is the new line character, or next line character, or return character. Function quote can be omitted (see Quote and Unquote). When screen or printer receives the delete (backspace) character, the previous character is
deleted; when the *tab* character is received, some number of spaces are substituted; when the *nl* character is received, further characters start on a new line.

Email input and output are made convenient by a mail program, but at the level of ProTem programming, emailing looks like this:

```
mail! "To: hehner@cs.utoronto.ca
Hey Rick, have a look at the exec program: ";
definition "exec"
```

The keyboard is a program that runs concurrently with other programs; you do not need to initiate it; it is already running. It monitors what key combinations are pressed, and for what duration, and outputs a string of characters. The shift-A combination is a single character “A”. Likewise the control-Q combination is a single character. The click button is just a key like any other; *click* is a character, and *doubleclick* is a character.

Input has two forms: without echo, and with echo. The first form, without echo, is

```
channelname ? data
```

Text from the keyboard (including the click button) can be received from channel *keys*. Five characters of input are received from channel *keys* by saying

```
keys? 5*char
```

What follows ? is called the pattern (or grammar). If input is not yet available, it is awaited. The input read is the earliest input on that channel that has not yet been read. The *tab*, *delete*, and *nl* characters may be part of the input; no corrections are made. The input is not echoed on the screen. The shortest input that fits the pattern is read. The program

```
keys? text; nl
```

reads text up to and including the first *nl* character, but

```
keys? text
```

just inputs the empty text.

Patterns *digit* and *numpat* are predefined as follows.

```
new digit:= "0", "1", "2", "3", "4", "5", "6", "7", "8", "9".
new numpat:= ("+", "–", ""); digit; *digit; (".", digit; *digit); ""
```

To receive a text that can be interpreted as a number, possibly preceded or followed by spaces, possibly preceded by a sign, ending in a new line character, input

```
keys? *" "; numpat; *" "; nl
```

Without *nl*, leading spaces and an optional sign and the first digit are read.

When input is received, it is referred to by the channel name followed by ?? . After the previous example input, we might have the assignment

```
x:= unquote (keys??) + unquote (keys??)
```

where *unquote* is a predefined function that converts from a text to the type required. Function *unquote* can be omitted (see *Quote and Unquote*), so we may write

```
x:= keys?? + keys??
```

Both occurrences of *keys??* refer to the same input, and *keys??* continues to refer to the same input until the next time new input is read from channel *keys*.

If *c* is the name of an input channel, then *c!!* is a binary expression with value ⊤ if there is written but unread data on the channel, and ⊥ if there is not. For example,

```
if keys!! [keys? char. screen! keys??] else [screen! “Are you still there?”]
```

(See *if-Program* and *Sequential Composition*.) Input on a channel that does not currently have any
written-but-not-yet-read data waits until data is written to the channel by a concurrent program.

If channel \( c \) is defined to input text, the program
\[
\text{c? “y”, “n”}
\]
inputs one character, either “y” or “n”, from channel \( c \). If the first available character on channel \( c \) is “a”, or more generally, if the input on the channel does not fit the pattern, what happens is undefined. Here are three options.

- The program cannot be executed, so execution ends.
- An error message is sent to channel \( \text{screen} \) to say that the input is unacceptable, and execution ends.
- An error message is sent to channel \( \text{screen} \) to say that the input is unacceptable, and the sender is given another opportunity to send an input that fits the pattern.

What happens depends on the implementation, on the channel, and on the number of attempts. Perhaps the last option is appropriate for channel \( \text{keys} \), and the first is appropriate for a secure channel.

An input program consisting of an input channel name, a question mark, and a pattern, does not echo the input on the screen; the input is invisible. This is useful, for example, when reading a password (see \text{Read Password}). To input and echo together, character by character, add an exclamation mark and the output channel name for the echo.

\[
\text{channelname ? data ! channelname}
\]

For example,
\[
\text{keys? text; nl !screen}
\]
This program inputs, from channel \( \text{keys} \), text to and including the first \( \text{nl} \) character, and outputs the same on channel \( \text{screen} \). Each character is echoed as it is input. A space \( \rightarrow \), tab \( \Rightarrow \), new line \( \rightarrow \), or delete character \( \leftarrow \) is displayed visibly as a graphic symbol.

In an input with echo, the pattern between the input question mark and the echo exclamation mark can be omitted. This results in a special pattern called the correcting pattern. For example,

\[
\text{keys?!screen}
\]
The correcting pattern reads a line of text to and including the first \( \text{nl} \) character, but this text is corrected according to delete (backspace) characters. The \( \text{nl} \) character is consumed, but not included in the value read. After this input, the value of \( \text{keys}?? \) is the corrected text, excluding the final \( \text{nl} \). If, during correction, there are more delete characters than other characters, the extra delete characters are ignored. The echo displays space, tab, and new line characters as spaces, tabs, and new lines, and displays delete characters as deletions of previous characters.

An output channel name can be omitted, in which case the output channel is \( \text{screen} \). For example,

\[
! \text{“Hello World”}
\]
prints \text{Hello World} on channel \( \text{screen} \). And
\[
! 2+2
\]
prints \text{4} on channel \( \text{screen} \). Thus ProTem can be used as a calculator. This program is short for
\[
\text{screen! quote (2+2)}
\]
An input channel name can be omitted, in which case the input channel is \( \text{keys} \). For example,
\[
? \text{char}
\]
reads one character from \( \text{keys} \), with no echo. The most recent text read on channel \( \text{keys} \) can be referred to as just \( ?? \). And \( !! \) is a binary expression saying whether there is written but unread data on channel \( \text{keys} \). If the input channel is omitted, and the name \( \text{keys} \) has been redefined, the input channel is the predefined channel \( \text{keys} \). If the output channel is omitted, and the name \( \text{screen} \) has been redefined, the output channel is the predefined channel \( \text{screen} \).
In a context requiring a number, the expression `unquote (keys??)` can be written `unquote ??` or `keys??` or `??` . But it cannot be written `unquote keys??` because that is parsed as `(unquote keys)??` . And it cannot be written `unquote ??` because the compiler will complain that `unquote` is not a channel. Similarly for `quote (keys!!)` .

The most common form of input `?!` reads one line from `keys` , correcting it according to `delete` characters, up to the first `nl` , which is not included in the value of `??` , and echoes character by character to `screen` .

In summary, output and input are, respectively,
```
channelname ! data
cchannelname ? pattern ! channelname
```
After reading input, the input most recently read is referred to as `channelname ??` .

The binary expression `channelname !!` says whether there is written but unread data on the channel. If the `channelname` is `keys` or `screen` it can be omitted. If input echoing is not wanted, omit both `!` and the echo `channelname` . In an input program with echo, omitting the pattern results in the correcting pattern.

**Sequential Composition**

Sequential composition is denoted by a period (point, dot). It is an infix connective; in other words, the period comes between and joins two programs.
```
program . program
```

**Concurrent Composition**

Concurrent composition has the form
```
program || program
```
The concurrent composition of programs `P` , `Q` , and `R` is `P||Q|R` . A variable defined before the concurrent composition remains a variable in at most one of the programs in the concurrent composition; in all the other programs of the concurrent composition, it becomes a constant. For example,
```
```
In the concurrent composition `[a:= 4. A] || [b:= 8. B]` , variable `a` can be reassigned in one of the concurrent programs, but not in both; it is reassigned in the left program `[a:= 4. A]` . Likewise variable `b` can be reassigned in one of the concurrent programs, but not in both; it is reassigned in the right program `[b:= 8. B]` . At the start of `A` , variable `a` has value 4 , constant `b` has value 2 , and data `c` has value 6 . At the start of `B` , constant `a` has value 1 , variable `b` has value 8 , and data `c` has value 9 . If `A` does not reassign `a` , and `B` does not reassign `b` , then at the start of `C` , variable `a` has value 4 , variable `b` has value 8 , and data `c` has value 12 . Concurrent programs cannot affect each other through assignments of variables. For co-operation, programs can communicate with each other on channels defined for the purpose (see Channel Definition).

We have previously seen that program brackets `[ ]` are scope limiters. In the previous paragraph, we see their other use: precedence. They are needed for a concurrent composition of sequential compositions because concurrent composition has precedence over sequential composition.
if-Program

An if-program has the form

\[
\text{if} \ data [ \ \text{program} ]
\]

The if-program

\[
\text{if} \ b [ \ P ]
\]

is executed as follows: binary expression \( b \) is evaluated; if its value is \( \top \), then program \( [P] \) is executed; if its value is \( \bot \), then program \( [P] \) is not executed. An if-else-program has the form

\[
\text{if} \ data [ \ \text{program} ] \ \text{else} [ \ \text{program} ]
\]

The if-else-program

\[
\text{if} \ b [ \ P ] \ \text{else} [ \ Q ]
\]

is executed as follows: binary expression \( b \) is evaluated; if its value is \( \top \), then program \( [P] \) is executed and program \( [Q] \) is not executed; if its value is \( \bot \), then program \( [P] \) is not executed and program \( [Q] \) is executed.

case-Program

A case-program has the form

\[
\text{case} \ data [ \ \text{program} ]
\]

in which the program is a composition of cases. For example, the case-program with 3 cases,

\[
\text{case } n [ P \parallel Q \parallel R]
\]

is executed as follows: natural expression \( n \) is evaluated; then one of the programs within the \([ ]\) brackets, separated by \( \parallel \), is executed. (The \( \parallel \) between \( P \) and \( Q \), and between \( Q \) and \( R \), do not indicate concurrent execution.) These programs, called cases, are numbered in order 0, 1, 2, and so on, and each is in a new scope. In the example, case 0 is \( [P] \), case 1 is \( [Q] \), and case 2 is \( [R] \). In the example, if \( n \) has value 1, then just \( [Q] \) is executed. If \( n \) is equal to or greater than the number of cases, an error message is printed and execution stops. The example case-program is logically equivalent to

\[
\text{if } n=0 [P] \ \text{else} \ [\text{if } n=1 [Q] \ \text{else} \ [\text{if } n=2 [R] \ \text{else} \ [\text{"error: case index too large". stop}]]]
\]

It is allowed, but senseless, for any of the cases to be just a simple name definition. For example, if \( n \) is 1, and \( Q \) is \( \text{new } x=2 \), then \( [\text{new } x=2] \) is executed, defining \( x \) and then immediately ending the scope of \( x \). A case can be an assignment or if-program or case-program or for-program or input or output or a call or any program enclosed in program brackets \([ ]\). For a case to include useful definitions, or be a sequential or concurrent composition of programs, the typical structure is

\[
\text{case } [ [ [ ] \parallel [ ] \parallel [ ] ] ]
\]

A case-else-program has the form

\[
\text{case} \ data [ \ \text{program} ] \ \text{else} [ \ \text{program} ]
\]

For example, the case-else-program with 3 cases,

\[
\text{case } n [ P \parallel Q \parallel R] \ \text{else} [S]
\]

is the same as the case-program, but if \( n \geq 3 \), then the program \( [S] \) after else is executed. The example case-else-program is logically equivalent to

\[
\text{if } n=0 [P] \ \text{else} \ [\text{if } n=1 [Q] \ \text{else} \ [\text{if } n=2 [R] \ \text{else} \ [S]]]]
\]

for-Program

A for-program has the form

\[
\text{for} \ \text{simplename} := \text{data} [ \ \text{program} ]
\]

The simplename becomes a constantname. Here is a nest of for-programs that computes the transitive closure of \( A : [n*\text{[n*bin]}] \).

\[
\text{for } j:= 0; \ldots \ n [ \text{for } i:= 0; \ldots \ n [ \text{for } k:= 0; \ldots \ n [ [\text{if } A i j \land A j k [A]:= (i;k) \rightarrow \top \lor A ]]]]]
\]
The *if*-program in the body of these *for*-programs
\[
\text{if } A \land \exists j (A(i,j) \rightarrow T \lor A)
\]
can be restated as
\[
A := (i;k) \rightarrow (A \lor (A(i,j) \land A(j,k))) \lor A
\]
if you prefer. The name being defined by *for* is known only within the loop body, and it is known there as a constant, and so it is not assignable. It is called a *for*-index. In the example, each of the *for*-indexes takes values 0, 1, 2, and so on up to but excluding \(n\).

For a second example, here is the sieve of Eratosthenes.

\[
\begin{aligned}
\text{new } n &: = 1000. \\
\text{new } prime &\text{: } n^* \text{bin} := 2 \uparrow (n-2) \uparrow \top. \\
\text{for } i &\triangleq 2; \ldots \text{ceil (sqrt } n) \text{ } [\text{if } \text{prime}_i [\text{for } j \triangleq i; \ldots \text{ceil (n/}i) [\text{prime} := \text{prime} \lor i \times j \downarrow \bot]]]
\end{aligned}
\]

A *for*-index is “by initial value”, so
\[
\text{for } i \triangleq x; x \text{ } [[x \triangleq i+1]]
\]
increases \(x\) by 1, not 2.

This next example prints the natural numbers forever.

\[
\begin{aligned}
\text{for } n &\triangleq 0; \ldots \infty \text{ } ![n; ""]
\end{aligned}
\]

After the := we can have any string expression; the index stands for each item in the string, in sequence. We can also have any bunch expression; the index stands for each element of the bunch, concurrently. As an example (note the use of ;.. rather than ;.. as earlier),
\[
\begin{aligned}
\text{for } i &\triangleq 0; \ldots \#L \text{ } [[L := i \rightarrow 0 \lor L]]
\end{aligned}
\]

makes the items of \(L\) be 0, concurrently. We could also write either of these:
\[
\begin{aligned}
\text{for } i &\triangleq []L \text{ } [[L := i \rightarrow 0 \lor L]] \\
L &:= \#L*0
\end{aligned}
\]

The domain of the *for*-index can also be a nonempty bunch of strings, or a string of nonempty bunches, and so on, so that sequential and concurrent execution can be nested within each other. (Note: distribution and factoring laws are not applied; the structure of the expression is the structure of execution.)

A *for*-index begins its scope after [] and ends its scope at the corresponding ]. Consequently, the *for*-index can be any simple name, even one that has already been defined in the scope that encloses the *for*-program. The domain of the *for*-index cannot use the *for*-index.

**Program Definition**

Program definition has the form
\[
\begin{aligned}
\text{new } \text{name } &\text{[ program ]}
\end{aligned}
\]
The name becomes a program name. Program definition gives a program a name, but does not execute the program. For example,
\[
\begin{aligned}
\text{new } \text{switchends } &\text{[s:= 0 } \rightarrow s \text{ 9 19 } \rightarrow s 0 1 s]
\end{aligned}
\]
Execution of this definition defines the program name *switchends*, but does not execute program \[[s:= 0 } \rightarrow s \text{ 9 19 } \rightarrow s 0 1 s]]\]. After execution of this definition, the name *switchends* can be used to call (cause execution of) the program it names. Program definitions can be recursive. Predefined program names include *await*, *exec*, *ok*, *stop*, *wait*.

A fancy name can be used as a specification. For example,
\[
\begin{aligned}
\text{new } <^x' > x &\text{ [x:= x+1]}
\end{aligned}
\]
The specification \( x' > x \) is implemented (refined, implied) by the program \([x := x+1]\). A prover is invoked by the [ctl v] command (see Verify). If the specification is written within the language that the prover understands, the prover attempts to prove that the specification is implemented (refined, implied) by the program. If the program makes use of a specification, the inner specification is used in the outer proof. For example,

\[
\text{new} \ « x' = 0 » \ [\text{if } x \neq 0 \ [x := x-1. \ « x' = 0 »]]
\]

In the program \([\text{if } x \neq 0 \ [x := x-1. \ « x' = 0 »]]\), the specification \( « x' = 0 » \) means exactly what it says, rather than the program that it names. Thus the use of specifications makes complicated fixed-point semantics unnecessary. If the prover fails to understand the specification, or fails to prove the refinement, it informs the programmer, and treats the specification as just a name. (See the paper Specified Blocks.)

**Named Program**

A named program has the form

simplename [ program ]

The simplename becomes a programname within the program that it names. It begins its scope after [ ] and ends its scope at the corresponding ] . Consequently, the name can be any simple name, even one that has already been defined in the scope that encloses the named program. The name is attached to the program (like a program definition), and the program is executed (unlike a program definition). One purpose of this naming is to make loops. Here is a two-dimensional search for \( x \) in an \( n \times m \) array \( A \) of integers (that is, \( A: [n^*[m^*\text{int}]] \)).

\[
\text{new } i: \text{nat} := 0.
\text{tryThisI} \ [\text{if } i = n \ [! x; \text{“ does not occur.”}]
\text{else} \ [\text{new } j: \text{nat} := 0.
\text{tryThisJ} \ [\text{if } j = m \ [i := i+1. \text{tryThisJ}]
\text{else} \ [\text{if } A i j = x \ [! x; \text{“ occurs at ”}; i; \text{“ ”}; j]
\text{else} \ [j := j+1. \text{tryThisJ}]]]]]
\]

The next example is a fast remainder program, assigning natural variable \( r \) to the remainder when natural \( a \) is divided by positive natural \( d \), using only addition and subtraction.

\[
r := a.
\text{outerloop} \ [\text{if } r \geq d \ [\text{new } dd: \text{nat} := d.
\text{innerloop} \ [r := r - dd. \ dd := dd + dd.
\text{if } r < dd \ [\text{outerloop}] \text{ else } \text{innerloop}]]]]]
\]

The use of a program name is semantically a call; it means the same as replacing it with the program it names (including the [ ] brackets). The fast remainder example means the same as

\[
r := a.
\text{outerloop} \ [\text{if } r \geq d \ [\text{new } dd: \text{nat} := d.
\text{innerloop} \ [r := r - dd. \ dd := dd + dd.
\text{if } r < dd \ [\text{if } r \geq d \ [\text{new } dd: \text{nat} := d.
\text{innerloop} \ [r := r - dd. \ dd := dd + dd.
\text{if } r < dd \ [\text{outerloop}]
\text{else } \text{innerloop}]]]]]
\]

else \ [\[r := r - dd. \ dd := dd + dd.
\text{if } r < dd \ [\text{outerloop}] \text{ else } \text{innerloop}]]]]]
\]

The calls outerloop and innerloop were replaced by the programs they name. They reappear, and again they mean the programs they name. Although semantically they are calls, in the previous two examples they are last actions (tail recursions), so they are implemented as branches (jumps, go to's).
The next example illustrates that named programs provide general recursion, not just tail recursion.

It computes the Fibonacci numbers \( x := \text{fib} \ n \) and \( y := \text{fib} \ (n+1) \) in \( \log n \) time.

\[
\text{Fib} \begin{array}{l}
\text{if } n=0 \text{ then } x := 0, y := 1 \\
\text{else } \text{if } \text{odd } n \text{ then } n := (n-1)/2, \text{Fib. } x := x^2 + y^2, y := 2nx y + y^2 \\
\text{else } n := n/2 - 1, \text{Fib. } x := 2nx y + y^2, y := n^2 + y^2 + x \\
\end{array}
\]

As in a program definition, a fancy name can be used as a specification. For example,

\[
\langle x' > x \langle x := x+1
\]

The specification \( \langle x' > x \) is implemented (refined, implied) by the program \( \langle x := x+1 \rangle \). A prover is invoked by the `ctl v` command (see `Verify`). If the specification is written within the language that the prover understands, the prover attempts to prove that the specification is implemented (refined, implied) by the program. If the program makes use of a specification, the inner specification is used in the outer proof. For example,

\[
\langle x' = 0 \rangle \text{ if } x \neq 0 \text{ then } x := x-1. \langle x' = 0 \rangle
\]

In the program, the specification \( \langle x' = 0 \rangle \) means exactly what it says, rather than the program that it names. Thus the use of specifications makes complicated fixed-point semantics unnecessary. If the prover fails to understand the specification, or fails to prove the refinement, it informs the programmer, and treats the specification as just a name. (For more on proving, see the paper Specified Blocks.)

Suppose a name is defined within a loop. For example, the name \( a \) in

\[
\text{infiniteLoop } \begin{array}{l}
\text{new } a := \text{"a". }!a. \text{ infiniteLoop}
\end{array}
\]

Executing this loop prints an infinite sequence of the letter “a”. Replacing the call with the called program, it is equivalent to

\[
\text{infiniteLoop } \begin{array}{l}
\text{new } a := \text{"a". }!a. \text{ new } a := \text{"a". }!a. \text{ infiniteLoop}
\end{array}
\]

In a general recursion, each call opens a new scope, and each new definition hides but does not destroy the previous definition. But when the recursive call is the last action performed in the named program (a tail recursion), as in this example, the old scope and its definitions cannot be used again, so the new scope replaces the old one; the scopes and variables do not pile up.

Let \( \text{name} \) be a new name (not defined in the local scope), and let \( \text{program} \) be a program, possibly using the name \( \text{name} \). Then the following three lines are equivalent to each other.

\[
\begin{array}{l}
\text{name } \text{[program]}
\text{[new name [program]. name]}
\text{new name [program]. name. old name}
\end{array}
\]

**Plan**

A plan is a program with a parameter. There are five forms of plan. The first is

\[
\text{plan } \text{simplename } := \text{data } [ \text{program} ]
\]

The simplename is being defined as a constant parameter within the program. It can be any simple name, even one that has already been defined in the current scope. Its type (after the := ) cannot make use of the parameter. The scope of the parameter is from [ to ]. For example,

\[
\text{plan } y := \text{real } [x := x3y]
\]

A plan can be argumented in the same way that lists are indexed and functions are argumented. The argument provides a value for the parameter. For example,

\[
\text{plan } y := \text{real } [x := x3y] 3
\]

is the same as

\[
x := x3
\]
A program with \( n+1 \) parameters is a program with 1 parameter whose body is a program with \( n \) parameters. For example, here is a program with two parameters.

\[
\text{plan } x := \text{int} \ [\text{plan } y := \text{int} \ [z := x+y]]
\]

Each argument reduces the number of parameters.

\[
\text{plan } x := \text{int} \ [\text{plan } y := \text{int} \ [z := x+y]] \ 3 \ 4
\]

is equivalent to

\[
\text{plan } y := \text{int} \ [z := 3+y] \ 4
\]

which is equivalent to

\[
z := 3+4
\]

A plan can be named; a plan can be argumented; and a plan can be the body of a plan. A plan that has been fully argumented can be used wherever any program can be used. For examples,

\[
\text{plan } x := \text{int} \ [\text{plan } y := \text{int} \ [z := x+y]]. \ z := 2 \quad \text{`this is not allowed}
\]

\[
\text{plan } x := \text{int} \ [\text{plan } y := \text{int} \ [z := x+y]] \ 3. \ z := 2 \quad \text{`this is not allowed}
\]

\[
\text{plan } x := \text{int} \ [\text{plan } y := \text{int} \ [z := x+y]] \ 3 \ 4. \ z := 2 \quad \text{`this is allowed}
\]

Here is a program to find the maximum value in nonempty list \( L \) in \( \log \ (\#L) \) time. (\( L \) is a variable, and its initial value is destroyed in the process.) We define \( \text{findmax } i \ j \) to find the maximum in the segment of \( L \) from index \( i \) to (but excluding) index \( j \), reporting the result as \( L \ i \).

\[
\text{new findmax } \text{plan } i := \square L \ [\text{plan } j := \square L+1
\]

\[
[\text{if } j–i \geq 2 \ [\text{findmax } i \ (\text{div } (i+j) \ 2) \ | \text{findmax } \ (\text{div } (i+j) \ 2) \ j.
\]

\[
L := i \rightarrow L \ i \ | \ L \ (\text{div } (i+j) \ 2) \ | \ L \]
\]

After execution of \( \text{findmax } 0 \ (\#L) \), the maximum value in the initial list is \( L \ 0 \).

In the previous paragraphs, the parameter is a constant (note the \( := \)); it is not assignable. It is “by initial value”, so

\[
\text{plan } i := \text{int} \ [x := i. \ y := i] \ (x+1)
\]

assigns both \( x \) and \( y \) to a value one greater than \( x \)'s initial value.

The second form of plan

\[
\text{plan } \text{simplename } : \text{data } [\text{ program }]
\]

(note the \( : \)) defines a variable parameter. For example,

\[
\text{plan } x \ := \text{int} \ [x := 3]
\]

A plan with a variable parameter applies to a variable argument. But it cannot be applied to a variable appearing in the plan. This restriction is required for reasoning about the plan. This example plan can be applied to any variable, even one named \( x \), because that \( x \) is nonlocal, and is not the local variable \( x \) appearing in the plan. But the plan

\[
\text{plan } x \ := \text{int} \ [x := 3. \ y := 4]
\]

cannot be applied to variable \( y \).

Here is a plan named \( \text{norm} \) to reduce rational \( \text{num/denom} \) to lowest terms. If \( a=8 \) and \( b=12 \), then after \( \text{norm } a \ b \), we have \( a=2 \) and \( b=3 \).

\[
\text{new norm } \text{plan } \text{num: } \text{nat+1} \ [\text{plan } \text{denom: } \text{nat+1} \ ` \text{normalize num/denom}
\]

\[
\text{[new gcd = } (a: \ (\text{nat+1}) \rightarrow (b: \ (\text{nat+1}) \rightarrow ` \text{greatest common divisor of } a \text{ and } b
\]

\[
a=b \quad a \equiv a \equiv b \equiv \gcd a (b-a) \equiv \gcd (a-b) b).
\]

\[
\text{new } g := \gcd \text{num denom. } \text{num:= num/g. } \text{denom:= denom/g}]
\]

The main use for variable parameters is probably to affect many files in the same way; for example, a plan to sort files.
The next form of plan

\texttt{plan \text{simplename} \text{data} \text{[ program ]}}

creates a plan with an output channel parameter. For example.

\texttt{plan c! text \text{[c! “abc”]}}

This plan can be applied to any channel that receives text. A plan with a channel parameter cannot be applied to a channel appearing in the plan. This example plan can be applied to any output channel, even one named \texttt{c}, because that \texttt{c} is nonlocal, and is not the local channel \texttt{c} appearing in the plan. But

\texttt{plan c! text \text{[c! “abc”. d! “def”]}}

cannot be applied to channel \texttt{d}. The channel name \texttt{screen} cannot be omitted when used as an argument for an output channel parameter.

The next form of plan

\texttt{plan \text{simplename} \text{data} \text{[ program ]}}

creates a plan with an input channel parameter. For example.

\texttt{plan c? text \text{[c? 3*char. screen! c??]}}

This plan can be applied to any input channel that delivers text. But

\texttt{plan c? text \text{[c? text; nl. d? text; nl]}}

cannot be applied to channel \texttt{d}. The channel name \texttt{keys} cannot be omitted when used as an argument for an input channel parameter.

The following program \texttt{pps} has three channel parameters. On the first, \texttt{a}, it reads the coefficients of a rational power series; on the second, \texttt{b}, it reads the coefficients of another rational power series; on the last, \texttt{c}, it writes the coefficients of the product power series.

\begin{verbatim}
new pps \text{[plan a? rat [plan b? rat [plan c! rat \text{[a? rat \text{|| b? rat. c! a??×b??.}\n
new a0:= a?? \text{|| new b0:= b?? \text{|| new d? rat! 0.}\npps a b d
\text{|| [a? rat \text{|| b? rat. c! a0×b??+a??×b0.}\nloop [a? rat \text{|| b? rat \text{|| d? rat. c! a0×b??+d??+a??×b0. loop]}}}]

The final form of plan

\texttt{plan \text{simplename} \text{\textbackslash [ program ]}}

creates a plan with a dictionary parameter. This plan can be applied to any dictionaryname.

\textbf{Dictionary Definition}

Dictionaries are the way you organize your programs and data. Dictionaries exist only in the persistent scope, outside all local scopes. The first form of dictionary definition is

\texttt{new \text{newname} \textbackslash}

When you define a \texttt{new} dictionary, the name must differ from all names in the persistent scope. The newname becomes a dictionaryname. To create a new dictionary named \texttt{abc}, write

\texttt{new \text{abc}\backslash}

(It does not matter whether there are spaces between the name and the backslash.)

Now you can define names within this dictionary. A name being defined in a dictionary must not already be defined in that dictionary. Each name in a dictionary is defined, using the keyword \texttt{new} and a compound name, to be one of the following: a variable name, a constant name, a data name, a program name, a channel name, a unit name, or a dictionary name. For example,

\texttt{new abc\textbackslash:= 2}
defines $x$ in dictionary $abc$ to be the constant $2$. (It does not matter whether there are spaces before or after the backslash.) This constant can then be used as $abc\backslash x$.

To define new dictionary $def$ within dictionary $abc$ write

```
new abc\def
```

When a name in a dictionary is defined to be a dictionary, this dictionary also can contain names, some of which can be defined as dictionaries, and so on. So a dictionary can be a tree structure. Suppose there is a dictionary named $ProTem$ within which there is a dictionary named $grammars$ within which there is a text named $LL1$. Its name is $ProTem\backslash grammars\LL1$.

A name within a dictionary can become undefined by $old$ (see Name Removal). For example,

```
old abc\x
```

ends the definition of $x$ in dictionary $abc$. And

```
old abc
```

ends the definition of dictionary $abc$. When a name becomes undefined, what it named remains in existence, anonymously, as long as something refers to it. When a dictionary becomes undefined, so do all the names within it.

Here is an example.

```
new stack\.
  new stack\s: *nat:= nil.
  new stack\push [plan x:= nat [s:= s; x]].
  new stack\pop [s:= s_(0;..leftrightarrow s–1)].
  new stack\top = s_(.leftrightarrow s–1).
old stack\s
```

Dictionary $stack$ now has three visible names in it: $push$, $pop$, and $top$. Variable $s$ still exists, but it is hidden.

The second form of dictionary definition is

```
new newname \ new dictionaryname
```

For example,

```
new parsestack\stack
```

creates a dictionary named $parsestack$ populated with the same definitions as $stack$. It is equivalent to writing

```
new parsestack\.
  new parsestack\s: *nat:= nil.
  new parsestack\push [plan x:= nat [s:= s; x]].
  new parsestack\pop [s:= s_(0;..leftrightarrow s–1)].
  new parsestack\top = s_(.leftrightarrow s–1).
old parsestack\s
```

Dictionary definitions, and definitions of names within dictionaries, do not obey the scope rules. If a dictionary definition occurs within program brackets $[ ]$, the dictionary is nonetheless in the persistent scope; its name must not already be defined in the persistent scope. But the dictionary name can already be defined within the local scope, and it does not cover the local definition. If a compound name definition occurs within program brackets $[ ]$, the definition is in a dictionary in the persistent scope; the name must not already be defined in that dictionary. But it can already be defined within the local or persistent scope. When a dictionary definition or definition of a name within a dictionary occurs within program brackets, it does not become undefined at the end of the local scope. It does become undefined by using $old$, even within a local scope.
There is a dictionary named *predefined* (see *Predefined Names*).

**Measuring Unit Definition**

There are three predefined units of measurement. They are $g$, representing mass in grams, $m$, representing distance in meters, and $s$, representing time in seconds. A unit of measurement has all the properties of an unknown positive finite real number constant. So, for example, we write $10\times m/s$ for the speed 10 meters per second. And we can define

\[
\text{new } km := 1000 \times m
\]
to make $km$ be a kilometer, and

\[
\text{new } h := 60 \times 60 \times s
\]
to make $h$ be an hour. So $1 \times m/s = 3.6 \times km/h$ evaluates to $\top$. To assign a variable to a quantity with units attached, the variable's type must have compatible units attached. For example,

\[
\text{new speed: real } m/s := 3.6 \times km/h
\]
assigns `speed` to $1 \times m/s$ (which could be written $m/s \times 1$ or $m \times 1/s$ or $1/s \times m$ or just $m/s$).

You can define a new unit of measurement, unrelated to the existing units. Measuring unit definition has the form

\[
\text{new } newname #1
\]
The newname becomes a unitname. For example,

\[
\text{new } sheet #1
\]
defines a new unit of measurement called the `sheet`. Now you can define the related units

\[
\text{new } quire := 25 \times sheet.
\]
\[
\text{new } ream := 20 \times quire
\]
Now you can define a variable using the new units.

\[
\text{new } order := 1500 \times sheet.
\]
This assigns `order` to $1500 \times sheet$. Another example is a monetary unit, such as

\[
\text{new } dollar #1.
\]
\[
\text{new } cent := dollar \%.
\]

When the value $5 \times m/s$ is converted to text by `quote`, the result is “$5 \times m/s$” without the $\times$ sign and without evaluating the unknown real value $m/s$. And `unquote` “$5 \times m/s$” = $5 \times m/s$. Similarly for all units of measurement. One more example: `quote` $(2 \times 3 \times km/h)$ = “1.6667 m/s”.

**Forward Definition**

Forward definition has the form

\[
\text{new } newname
\]
The newname becomes either a dataname or a programname. For example

\[
\text{new } abc
\]
is a notice that a definition of `abc` will follow later in the same scope. In a data definition or program definition, the scope of the name being defined starts with the definition. A forward definition facilitates mutual recursion by starting the scope of a data name or program name even before its definition. For example, leaving gaps for missing parts, in

\[
\text{new } f := 3. \text{[new } f, \text{ new } g = f \text{ g . new } f = f \text{ g . ]}
\]
the inner `f` and `g` are each defined in terms of both of them. Without the forward definition of `f` (following `,`), `g` would be defined in terms of the earlier constant definition `new f := 3`.
Channel Definition

Channel definition has the form

\[
\text{new } \text{name} ? \text{data} ! \text{data}
\]

The name becomes a channel name. The definition

\[
\text{new } \text{c'?nat! } 0
\]

defines \(c\) to be a new local channel that transmits values of type \(\text{nat}\), with \(0\) as initial output and input. Channel \(c\) can be used for output and input. Now \(c'??\) refers to the most recent input on the channel, and \(c'!!\) is a binary expression saying whether there is written but unread data on channel \(c\). Before there has been any output or input, \(c'??\) refers to the initial output and input supplied in the channel definition, and \(c'!!\) is \(\bot\). The type of the channel cannot use the name of the channel being defined. Concurrent programs cannot use the same channel for output. Concurrent programs can use the same channel for input only if the concurrent composition is not sequentially followed by a program that uses that channel for input. When concurrent programs read from the same channel, they read the same inputs independently.

\[
\begin{align*}
\text{new } & \text{c'?nat! } 0. \ x:= c'?? & \text{assigns } x \text{ to } 0 \\
\text{new } & \text{c'?nat! } 0. \ c'! 7. \ x:= c'?? & \text{assigns } x \text{ to } 0 \\
\text{new } & \text{c'?nat! } 0. \ c'! 7. \ c'\text{?nat. } x:= c'?? & \text{assigns } x \text{ to } 7 \\
\text{new } & \text{c'?nat! } 0. \ c'\text{?nat. } c'! 7. \ x:= c'?? & \text{deadlock, stuck at } c'\text{?nat} \\
\text{new } & \text{c'?nat! } 0. \ [c'\text{?nat. } x:= c'??] \ll [c'\text{?nat. } y:= c'??] & \text{assigns } x \text{ and } y \text{ to } 7
\end{align*}
\]

Name Removal

Names defined with the keyword \texttt{new} can be undefined with the keyword \texttt{old}. Name removal has the form

\[
\text{old } \text{name}
\]

Ironically, by saying \texttt{old x}, the name \(x\) becomes available for reuse as a new name. Even though a name becomes undefined, what it named will remain as long as there is an indirect way to refer to it. For example,

\[
\begin{align*}
\text{new } s: & *\text{all:= nil.} \\
\text{new } push & [\text{plan } x:= \text{all } [s:= s;x]]. \\
\text{new } pop & [s:= s_0;e\leftrightarrow s-1]]. \\
\text{new } top & = s_(e\leftrightarrow s-1). \\
\text{new } empty & = s(nil. \\
\text{old } s
\end{align*}
\]

The names \texttt{push}, \texttt{pop}, \texttt{top}, and \texttt{empty} are now defined and ready for use. The name \(s\) was defined for the purpose of defining the other names, and then removed, leaving the other names dependent upon an anonymous variable.

In predefined dictionary \texttt{rand} there are four names \texttt{init}, \texttt{next}, \texttt{Int}, and \texttt{Real}. They might have been defined as:

\[
\begin{align*}
\text{new } randrv & : 0..\text{maxnat}:= 123456789. \ `\text{will be hidden} \\
\text{new } rand\text{init} & [\text{plan } seed:= 0..\text{maxnat } [randrv:= seed]]. \\
\text{new } rand\text{next} & [randrv:= \text{mod } (rv \times 5^{13}) \text{ maxnat}]. \\
\text{new } rand\text{Int} & = \{\text{from: int } \rightarrow \{\text{to: int } \rightarrow \text{floor } (\text{from } + (\text{to-from})\times randrv/maxnat)\}}. \\
\text{new } rand\text{Real} & = \{\text{from: real } \rightarrow \{\text{to: real } \rightarrow \text{from } + (\text{to-from})\times randrv/maxnat)\}}. \\
\text{old } randrv
\end{align*}
\]
Variable `randrv` is now hidden; its name is removed, but `randinit`, `randnext`, `randInt`, and `randReal` still use it. We can use these definitions as follows:

```
randinit 555555555.
randnext.
n := randInt 0 10
```

The following sequence swaps the data names `i` and `j`.

```
new t = i. old i. new i = j. old j. new j = t. old t
```

**Synonym Definition**

Synonym definition has the form

```
new newname oldname
```

The newname becomes a synonym for the oldname. One use is to shorten all names that are deep within several dictionaries. For example, if dictionary `a` contains dictionary `b`, which contains dictionary `c`, which contains dictionary `d`, which contains variable `x`, then

```
new x a ∥ b ∥ c ∥ d
```

shortens the name `a ∥ b ∥ c ∥ d` to just `x`. The definition

```
new d a ∥ b ∥ c ∥ d
```

shortens all names within `a ∥ b ∥ c ∥ d`, for example, from `a ∥ b ∥ c ∥ d` to `d`.

Another use is to rename something. To rename `a` to `b`, write

```
new b a. old a
```

**Format**

Although not part of the ProTem language, here are some suggested formatting (indentation) rules. The choice of alternative depends on the length of component data and programs.

```
A. B
or
A.
B
------------------------------------ ------------------------------------
A || B
or
A
|| B
------------------------------------ ------------------------------------
if A [B] else [C]
or
if A [B]
else [C]
or
if A [B]
else [C]
------------------------------------
result x: A := B [C]
or
result x: A := B
[C]
------------------------------------
(x: A → ⟨y: B → C⟩)
or
⟨x: A → ⟨y: B → C⟩⟩
```

More indentation would show the structure better, but it would crowd programs onto the right side of
the page. Consistent indentation improves readability, and is useful redundancy for error checking.

Commands

There are 11 commands in ProTem. They are not presented in the grammar, and they cannot be part
of a stored program. They can be used only by a human at a keyboard. A command may be given at
any time; it does not have to respect the grammatical structure of a program; it interrupts execution.
Each command is the control character combined with a letter. The commands are:

- **ctl x** execute
- **ctl a** abort execution
- **ctl p** pause or resume execution
- **ctl s** stop current session and start new session
- **ctl u** undo current session
- **ctl e** enter or exit editor for saved program or data
- **ctl d** display source or object code for saved program or data
- **ctl n** display names defined in current scope or persistent scope or in dictionary
- **ctl m** attach or modify or retrieve memo to defined name
- **ctl c** generate context comments
- **ctl v** verify program according to a specification

Execute

Use **ctl x** to execute the program keyed in since the latest prompt.

Abort

Use **ctl a** to abort execution of the currently executing or paused program.

Pause

If there is a program being executed, the **ctl p** command pauses its execution. If there is a paused
program, **ctl p** resumes its execution.

Session

Sessions are defined for security and error recovery. When the computer is turned on, a session
begins. When some idle time passes (how much time is a parameter of the system and may be set to
infinity), a session ends and a new one begins. When the computer is turned off, a session ends. The
**ctl s** command causes the current session to end and a new session to begin. If there is a currently
executing or paused program, ending the session asks if you want to abort it.

Sessions do not define the lifetime of definitions. A definition in the persistent scope, outside all \([\ ]\)
pairs, lasts from the execution of the definition ( **new** ) to the execution of the corresponding name
removal ( **old** ). This may be less than a session, or more than a session. Turning off the computer
should not cut the power instantly, but should first cause the values of any variables in the persistent scope to be saved in nonvolatile memory.

At the start of each session, a programmer must login. This connects the programmer to their persistent scope. Then channels `keys`, `screen`, `microphone`, `speaker`, and `printer` are initialized and connected to the session. The data definition `session`, which is dependent on channel `keys`, is initialized. It is a text consisting of all keystrokes since the start of the current session. (This is quite practical: an hour's hard work produces only 10kbytes of keystrokes.) This text can be saved as a record of work done, or for error recovery (see `Undo`).

**Undo**

The command `ctl u` undoes a session (except for inputs and outputs and `session`). Implementing it requires capturing the state at the start of a session. On many computers, returning to the prior state may be cheap; nonvolatile memory (that does not require power) contains the state as it was at the start of the current session, and volatile memory (that requires power) contains the current state. After undo, you can capture the current value of `session`, let us call it `recovery`,

```
new recovery: text:= session
```

then reassign `recovery`, and then execute the result by writing `exec recovery`. This gives us perfectly flexible error recovery for the modest cost of a keystroke file.

**Edit**

The edit command `ctl e` is used to modify an existing persistent program or data definition. It invokes a dialogue using `keys` and `screen` to determine which definition. It then invokes an editor. In the editor, `ctl e` exits the editor, and asks if you want to throw away the old definition, and save and compile the new definition. If the new definition has an error, you receive an error message, an error comment is inserted into the saved source, and the compiled object code, when executed, prints “unable to execute [definition name]”. If you want to create a definition using the editor, first create the definition, for example, `new p [ok]`, and then invoke the editor to modify it. If you want to delete a persistent definition, use `old`.

**Display**

The command `ctl d` starts a dialogue using `keys` and `screen` to determine the name (simple or compound) of the program or data whose source or object code you want to view.

**Names**

The command `ctl n` begins a dialogue using `keys` and `screen` to determine whether you want the names defined in the current scope, the persistent scope, or in a dictionary (which may be a subdictionary). In a (sub)dictionary you will see only the first-level names, not the names in its subdictionaries.

**Memo**

Each definition can optionally have a memo attached to it. The memo might explain the purpose or use of the definition. It is there to be read by a human, not for execution. A memo is similar to a comment that you would make at the point of definition, but differs in that you can retrieve it anytime. The command `ctl m` starts a dialogue using `keys` and `screen` to determine which name
(simple or compound), whether you want to attach a new memo, modify an existing memo, or retrieve an existing memo. For example, you may say that you want to attach the memo.

This variable accumulates the sum of the products.

to name \( x \). Asking for the memo attached to predefined name \( e \) prints \( e := 2.718281828459045 \) (approximately) constant The base of the natural logarithms.

**Context**

The command \( \texttt{ctl c} \) starts a dialogue using *keys* and *screen* to determine the program, bracketed by \( \langle \rangle \), for which context comments are wanted. The comments are then generated. These comments say which nonlocal names are used, and in what way they are used. Here is the format.

- `input: on these channels`
- `output: on these channels`
- `use: the values of these variables, constants, data names, units, function names, and identities`
- `assign: these variables`
- `call: these program names and plan names`
- `refer: to these dictionaries`

If there already are comments in this format, they are replaced. (For examples of context comments, see Example Programs.) Additionally, a programmer may want to include comments like

- `spec: specification`
- `pre: precondition`
- `post: postcondition`
- `inv: invariant`

but these are not generated by \( \texttt{ctl c} \).

**Verify**

The command \( \texttt{ctl v} \) starts a dialogue using *keys* and *screen* to determine the program, bracketed by \( \langle \rangle \) and named by a fancy name, for which verification is wanted. The verification is then attempted. (See Program Definition and Named Program.)

**Predefined Names**

The predefined names are defined in dictionary *predefined* in the persistent scope (see Scope). It has permit-list *everyone* (see Permit). Predefined names can be redefined in a local scope. For example, one of the predefined names is the imaginary number \( i \) (a square root of \(-1\)). You may also want to define a local variable \( i \). If you do, you can still refer to the predefined \( i \) as predefined\( i \) (even if you have covered the name *predefined* with a local definition because the search for a compound name begins in the persistent scope). If predefined name \( i \) is covered by a definition in a scope outside the local scope where you are working, you can get back the simple name \( i \) as the imaginary number in these three ways:

- `new i := predefined\( i \)` \ `constant definition`
- `new i predefined\( i \)` \ `synonym definition`
- `new i := 0\&1` \ `constant definition`

The command \( \texttt{ctl n} \) is used to list the names in the *predefined* dictionary. The command \( \texttt{ctl m} \) is used to get a description of a predefined name.

Each predefined name is one of:
Some definitions use § (solutions, those) which is not part of ProTem; it is defined in *a Practical Theory of Programming*. Here are the predefined names.

\[ abs: \text{com} \rightarrow \text{real} \quad \text{data} \quad \text{Absolute value.} \quad abs \ x = \sqrt{x^2 + y^2} \ . \]

\[ all = \text{com}, \text{char}, \text{bin}, \text{all}, [\*\text{all}] \quad \text{data} \quad \text{All ProTem items.} \]

\[ arc: \text{com} \rightarrow \{r: \text{real} \rightarrow 0 \leq r < 2 \times \pi\} \quad \text{data} \quad \text{The angle or arc of a complex number.} \]

\[ \text{arccos}: \{r: \text{real} \rightarrow -1 \leq r \leq 1\} \rightarrow \{r: \text{real} \rightarrow 0 < r < \pi/2\} \quad \text{data} \quad \text{A trigonometric function.} \]

\[ \text{arcsin}: \{r: \text{real} \rightarrow -1 \leq r \leq 1\} \rightarrow \{r: \text{real} \rightarrow 0 < r < \pi/2\} \quad \text{data} \quad \text{A trigonometric function.} \]

\[ \text{arctan}: \text{real} \rightarrow \{r: \text{real} \rightarrow 0 < r < \pi/2\} \quad \text{data} \quad \text{A trigonometric function.} \]

\[ \text{await} \quad \text{program} \quad \text{A plan with one constant parameter of type \textit{real}s}. \quad \text{If the argument represents the present or a future time, its execution does nothing but takes time until the instant given by the argument. If the argument represents the present or a past time, its execution does nothing and takes no time. See \textit{time} and \textit{wait} and \textit{s}.} \]

\[ \text{back}: \*\text{n} \rightarrow \*\text{n} \quad \text{data} \quad \text{If} \ i \ \text{is an item, back} \ (s; i) = s \ . \]

\[ \text{bin}: = \top, \bot \quad \text{constant} \quad \text{The binary values.} \]

\[ \text{bold}: \text{text} \rightarrow \text{text} \quad \text{data} \quad \text{Same text but in bold font.} \]

\[ \text{ceil}: \text{real} \rightarrow \text{int} \quad \text{data} \quad r \leq \text{ceil} \ r < r+1 \]

\[ \text{char} \quad \text{data} \quad \text{The characters.} \]

\[ \text{charnat}: \text{char} \rightarrow \text{nat} \quad \text{data} \quad \text{A one-to-one function with inverse \textit{natchar}. The encoding might be extended ASCII or unicode. Character combinations, for example shift-option-a, also have numeric encodings.} \]

\[ \text{click}: \text{char} \quad \text{constant} \quad \text{The click character.} \]

\[ \text{com} = \text{real} & \text{real} \quad \text{data} \quad \text{The complex numbers.} \]

\[ \text{cos}: \text{real} \rightarrow \{r: \text{real} \rightarrow -1 \leq r \leq +1\} \quad \text{data} \quad \text{A trigonometric function.} \]

\[ \text{cosh}: \text{com} \rightarrow \text{com} \quad \text{data} \quad \text{A hyperbolic function.} \]

\[ \text{ctlx}: \text{char} \quad \text{data} \quad \text{The combination of the control and x characters.} \]

\[ \text{cursor}: \text{nat} ; \text{nat} \quad \text{data} \quad \text{A data name whose value is the current cursor position.} \]

\[ \text{definition}: \text{text} \rightarrow \text{text} \quad \text{data} \quad \text{If the argument is the name of a persistent definition for which you are on the permit-list, then the result is the textual definition. For example, definition “x” = “new x = 2”. Otherwise the result is “error”.} \]

\[ \text{delete}: \text{char} \quad \text{constant} \quad \text{The delete or backspace character.} \]

\[ \text{digit}: \text{char} \quad \text{constant} \quad \text{The decimal digits.} \]

\[ \text{div}: \text{real} \rightarrow \{r: \text{real} \rightarrow r>0\} \rightarrow \text{int} \quad \text{data} \quad \text{div} \ a \ d \quad \text{is the integer quotient when} \ a \ \text{is divided by} \ d \ . \]

\[ (0 \leq \text{mod} \ a \ d < d) \wedge (a = \text{div} \ a \ d \times d + \text{mod} \ a \ d) \]

\[ \text{doubleclick}: \text{char} \quad \text{constant} \quad \text{The doubleclick character.} \]

\[ e:= 2.718281828459045 \quad \text{(approximately)} \quad \text{constant} \quad \text{The base of the natural logarithms.} \]

\[ \text{end}: \text{char} \quad \text{constant} \quad \text{The end-of-file character. It is greater than all other characters.} \]

\[ \text{even}: \text{int} \rightarrow \text{bin} \quad \text{data} \quad \text{A function that says whether its argument is even.} \]

\[ \text{everyone} \quad \text{data} \quad \text{All identities.} \]

\[ \text{exec} \quad \text{program} \quad \text{A plan with one text parameter. If the argument represents a ProTem program, the execution is that of the represented program. It “unquotes” its argument. If applied to \text{“x:= x+1”}, the “x” refers to whatever \ x \ refers to at the location where exec “x:= x+1”} \]
occurs. If the argument is the empty text, compile and execute the input from keys. If the argument is nonempty and does not represent a ProTem program, execution displays an error message.

exp: com→com data The exponential function. exp x = e^x .
false:= ⊥ constant A binary value.
find: all→*all→nat data If i is an item in string S , then find i S is the index of its first occurrence; if not, then find i S = ↔ S .
fit: int→text→text data If i ≥0 then fit i t is a text of length i obtained from t by either chopping off excess characters from the right end or by extending t with spaces on the right end. If i ≤0 then fit i t is a text of length –i obtained from t by either chopping off excess characters from the left end or by extending t with spaces on the left end.
floor: real→int data floor r ≤ r < 1 + floor r
form: nat→nat→(nat+1)→real→text data Format a real number. form d e w r is a text representing real r with the final digit rounded. d is the number of digits after the decimal point; if d =0 the point is omitted. e is the number of digits in the exponent; if e >0 the decimal point will be placed after the first significant digit; if e =0 the ^^^ is omitted and the decimal point will be placed as necessary. w is the total width; if w is greater than necessary, leading blanks are added; if w is less than sufficient, the text contains blobs.
form 4 1 10 pi = “3.1416^^0” form 2 0 6 (–pi) = “–3.14”
form 0 0 3 5 = “5” form 0 0 3 (–5) = “–5” form 0 0 2 123 = “••”.
g unit A mass of one gram.
i:= 0&1 constant An imaginary number: a square root of –1 .
im: com→real data The imaginary part of a complex number.
infinity:= ∞ constant An infinite number, greater than all other numbers.
int = nat, –nat data The integers.
italic: text→text data Same text but in italic font.
keys? text! “” channel To the program that monitors key presses, it is an output channel; to all other programs, it is an input channel.
lb:勰(r: real → r>0) → real data The binary (base 2 ) logarithm.
ln:勰(r: real → r>0) → real data The natural or Napierian (base e ) logarithm.
log:勰(r: real → r>0) → real data The common (base 10 ) logarithm.
m unit A distance of one meter.
mail channel A text input and output channel for email.
match: *all→*all→nat data If pattern occurs within subject , then match pattern subject is the index of its first occurrence. If not, then match pattern subject = ↔subject .
maxint: int constant The maximum representable integer (machine dependent).
maxnat: nat constant The maximum representable natural (machine dependent).
microphone? *sound! silence channel To the microphone, it is an output channel; to all other programs, it is an input channel.
minint: int constant The minimum representable integer (machine dependent).
mod: real →勰(r: real → r>0) → real data mod a d is the remainder when a is divided by d .
(0 ≤ mod a d < d) ∧ (a = div a d × d + mod a d)
movie = *picture data A string of pictures.
nat = 0,∞ data The natural numbers.
natchar: nat→char data A one-to-one function with inverse charnat . The encoding might be extended ASCII or unicode. Character combinations, for example shift-option-a, also have numeric encodings.
nil constant The empty string.
nl: char constant The new line character or next line character or return character.
null constant The empty bunch.
numpat: text constant A text pattern for numbers, useful for reading a number from a text channel.
odd: int→bin data A function that says whether its argument is odd.
ok program A program whose execution does nothing and takes no time.
ord = real, char, bin, all, *ord, [ord] data The ordered type, for which ∧ ∨ < > ≤ ≥ are defined.
pi:= 3.141592653589793 (approximately) constant The ratio of a circle’s circumference to its diameter.
picture = [x*[y*(0,..,z)]]} data where x is the number of pixels in the horizontal dimension, y is the number in the vertical dimension, and z is the number of pixel values.
plain: text→text data Same text but in non-italic and non-bold font.
point data A function that applies to a list and gives its deep domain (a bunch of strings of indexes).
pre: char→char constant The character predecessor function.
printer? text! “” channel To the printer, it is an input channel; to all other programs, it is an output channel.
ProTem: text constant This document.
quote: *all→text data produces a text representation of its argument. The argument is evaluated before quoting. See unquote and form.
rand\ dictionary containing four definitions.
  init program A plan with one constant natural parameter. Assigns a hidden variable to the argument.
  next program Assigns a hidden variable to the next value in a random sequence.
Int: int→int→int data A reasonably uniform function, dependent on a hidden variable, over the interval from (including) the first argument to (excluding) the second argument.
  Real: real→real→real data A reasonably uniform function, dependent on a hidden variable, over the interval between the arguments.
rat = int/(nat+1) data The rational numbers.
re: com→real data The real part of a complex number.
real data The real numbers.
round: real→int data r–0.5 ≤ round r < r+0.5
s unit A time of one second.
screen? text! “” channel To the screen, it is an input channel; to all other programs, it is an output channel.
session data A text consisting of joining all texts from channel keys since the start of a session.
sign: real → (–1, 0, 1) data The sign of a real number.
silence: sound data The silent sound.
sin: real → $\{r: real \rightarrow –1 ≤ r ≤ +1\}$ data A trigonometric function.
sinh: com→com data A hyperbolic function.
sort: *ord→*ord data Sorts in nondecreasing order.
sound data The sounds.
speaker? *sound! silence channel To the speaker, it is an input channel; to all other programs, it is an output channel.
sqrt: com→com data The principal square root. $4^{(1/2)} = 2, –2$ but $sqrt 4 = 2$.
stop program Its execution does nothing and takes forever so that no computation can follow.
sub: *all→nat→nat→*all→*all data sub s n m t is a string formed from string s by replacing the substring from index n to index m with string t. The substring being replaced s_(n;..,m) does not have to be the same length as the string t replacing it. If n=m this is insertion. If t=nil this is deletion. sub s n m t = s_(0;..,n); t; s_(m;..,s)
subst: *all→all→all→*all data subst s x y is a string formed from string s by replacing all
occurrences of item \( x \) with item \( y \).

\[
\text{suc: char} \rightarrow \text{char} \quad \text{constant}
\]
The character successor function.

\[
\text{tab: char} \quad \text{constant}
\]
The tab character.

\[
\text{tan: real} \rightarrow \text{real} \quad \text{data}
\]
A trigonometric function.

\[
\text{tanh: com} \rightarrow \text{com} \quad \text{data}
\]
A hyperbolic function.

\[
\text{text = \*char} \quad \text{data}
\]
The character strings.

\[
\text{texttine: text} \rightarrow (\text{real} \times s, \text{“error”}) \quad \text{data}
\]
If the argument represents a time, possibly preceded by space, tab, and new line characters, possibly followed by space, tab, and new line characters, the result is the represented time in seconds since 2000 January 1 at 0:00 UTC (the midnight that begins 2000 January 1 at longitude 0). Times before then are negative. For example, \text{texttime} \( \text{“1947 September 16 at 14:24:32.5 UTC–5”} = -68675727.5s \). Otherwise the result is “error”. See \text{timetext}.

\[
\text{time: real} \times s \quad \text{data}
\]
A data name whose value depends on a clock. It gives the current time in seconds since 2000 January 1 at 0:00 UTC (the midnight that begins 2000 January 1 at longitude 0).

\[
\text{timetext: (real} \times s) \rightarrow (–12..12) \rightarrow \text{text} \quad \text{data}
\]
Given the time in seconds since 2000 January 1 at 0:00 UTC (the midnight that begins 2000 January 1 at longitude 0), and a time zone, the result is a readable text. Times before then are negative. See \text{texttime}. For example, \text{timetext} \( -(68675727.5s) \text{ } (-5) = \text{“1947 September 16 at 14:24:32.5 UTC–5”} \)

\[
\text{trim: text} \rightarrow \text{text} \quad \text{data}
\]
A text formed from the argument by removing all leading and trailing space, tab, and new line characters.

\[
\text{true} := \top \quad \text{constant}
\]
A binary value.

\[
\text{unquote: text} \rightarrow \text{\*all} \quad \text{data}
\]
If the argument represents a ProTem data expression, the result is the value of the represented data. The argument is evaluated after unquoting. If the argument does not represent a ProTem data expression, the result is “error”. See \text{quote}.

\[
\text{wait program}
\]
A plan with one constant parameter of type \text{real} \times s. If the argument is nonnegative, its execution does nothing and takes the time given by the argument. If the argument is nonpositive, its execution does nothing and takes no time. See \text{await} and \text{time} and \text{s}.

**Miscellaneous**

The ProTem equivalent of enumerated type is shown here.

\[
\text{new color} := \text{“red”, “green”, “blue”}.
\]

\[
\text{new brush: color} := \text{“red”}
\]

The ProTem equivalent of the record type (structure type) is as follows.

\[
\text{new person} := \text{“name”} \rightarrow \text{text} \mid \text{“age”} \rightarrow \text{nat}.
\]

\[
\text{new p: person} := \text{“name”} \rightarrow \text{“Josh”} \mid \text{“age”} \rightarrow \text{16}
\]

The fields of \( p \) can be selected by data that evaluates to text, for example

\[
\text{p} \text{ “name”}
\]

is the text “Josh”. The value of \( p \) can be changed using a function arrow and selective union.

\[
\text{p} := \text{“age”} \rightarrow \text{17 } \text{p}.
\]

\[
\text{p} := \text{“name”} \rightarrow \text{“Amanda”} \mid \text{“age”} \rightarrow \text{2}
\]

We can even have a whole file (string) of records and join new records onto its end.

\[
\text{new file: \*person} := \text{nil}.
\]

\[
\text{file} := \text{file; p}
\]

The efficiency of pointers is obtained through the use of the predefined function \text{point}. When applied to a list argument, it yields the deep domain of the list. For example,

\[
\text{point} \quad [10; [11; 12]; 13] \quad = \quad 0, 1;(0, 1), 2 \quad = \quad 0, 1;0, 1;1, 2
\]

The use of \text{point} is a signal to the implementation that its strings of natural numbers will be used
only as indexes into the list (and the implementation will check that this is so). For example, we can define a linked list \( G \) as follows.

\[
\text{new } G [\text{"name" } \rightarrow \text{text} | \text{"next" } \rightarrow \text{point } G ]:=[\text{"name" } \rightarrow \text{end} | \text{"next" } \rightarrow \text{0}].
\]

\( \text{new first: point } G := \text{0} \)

We can add a constant to \( \text{first} \) or subtract a constant from it, for example

\[
\text{first }:=\text{first}+1
\]

and similarly for the “next” field of each record of \( G \). We can join it, for example

\[
\text{first }:=\text{first};\text{0}
\]

But we cannot multiply it, or use it in any other way than as indexes into \( G \), for example

\[
\text{first }:=G@\text{first }\text{“next”}.
\]

\[
G := \text{first }\rightarrow (\text{"name" } \rightarrow \text{“Aaron”} | \text{“next” } \rightarrow \text{first}) | G
\]

With this limited use, the implementation of these indexes can be memory addresses. This way we obtain all the performance benefits of pointers without destroying the logic of our language.

The previous example, with linked list \( G \), does not show the full generality of \( \text{point} \). Here is a tree-structured example.

\[
\text{new tree }=[\text{nil}, [\text{tree}; \text{all}; \text{tree}]].
\]

\( \text{new t: tree }:=\text{[nil]} \)

\( \text{new p: point t }:=\text{nil} \)

To move \( p \) down to the left in the tree we reassign it this way:

\[
p := p; \text{0}
\]

To move it down to the right, reassign it this way:

\[
p := p; \text{2}
\]

Thus \( p \) is a string of indexes indicating a subtree \( t@p \) of \( t \). We can replace this subtree with tree \( s \) using the assignment

\[
t := p \rightarrow s \mid t
\]

We can express the information at the node indicated by \( p \) as

\[
t@p \text{ 1 } \text{or } t@(p; \text{1})
\]

and we can replace the information at this node with the integer \( 6 \) using the assignment

\[
t := (p; 1) \rightarrow \text{6 } \mid t
\]

To move up in the tree, we just remove the final item of \( p \), and to make that easy, the predefined

\[
\text{new back }=\langle p : (* \text{nat}) \rightarrow p_0; (0; \leftrightarrow p - 1) \rangle
\]

allows us to move \( p \) up to its parent by writing

\[
p := \text{back } p
\]

The “procedure”, “method”, or “function” of some other programming languages is a combination of naming, scope, and parameter(s). For example,

\[
\text{new transform } \llbracket \text{plan magnification }:= \text{real} \llbracket \text{plan translation }:= \text{real} \\
\llbracket x := \text{magnification } \times x + \text{translation} \rrbracket \rrbracket
\]

Here is a definition of a plan with one parameter

\[
\text{new translate } \llbracket \text{transform } \text{1} \rrbracket
\]

formed by providing one argument to a two-parameter plan. To provide an argument for just the second parameter is a little more awkward, but not too bad.

\[
\text{new magnify } \llbracket \text{plan magnification }:= \text{real} \llbracket \text{transform magnification } \text{0} \rrbracket \rrbracket
\]

We can now obtain a three-times magnification of \( x \) in either of these ways.

\[
\text{magnify } \text{3} \\
\text{transform } \text{3 } \text{0}
\]

In some other programming languages, the “function” is a combination of naming, scope, parameter(s), and result-data. For example,
new factorial = \langle n: \text{nat} \rightarrow \text{result} f: \text{nat}=1 \ [\text{for } i:=1;..n+1 \ [f:=f\times i]] \rangle

Exception handling is provided by if or \text{elseif} or \text{if} \text{else} \text{if}. For example,
new divide = \langle \text{dividend: com} \rightarrow \langle \text{divisor: com} \rightarrow \\
\text{divisor}=0 \Rightarrow \text{“zero divide”} = \text{dividend}/\text{divisor} \rangle 

Then
\text{divide: com} \rightarrow \text{com} \rightarrow \langle \text{com}, \text{“zero divide”} \rangle

The selective union operator applies its left side to an argument if that argument is in the stated domain of its left side; otherwise it applies its right side. Let us define
new weekday = \langle d: (0,..7) \rightarrow 1\leq d \leq 5 \rangle

Then in the expression
\langle \text{weekday} | \forall \text{all} \rightarrow \text{“domain error”} \rangle

if \ i \ fails to be an integer in the range 0,..7, the left side of if “catches” the exception and “throws” it to the right side, where it is “handled”.

Input choice, as in CSP, can be obtained as follows.

In the persistent scope, ProTem functions as an operating system, where programs are executed as soon as they are entered. Unix directories are dictionaries. Unix files are variables. Unix cp is an assignment. Unix rm is ProTem's \text{old}. Unix mv is a synonym definition followed by \text{old}. The commands [\text{ctrl n}] and [\text{ctrl m}] are the Unix ls and man commands. The effect of Unix pipes is obtained by channel parameters. For example, suppose \text{trim} is a plan to trim off leading and following blanks and tabs from lines of text, and \text{sort} is a plan to sort texts. (Please excuse the informal body since it is not the point.)
new trim [plan in? text [plan out! text [Repeatedly read from \text{in}, trim off leading and trailing space, output to \text{out}, until \text{end} is read and output.]]]
new sort [plan in? text [plan out! text [Repeatedly read from \text{in} until \text{end} is read, and output the sorted texts and \text{end} to \text{out}.]]]

We can feed the output from \text{trim} to the input of \text{sort} by defining a channel for the purpose. If the original input comes from \text{keys}, and the final output goes to \text{screen}, then
new pipe? text! "\text{trim keys pipe. sort pipe screen. old pipe}"

Even better:
new pipe? text! "\text{trim keys pipe || sort pipe screen. old pipe}"

If \text{sort} wants input before it is available from \text{trim}, \text{sort} waits. If \text{trim} sends output before \text{sort} wants it, it is buffered.

Unix mail is ProTem's \text{mail} channel. If you are the creator of the definition of \text{something} in the persistent scope, and you want to send it to \text{someone} for them to make changes, then
\text{mail: “To: someone@address.domain”; definition “something”}
(see predefined \text{definition}). When \text{someone} sends back the changed definition, receive it, delete your old definition, and then redefine it (see predefined \text{exec}) by
\text{mail? text; end. old something. exec mail??(0;..\rightarrow mail??–1)}

An implementation may provide plans for a variety of languages. For example, it may provide a plan named \text{Python}, with one text parameter, whose execution is that of the Python fragment represented by the argument. It may provide \text{asm}, whose execution is that of the assembly-language program represented by the argument.
ProTem considers object orientation to be a programming style, rather than a programming-language style, or collection of language features. Object-oriented programming (as a style of programming) can be done in ProTem. Data structures, and the functions and procedures that access and update them, can be defined together in one dictionary. If many “objects” of the same type are wanted, new dictionaries just like old ones are easily defined using `\` (see the `parsestack` example in Dictionary Definition).

To execute a program stored on someone else's computer, just invoke that remote program using its full address (computername and programname). For efficiency, it might be best to compile that remote program for your own computer and run it locally. Any nonlocal names (variables, channels, and so on) refer to entities on the computer where the program is compiled.

The keyword `else` is redundant; I could have left it out of ProTem, reducing the number of keywords; then every keyword would begin its construct. For keyword `result` I could have reused `new`, and for symbols `??` and `!!` I could have reused `?` and `!`, all without ambiguity. But I think these keywords and symbols are useful redundancy for both error detection and readability. For more redundancy, `new` could be split into 9 keywords `variable`, `constant`, and so on, but I think that redundancy is not useful. Would `value` be a better choice of keyword than `result`?

In a `case`-program, I dislike reusing `||` for separating the cases; I would prefer that `||` be used exclusively for concurrent composition. I would prefer to write a 3-case-program as `case n [P] [Q] [R]` but that would require a third nonterminal in the presentation grammar, and that is too big a price. As it is, I must choose between `.` and `||`, and I chose the latter because `||` looks more like `][`.

I would prefer to use the symbols `↑` and `↓` for maximum and minimum as in `unified algebra`, rather than `∨` and `∧`. But `↑` and `↓` are not the tradition for binary disjunction and conjunction, nor for set union and intersection, and there are no good keyboard substitutes for them.

As a character within a text, a left- or right-double-quote character must be underlined. For example, “Just say “no”.”. As a character within a text, an underlined left- or right-double-quote character must be underlined again. And so on. Thus every character can occur within a text. But we cannot write a self-reproducing text with this convention (I challenge you). For that purpose, we need another convention, such as repeating the left- and right-double-quote characters within a text. For example, ““Just say ““no””.”. Using this convention, here is a self-reproducing text (perform the indexing to see what you get).

```
"""_(0;0;(0;..32);31;31;(1;..31))"""_(0;0;(0;..32);31;31;(1;..31))
```

Sounds and pictures are data structures. This part of ProTem is not yet designed. Perhaps a picture is an element of `[x*y*(0,..z)]` where `x` is the number of pixels in the horizontal direction, `y` is the number of pixels in the vertical direction, and `z` is the number of pixel values. A picture could therefore be expressed in the same way as any other two-dimensional array, and one could refer to the pixel in column 3 and row 4 of picture `p` as `p 3 4`. Perhaps a movie is a string of pictures. The operations on movies would be those of strings, such as substring and join. To help in the creation of movies, one of the pixel values should be transparent, and one of the operations on pictures should be overlaying. Predefined `silence` is a sound, and predefined `sound` is all sounds. Sounds are input on channel `microphone`; pictures are input on channel `camera`. A constant can be defined as a sound or picture. A variable can be assigned to a sound or picture. Sounds and pictures can be included in a data structure, and manipulated using the operators on that data structure. Sounds can be output on channel `speaker`; pictures can be output on channel `screen`. 
I am perfectly well aware that “data” is a Latin word; it is the plural gerund from the verb “dare” which means “to give”, so the data are the givens. The singular is “datum”. But this is an English document, and I have decided to use the word “data” for both singular and plural. I have also decided to say “indexes” rather than “indices”.

**Intentionally Omitted Features**

Each of the following omitted features would be a small syntactic convenience, and would be easy to add to the language. But they would make the language larger, and that is a cost. And they move away from the form needed for verification. So they are not included in ProTem.

**assertion**

\[
\text{assert } x \leq y \quad \text{means} \quad \text{if } -(x \leq y) \quad \text{[! “assert failure”. stop]}\]

**name grouping**

\[
\text{new } x, y : \text{int} := 0 \quad \text{means} \quad \text{new } x \parallel \text{new } y : \text{int} := 0
\]

\[
\text{old } x, y \quad \text{means} \quad x := 0 \parallel y := 0
\]

\[
\langle a, b : \text{nat} \rightarrow a+b \rangle \quad \text{means} \quad \langle a : \text{nat} \rightarrow \langle b : \text{nat} \rightarrow a+b \rangle \rangle
\]

**item assignment**

\[
S_3 := 5 \quad \text{means} \quad S := S \triangleleft 3 \triangleleft 5
\]

\[
L 3 := 5 \quad \text{means} \quad L := 3 \rightarrow 5 \mid L
\]

\[
L 3 4 := 5 \quad \text{means} \quad L := (3; 4) \rightarrow 5 \mid L
\]

**looping constructs**

\[
\text{while } n > 0 \quad [n := n-1] \quad \text{means} \quad \text{while } [n > 0 \quad [n := n-1. \quad \text{while}]]
\]

\[
\text{repeat } [n := n-1] \quad n = 0 \quad \text{means} \quad \text{repeat } [n := n-1. \quad \text{if } -(n=0) \quad [\text{repeat}]]
\]

\[
\text{loop } [n := n-1. \quad \text{if } n=0 \quad [\text{exit 1}]. \quad \text{loop } [m := m-1. \quad \text{if } m=0 \quad [\text{exit 2} \quad \text{else } [\text{exit 1}]]] \quad \text{means} \quad \text{loop } [n := n-1. \quad \text{if } -(n=0) \quad [m := m-1. \quad \text{if } -(m=0) \quad [\text{loop}]]]
\]

**return from program**

\[
\text{if } n=0 \quad [\text{return}]. \quad \text{restOfProgram} \quad \text{means} \quad \text{if } -(n=0) \quad [\text{restOfProgram}]
\]

The assignment \( L := 3 \rightarrow 5 \mid L \) should be compiled the same as \( L 3 := 5 \) would be if it were included in ProTem; the list \( L \) should not be copied. The same for string item assignment. In the loop

\[
\text{while } [n > 0 \quad [n := n-1. \quad \text{while}]]
\]

the last-action (tail recursive) call should be compiled as a branch (jump) instruction, with no stack activity, the same as a while-loop would be if it were included. Omitting string and list item assignment and special looping constructs should not cost execution time.

**Program parameters and arguments**

\[
\text{plan } \text{simplename} \parallel [\text{program} ] \quad \text{plan, parameter is program}
\]

\[
\text{program } \text{program} \parallel \text{plan, program argument}
\]

were considered and rejected due to syntactic and semantic ambiguities.

As a direct counterpart to the Unix cd command, I considered

\[
\text{open } \text{dictionaryname}
\]

\[
\text{close } \text{dictionaryname}
\]

to allow names in that dictionary to be referred to without stating the dictionary. For example, if we have dictionary \( abc \), and within it names \( x \) and \( y \), we refer to these names as \( abcx \) and \( abcy \). By saying

\[
\text{open } abc
\]

we can then refer to them as just \( x \) and \( y \). But the interaction between open and scope is complex, we can already refer to names within predefined, and we can shorten names by synonym
definition, so I left out open and close.

There is no frame construct in ProTem, but \texttt{ctl c} serves a similar purpose.

In some languages there is a module or object construct for the purpose of grouping together related definitions. In ProTem, dictionaries serve that purpose.

In order to allow sharing of variables in the persistent scope, I created an identity type and a scheme of permits to say who can use and change what. The scheme was more flexible than Unix chmod. But with sharing, all mathematical reasoning is invalid; $x = x$ might evaluate to $\bot$. And with sharing, locks are required so that assignments do not interfere with uses, and assignments do not interfere with other assignments. All sharing problems are solved by the use of channels: anyone can email anything to anyone else. So identities and shared variables are intentionally omitted.

On input, do we ever want the correcting pattern without an echo? For a password, we usually want to output some character, like • , for each key press, and program the corrections, rather than using the correcting pattern (see \texttt{Read Password}). If there is a reason anyone wants the correcting pattern without an echo, we can add it, but then we will have to use a symbol, perhaps _, for the correcting pattern. Input with correcting pattern and no echo would be $?_ and input with correcting pattern and echo would be $?! . I believe input with correcting pattern but without echo is rarely wanted, perhaps never wanted, and so it is not worth lengthening the input forms that are frequently wanted.

Two binary operators $\Delta$ (nand) and $\nabla$ (nor) are missing. They are not wanted very often, there are no good keyboard substitutes for them, and they are easily synthesized:

\[
\begin{align*}
  x \Delta y &= -(x \land y) \\
  x \nabla y &= -(x \lor y)
\end{align*}
\]

**Implementation Philosophy**

Ideally, an implementation checks whether the text presented to it represents a program, and issues an error message if it does not. That check should include determining whether every variable assignment is to a value that is included in the type of the variable. That determination is most helpful if it can be made before execution; but if not, it is still helpful if it can be made during an execution attempt.

While not an error, there are also expressions that cannot or should not be evaluated further. That presents an implementation problem, but not a semantic problem. For example,

\[
\begin{align*}
  ! -3 & \text{ prints } -3 \\
  ! 1/0 & \text{ prints } -3
\end{align*}
\]

ProTem does not evaluate the application of the negation operator – to the operand 3 (see \texttt{Number Representation}); it just prints the operator and operand. Similarly

\[
\begin{align*}
  ! 1/0 & \text{ should print } 1/0 \\
  ! \{0; 1\} 2 & \text{ should print } \{0; 1\} 2 \\
  ! \langle r: rat \rightarrow 5 \rangle (1/0) & \text{ should print } 5 \\
  ! 1/0 = 1/0 & \text{ should print } \top \\
  ! \{0; 1\} 2 = \{0; 1\} 2 & \text{ should print } \top
\end{align*}
\]

Due to the difficulty of implementation, it is permissible for an implementation to behave differently.

No programming language has ever been, or will ever be, implemented entirely. Every programming language is infinite; every implementation is finite. There is always a program too big for the implementation. There is a multitude of size limitations: the parse stack might overflow,
dictionary (symbol table) might be too small, the forward branch fixup list might be exceeded, and so on. It would be ugly to define a programming language by listing all the size limitations of programs. And it would be counter-productive because it would exclude implementations that can accommodate larger programs.

Whenever a program exceeds a size limitation, the implementation should not say “Error: limitation exceeded.”, because the program is not in error. The implementation should say “Apology: this implementation is too limited to accommodate your program.”. An “error” message tells a programmer to correct the error; there is no other option. An “apology” message gives the programmer 3 options: change the program to live within the limitation; change the implementation options to increase the limit that was exceeded; take the program to a different implementation.

Natural numbers and integers are usually limited to those that are representable in a specific number of bits, for example, 32 bits. This is a size limitation, just the same as other size limitations. It is more complicated and uglier to define arithmetic within finite limitations than to define the naturals and the integers. And it is counter-productive to do so, because it excludes an implementation with 64-bit arithmetic. As with other implementation limitations, numeric overflow should not get an “error” message; it should get an “apology” message.

Floating-point numbers and arithmetic should never be offered as a language feature. The programmer wants rational or real numbers and arithmetic, but may be willing to accept the floating-point approximation for the sake of efficiency. Floating-point, with a specific number of bits, is an implementation limitation. Any alternative to floating-point that increases the accuracy without taking too much time or space should be welcome.

ProTem is a rich programming system, offering many kinds of data and operators on data, and many ways to structure a computation. Some features may be difficult to implement. And some features may be of little use to most programmers. It may be a wise decision not to implement some features. For example, an implementer might decide that in a variable definition, the type must be one of

\[
\text{int} \ \text{rat} \ \text{bin} \ \text{text} \ \text{everyone} \ [n*\text{type}]
\]

where \(n\) is a natural number and \(\text{type}\) is any of these types just listed. An implementer may decide not to implement concurrent execution. No-one can complain that the complete language is not implemented, since it is impossible to completely implement any language. But ProTem is defined to allow all type expressions that make sense, and to allow concurrency, so the next implementation can accommodate programs that previous implementations could not accommodate.

**Example Programs**

**Portation Simulation**

```protem
new simport ` a program to simulate portation
[  `input: keys
  `output: screen
  `use: ceil m nat nil nl point rat real s sqrt time
  `call: await stop
  `refer: rand

` Distance between control boxes is always 1 m.
` Merges do not overlap, so there is at most 1 corresponding box on the merging portway.
` Each divergence has a left branch and a right branch; there is no straight.
```
Leading to a divergence, boxes record only one square speed.

` start of definitions

new km := 1000×m. new h := 60×60×s. ` kilometer and hour

new maxaccel := 1.5×m/s/s. ` maximum deceleration = −maxaccel
new speedlimit := 60×km/h. ` speed limit is 60 km/h everywhere
new cushion := 1×s. ` reaction time for all porters
new impatience := 10/s. ` acceleration factor
new maxdistance := ceil(speedlimit^2 / (2×maxaccel)). ` max search distance ahead
new numporters := 120.
new numboxes := 7480.
new visualDelayTime := 0.5×s. ` for human viewing

new porter. ` so porter can be referenced before it is defined

new box: [numboxes *(("ahead left", "ahead right", "behind left", "behind right") → point box
| "beside" → point box
| "above" → point porter, numporters
| ("horizontal", "vertical") → nat)] ` box position on screen
:= [numboxes *(("ahead left", "ahead right", "behind left", "behind right") → 0
| "beside" → 0
| "above" → numporters ` indicates no porter above
| ("horizontal", "vertical") → 0)].

new porter: [numporters *(("below" → point box ` what is beneath
| "arrival time" → reals ` arrival time at this box
| "speed" → reals×m/s )] ` current speed
:= [numporters *(("below" → 0
| "arrival time" → 0×s
| "speed" → 0×m/s )].

new draw [plan b := nat [plan c := "grey", "blue", "red" [UNFINISHED]]]. ` end of draw
` draws a box at screen position (box b "horizontal") (box b "vertical") of color c.
` "grey" means no porter present, "blue" means porter present, "red" means crash
` UNFINISHED because graphical output has not yet been designed

` end of definitions, start of initialization

for b := 0..numboxes
[ ! "What box is ahead-left of box ", b; "? ", ?!
  box := (b; "ahead left") → ?b (??; "behind left") → b \ box.
  ! "What box is ahead-right of box ", b; "? ", ?!
  box := (b; "ahead right") → ?b (??; "behind right") → b \ box.
  ! "What box is beside box ", b; "? ", ?!
  box := (b; "beside") → ?? \ box.
  ! "What are the horizontal and vertical coordinates of box ", b; "? ". ?!
  box := (b; "horizontal") → ?? \ box.
  ?!. box := (b; "vertical") → ?? \ box.
draw b "grey"]. ` default color; may be changed below

for p := 0..numporters
[ ! “Porter ”; p; “ is over what box? ”. ?!
  porter:= (p; “below”) -> ?? | porter. box:= (??; “above”) -> p \ box.
draw (??) "blue"].

randInit 123456789. ` initialize a random number generator

` end of initialization, start of simulation

infiniteLoop
[ new iterationStartTime:= time. ` the time of the start of each iteration of the infiniteLoop

new p: point porter:= 0. ` p:= the porter that arrived at its current position first
new t: real:= ∞xs. ` t is a time, initially an infinite time
for q:= 0..numporters [if porter q “arrival time” < t [t:= porter q “arrival time”. p:= q]].
old t.

new b:= porter p “below”. ` the box below porter p
new bb:= box b “beside”. ` the box beside b; if none then bb=b
new boxesToDo: *[point box; natm]:= nil.
  ` queue of boxes to be explored; their distances ahead of porter p
  ` queue is sorted by increasing distance ahead
  ` difference between any two distances in the queue is at most 1

` initialize boxesToDo
if bb = b [boxesToDo:= nil]
else [if box bb “above” = numporters [boxesToDo:= nil]
  else [if porter (box bb “above”)
    “speed” < porter p “speed” [boxesToDo:= nil]
    else [boxesToDo:= [bb; 0\x]].
  ]
boxesToDo:= boxesToDo; [box b “ahead left”; 1\x].
if box b “ahead left” ≠ box b “ahead right” [boxesToDo:= boxesToDo; [box b “ahead right”; 1\x]].
old b. old bb.

new accel: real\x/s/s:= maxaccel. ` acceleration for porter p

` using boxesToDo calculate accel for porter p

nextBox [new b:= (boxesToDo_0) 0. `the box we are looking at
  new d:= (boxesToDo_0) 1. `its distance ahead of porter p
  boxesToDo:= boxesToDo_(1;..→boxesToDo).
  if d≤maxdistance
  [new desiredspeed = `according to porter pa
    \{pa: (point porter, numporters) \}→
    pa=numporters \I speedlimit
    = ( sqrt ( porter pa “speed”^2 + 2\maxaccel\x
        + (maxaccel\cushion)^2 )
        – maxaccel\cushion ) \I speedlimit).
  accel:= ( DesiredSpeed (box b “above”)

∧ desiredspeed (porter (box b “beside”) “above”)
– porter p “speed”
× impatience
∨ –maxaccel ∧ maxaccel.
if box b “above” = numporters = porter (box b “beside”) “above”
" add boxes ahead to queue and continue
boxesToDo := boxesToDo; [box b “ahead left”; d+1×m].
if box b “ahead left” ≠ box b “ahead right”
[bboxesToDo := boxesToDo; [box b “ahead right”; d+1×m]].
nextBox]
else [if ↔boxesToDo > 0 [nextBox]]].
old boxesToDo.

` using accel, move porter p ahead one box
new b: point box := porter p “below”.
box := (b; “porter”) → numporters \ box. draw b “grey”.
randnext.
b := box b (randInt 0 2 = 0 \ “ahead left” \ “ahead right”).
if box b “porter” < numporters [draw b “red”. stop].` crash
porter := (p; “below”) \ b \ porter. box := (b; “above”) \ p \ box. draw b “blue”.
old b.
new speed := sqrt (porter p “speed”^2 + 2×accel×m) ∧ speedlimit.
porter := (p; “arrival time”) → porter p “arrival time” + 2×m/(porter p “speed” + speed)
\ (p; “speed”) → speed
\ porter.

old speed. old accel. old p. `these olds are not really necessary

await (iterationStartTime+visualDelayTime).
infiniteLoop ]]` end of simport

Quote Notation Lengths

` program to compare quote notation lengths with numerator/denominator lengths

`output: screen
`use: bin div even nat odd

new shl = ⟨n: nat → ⟨m: nat → ` shift n left m places; n×2^m
result r: nat := n [for i := 0;..m [r := r×2]]⟩⟩.

new shr = ⟨n: nat → ⟨m: nat → ` shift n right m places; floor (n×2^−m) or div n (2^m)
result r: nat := n [for i := 0;..m [r := div r 2]]⟩⟩.

new gcd = ⟨a: (nat+1) → ⟨b: (nat+1) → ` greatest common divisor of a and b
a=b ⇒ a \ a<b ⇒ gcd a (b−a) \ gcd (a−b) b⟩⟩.

new norm [plan num: nat+1 [plan denom: nat+1 ` normalize num/denom
[new g:= gcd num denom. num:= num/g. denom:= denom/g]]]].
new count: nat := 0. ` number of examples
new qlen: nat := 0. ` total length of quote representations
new rlen: nat := 0. ` total length of numerator/denominator representations

for length := 1;..15
  [for string := 0;..(shl 1 length) ` each string of that length
   [for quote := 0;..length ` each quote position (at least one bit to left of quote)
     [if even (shr string (length–1)) ≠ even (shr string (quote–1)) ` roll-normalized
      [if ` repeat-normalized
        result repeatnorm: bin := ⊤
        [new len: nat := div (length–quote) 2. ` the length of the possibly repeating part
          trythislen [if len>0 ` 1 ≤ len ≤ (length–quote)/2
            [new extract = 〈i: nat → 〈l: nat → ` index i length l shr string i – shl (shr string (i+l) l)〉〉.
            new ex:= extract quote len.
            if ` the negative part is a repetition (twice or more) of ex
              result r: bin := ⊤
              [new i: nat := quote+len. ` i+len ≤ length
                iloop [new ey:= extract i len.
                   if ex=ey [i:= i+len. ` i≤length
                      if i+len ≤ length [iloop]
                      else [r:= ⊥]]]
                else [r:= ⊥]]]]
          else [repeatnorm := ⊥]]]
        else [len := len–1. trythislen]]]]
      else ` the rightmost bit is 1 or it is to the left of quote or point
        odd string ν (quote=0) ν (point=0)
      ] ` convert to numerator/denominator
      if num<0 [num := –num].
      new denom: nat := shl (shl 1 (length–quote) – 1) point.
      norm num denom.
      ` update statistics
      count:= count+1. qlen:= qlen+length.
      rlen:= rlen+1. ` for the sign
      loop [num:= div num 2. rlen:= rlen+1.
        if num>0 [loop]].
      loop [denom:= div denom 2. rlen:= rlen+1.
        if denom>0 [loop]]]
    ]
  ]
]

! “In ”; count; “ examples, quote average length = ”; qlen/count; “, num/denom average length = ”; rlen/count.

old shl. old shr. old gcd. old norm. old count. old qlen. old rlen

Minimum Redundancy Codes

new MRC ` a program to compute minimum redundancy prefix codes (Huffman codes)
` input: keys
` output: screen
` use: back find nat nil nl point text
new tree = [text], [tree; tree]. ` a binary tree with texts at the leaves
new forest: *(nat; tree):= nil. ` the data structure. A string of trees, with a frequency for each tree

inputstart
[!] “Enter a frequency, then a colon, then a message, then a new line, and repeat. ”;
“To end, just enter a new line.”; nl.
readloop
[?].
if ↔?? = 0 ` Just new line was pressed.
[if ↔forest = 0 `We have not had any input yet. We need at least one
[!] “Insufficient input. Try again.”. inputstart]
new c:= find “;” ??.
if c = ↔?? [! “Bad format: no colon. Try again.”. readloop]
new freq:= ??_(0;..c).
if freq = “error” [! “Bad frequency format. Try again.”. readloop]
new message:= ??_ (c;.. ↔??).
` find where the new data goes in forest and put it there.
new i: nat:= 0.
findloop [if i = ↔forest ν (freq ≤ (forest_i)0) ` found where it goes
[forest:= forest_0;..i); [freq; message]]; forest_(i;..↔forest]
else [i:= i+1. findloop]. readloop]]].

` forest is now a nonempty string of pairs, each pair consisting of a frequency and a tree, each
` tree is a single leaf, each leaf is a list-text. They are in non-decreasing frequency order.
` For example: [3; [“a”]]; [4; [“b”]]; [9; [“c”]]; [12; [“d”]]; [15; [“e”]]; [20; [“f”]]

new here: nat:= 0. ` A new tree must be moved to position here or later.
loop [if ↔forest ≥ 2 ` combine the first two trees into a new tree  t
[ new t:= [(forest_0)0 + (forest_1)0; (forest_0)1 ; (forest_1)1]].
` remove those first two trees from the forest
forest:= forest_2;..↔forest).
` put tree  t into its place in the forest
innerloop [if here = ↔forest ν (t 0 < (forest_here)0) ` we have found where it goes
[forest:= forest_0;..here); t,forest_(here;..↔forest). loop]
else [here:= here+1. innerloop]]].

` forest is now a single pair consisting of the total of all frequencies and a code tree.
new t:= forest_1. ` the code tree
` Walk the tree, depth-first, printing leaves and their codes
new p: point t:= nil. ` a path within t starting at the root
new pt: text:= “”. ` same path as p but as a text for printing
loop [if ¬(t p): text ` we are at a leaf
[!] “code:”; pt; “; message:”; ¬(t p); nl]
Read Password

` program to read a password, allowing corrections, displaying blobs
` input: keys
` output: screen
` use: char delete nl text
new password: text:= "".
pswd ["Please enter password followed by return: ".
read [? char.
    if ??=nl [if password="" ["Empty password. Try again."; nl. pswd]
    else [!nl]]]
else [if ??=delete [if password="" [password:= password_(0;..↔password−1). !delete]]
    else [password:= password; ??. ["•"]]
    read]]]

Grammars

LL(1) Grammar

In this grammar, for each nonterminal, every production except possibly the last begins with a
different terminal. Director sets are needed to create the parser, but they are not needed for parsing,
and that is a special case of LL(1) that deserves its own name; perhaps LL(1/2). To parse a program,
the parse stack begins with only the program nonterminal on it, and ends empty with no more input.
A name control program is responsible for classifying names. For efficiency, the productions (except
possibly the last) for each nonterminal should be placed in order of frequency. The following
nonterminals can be eliminated by replacing them with their one production: program sequent data
data6 data5 data4 data3 data1. This leaves the grammar with 31−8 = 23 nonterminals.

program sequent moreprogram
moreprogram . program empty
sequent phrase moresequent
moresequent || sequent empty
phrase new simplename afternewname
old simplename compounder
[ program ]
if data [ program ] elsepart
case data [ sequent ] elsepart
for simplename := data [ program ]
plan simplename parameterkind [ program ] arguments
! data
? inputafterq
simplename aftersimplename
afternewname : data := data
= data
:= data
? data ! data
[ program ]
\ afterbackslash
#1
simplename compounder
empty

afterbackslash
simplename afternewname
\ simplename compounder
empty

compounder
\ simplename compounder
empty

elsepart
else [ program ]
empty

parameterkind
:= data
: data
! data
? data
\n
aftersimplename
[ program ]
compounder aftername

aftername
:= data
! data
? inputafterq
arguments

inputafterq
! echo
data afterpattern

afterpattern
! echo
empty

echo
simplename compounder
empty

arguments
number arguments
∞ arguments
text arguments
⊤ arguments
⊥ arguments
result simplename : data := data [ program ] arguments
{ data } arguments
[ data ] arguments
(data) arguments
〈simplename : data0 → data〉 arguments
simplename compounder arguments
?? arguments
!! arguments
empty

data

data6 moredata

moredata

⊨ data = data6 moredata
empty

data6

data5 moredata6

moredata6

=data5 moredata6
≠ data5 moredata6
< data5 moredata6
> data5 moredata6
≤ data5 moredata6
≥ data5 moredata6
: data5 moredata6
:: data5 moredata6
∈ data5 moredata6
empty

data5

data4 moredata5

moredata5

, data4 moredata5
.. data4 moredata5
l data4 moredata5
← data = data4 moredata5
empty

data4

data3 moredata4

moredata4

+ data3 moredata4
– data3 moredata4
; data3 moredata4
: data3 moredata4
:: data3 moredata4
‘ data3 moredata4
empty

data3

data2 moredata3

moredata3

× data2 moredata3
/ data2 moredata3
∧ data2 moredata3
∨ data2 moredata3
empty
data2

- data2
~ data2
+ data2
□ data2
≠ data2
* data2
e data2
$ data2
↔ data2
data1 moredata2

data1 data0 moredata1

moredata2

* data2 moredata2
_ data2 moredata2
→ data2 moredata2
^ data2 moredata2
^^ data2 moredata2
empty

data0 number
∞
text
⊤
⊥
result

simplename : data := data [ program ]
{ data }
[ data ]
( data )
⟨ simplename : data0 → data ⟩
simplename compounder
??
!!

LR(0) Grammar

The following grammar has no reduce-reduce choices and no shift-reduce choices. It has shift-shift choices. Such a grammar is commonly called LR(0), but it should not be, because a shift action pushes an input symbol onto the parse stack, and therefore a shift action depends on the input symbol. It is a special case of LR(1) that deserves its own name, but not LR(0); perhaps LR(1/2). To parse a program, the parse stack begins empty, and ends with only the program nonterminal on it.
and no more input. A name control program is responsible for classifying names.

\[
\text{program} \quad \text{sequent} \\
\text{program } . \text{sequent}
\]

\[
\text{sequent} \quad \text{phrase} \\
\text{sequent} \parallel \text{phrase}
\]

\[
\text{phrase} \quad \textbf{new} \text{ name } : \text{ data } := \text{ data} \\
\textbf{new} \text{ name } := \text{ data} \\
\textbf{new} \text{ name } = \text{ data} \\
\textbf{new} \text{ name } [ \text{ program } ] \\
\textbf{new} \text{ name } ? \text{ data } ! \text{ data} \\
\textbf{new} \text{ name } \#1 \\
\textbf{new} \text{ name } \backslash \\
\textbf{new} \text{ name } \backslash \backslash \text{ name} \\
\textbf{new} \text{ name } \text{ name } \\
\textbf{new} \text{ name } \\
\textbf{old} \text{ name } \\
\text{ name } := \text{ data} \\
\text{ name } ! \text{ data} \\
! \text{ data} \\
\text{ name } ? \text{ data} \\
? \text{ data} \\
\text{ name } ? \text{ data } ! \text{ name } \\
? \text{ data } ! \text{ name } \\
\text{ name } ? \text{ data } ! \\
? \text{ data } ! \\
\text{ name } ? \text{ ! name} \\
? \text{ ! name} \\
\text{ name } ? ! \\
? ! \\
\text{ simplename } [ \text{ program } ] \\
\textbf{if} \text{ data } [ \text{ program } ] \\
\textbf{if} \text{ data } [ \text{ program } ] \textbf{else} [ \text{ program } ] \\
\textbf{case} \text{ data } [ \text{ sequent } ] \\
\textbf{case} \text{ data } [ \text{ sequent } ] \textbf{else} [ \text{ program } ] \\
\textbf{for} \text{ simplename } := \text{ data } [ \text{ program } ] \\
[ \text{ program } ] \\
\text{plan}
\]

\[
\text{plan} \quad \textbf{plan} \text{ simplename } := \text{ data } [ \text{ program } ] \\
\textbf{plan} \text{ simplename } : \text{ data } [ \text{ program } ] \\
\textbf{plan} \text{ simplename } ? \text{ data } [ \text{ program } ] \\
\textbf{plan} \text{ simplename } ! \text{ data } [ \text{ program } ] \\
\textbf{plan} \text{ simplename } \backslash [ \text{ program } ] \\
\text{plan} \text{ data0} \\
\text{name}
\]

\[
\text{data} \quad \text{data6 } \models \text{ data } \because \text{ data}
\]
data6

data6 = data5
data6 ≠ data5
data6 < data5
data6 > data5
data6 ≤ data5
data6 ≥ data5
data6 : data5
data6 :: data5
data6 ∈ data5
data5

data5 , data4
data5 .. data4
data5 1 data4
data5 ∈ data4.. data4
data4

data4 ; data3
data4 ;.. data3
data4 ;; data3
data4 + data3
data4 – data3
data3

data3 × data2
data3 / data2
data3 ∧ data2
data3 ∨ data2
data2

data2 + data2
– data2
∈ data2
$ data2
↔ data2
# data2
~ data2
□ data2
≠ data2
∗ data2
data1 * data2
data1 → data2
data1 ^ data2
data1 _ data2
data1 ^^ data2
data1
data1
  data1 data0
  data1 @ data0
  data1 %
  data1 & data0
  name ??
  name !!!
  data0

data0
  number
  ∞
  text
  ⊤
  ⊥
  [ data ]
  { data }
  ( data )
  ⟨ simplename : data0 → data ⟩
  result simplename : data := data ⟨ program ⟩
  ??
  !
  name

name
  simplename
  name \ simplename

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The first public mention of ProTem was


Theo Norvell wrote an MSc thesis in 1988 titled “Expressions, Types, and Data Structures in ProTem”. Jim Horning suggested error recovery using the session file. Hugh Redelmeier acted as design consultant and critic in 1990. Brian Parkinson found a bug in the implementation in 1990, and he wrote an MSc thesis in 1991 titled “Automated Theorem Proving in the ProTem Programming Language”. The design of ProTem has been improved since then, and the old implementation is now out-of-date. A new implementation is partly written.