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 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 specification within the block of code. For example,

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

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

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

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. (Python has 35, C has 36, 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 25 nonterminals and an LR(0) grammar with 14 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. I am not completely happy with input patterns. I need to describe and compose picture and sound elements. I need to define touchpad and touchscreen gestures. I may need to define regions of documents and regions of the screen to be clickable links. An implementation of ProTem is partly written in ProTem.
As you read this document the first time, you will encounter language constructs that have not been defined yet. This document has been written to minimize the problem, but due to the highly mutually recursive nature of the language constructs, there is no linear order that completely avoids the problem. (The same was true of the ALGOL-60 report, and every decent programming language document since.) When you encounter a not-yet-explained language construct, understand whatever you can about it, but do not be stopped by it. During the second and subsequent readings of this document, all language constructs fall into place.

This document defines the ProTem language, and also the terminology that describes ProTem programs. For example, a “function” is not a general word to describe any ProTem feature; it specifically describes expressions of the form \langle p: D. B \rangle. A variable is not assigned a value; a variable is assigned to a value. Please use the correct terminology.
Symbols

ProTem has 8 keywords, plus 4 kinds of lexeme, and 71 other symbols; altogether they are:

**case**  **else**  **for**  **if**  **new**  **old**  **plan**  **value**

number  name  comment

"  "  «  »  `  '  ,  ,..  ;  ;;  ;..  .  !  ?  ??  :  ::  :=  =
≠
<  >
≤
≥
#  #1

\  |
∞
&  %
⊤  ⊥

+  –  ×  /  _  →  ↔  ∧  ∨  ^  ^^  @  *  ~
¢  $
∈  ☐
⊲  ⊳
⊨
⫤
(  )  { }  [ ]  〈  〉

Keywords and multicharacter symbols cannot have spaces between the characters.

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 >>
≠ use /= for
≤ use <= for
≥ use >=
– use - for
× use >< for
→ use -> for
↔ use <>
∧ use / \ for
∨ use \ / for
use //
infinity
true
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. Commas and spaces between digits are not allowed. 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 italic and 26 capital italic 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 characters except », not limited to any alphabet, and ends with ». A compound name is composed of two or more simple names joined with backslash \ characters. For examples:

plain simple names:  x  A1  George  refStack
fancy simple names:  «Rick & Margaret»  «x' ≥ x »  «left«center»right»
compound names:  ProTem\grammars\LL1  DCS\«grad recruiting»\«2016-9-8»

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 in the current scope.

oldname: a simple name that is defined in the current scope,
or a compound name that is defined in its dictionary in the current scope.

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

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❤ProTem
**Presentation Grammar**

ProTem will be explained in complete detail in the following sections. In this section, for reference, we present the grammar. There are 35 ways of forming a program. There are a few words of explanation on the right side.

```plaintext
new newname : data := data
new newname := data
define variablename with type and initial value
new newname ( data )
define constantname and evaluate data
new newname [ program ]
define dataname but do not evaluate data
new newname ? data ! data
define programname but do not execute program
new newname #1
define channelname with type and initial value
new newname \ de
define measuring unitname
new newname \ \ dictionaryname
define dictionaryname
new newname oldname
define synonym
new newname forward de
definition of dataname or programname
old oldname
assign variable to value
unde, remove, or hide
variablename := data
channelname ! data to channel send output
channelname ? data ! channelname from channel receive input in this pattern and echo
channelname ? data from channel receive input in this pattern

simplename [ program ]
de
define programname and execute program
programname execute (call) named-program
program . program sequential composition
program || program concurrent composition
if data [ program ]
if-program
if data [ program ] else [ program ]
if-else-program
case data [ program ]
case-program
case data [ program ] else [ program ]
case-else-program
program [ program ]
case separator in a case-program or case-else program
for simplename : data [ program ]
for-program, index is constantname
plan simplename : data [ program ]
plan, parameter is constantname
plan simplename := data [ program ]
plan, parameter is variablename
plan simplename ! data [ program ]
plan, parameter is output channelname
plan simplename ? data [ program ]
plan, parameter is input channelname
plan simplename \ [ program ]
plan, parameter is dictionaryname
plan data
plan, data argument
program variablename
plan, variable argument
program channelname
plan, channel argument
program dictionaryname
plan, dictionary argument
program brackets, scope
[ program ]

There are 60 ways of expressing data. Examples and pronunciations are shown on the right side.
```

number
∞
data & data
percentage x% = x/100
+ data
– data

0 1.2
infinity, the infinite number
complex number x&y = x + iy
plus, identity
minus, negation, not
plus, addition
minus, subtraction
times, multiplication
divided by, division
to the power, exponentiation
scale, scientific notation $x^y = x \times 10^y$
top, true
bottom, false
minimum, conjunction, and, set intersection
maximum, disjunction, or, set union
equals, equation
not equals, differs from, exclusive or
less than, strict implication, strict subset
greater than, strict reverse implication, strict superset
less than or equal to, implication, subset
greater than or equal to, reverse implication, superset
bunch union $(0,2),(2,5) = 0,2,5$
bunch from (including) to (excluding) $0..3 = 0,1,2$
bunch intersection $(0,2,5) \setminus (2,5,9) = 2,5$
bunch inclusion $2,5 \subseteq 0,2,5,9$
reverse bunch inclusion $0,2,5,9 \supseteq 2,5$
bunch size, bunch cardinality $\phi(0,..5) = 5$
set $\{0,2,5\} \{0,..5\}$
contents of a set or list $\sim \{0,2,5\} \{0,..5\}$
set size, set cardinality $\$ \{0,2,5\} = 3$
elements of a set $2,3 \in \{0,2,3,5\}$
power $\#(0,1) = \{null\}, \{0\}, \{1\}, \{0,1\}$
string join $0;2;5$
string from (including) to (excluding) $0;..3 = 0;1;2$
string indexing $(2;3;7;3) \_2 = 7$
string modification $3;4;5 \leftarrow 6 = 3;6;5$
string length $\leftrightarrow (2;3;7;3) = 4$
definite repetition $3^2 = 2;2;2$
indefinite repetition $*2 = \text{nat}^\ast 2$
list $[3;6;5]$\list join $[3;6];[7;4] = [3;6;7;4]$
list length, function size $\#[2;3;7;3] = 4$
list index, function argument, composition $f \ x$
pointer indexing $L\langle i; j \rangle = L \_i \_j$
function, parameter is constantname $\langle n: \text{nat}. \ n+1 \rangle$
function, function space $\text{nat} \rightarrow \text{bin} = \langle n: \text{nat}. \ \text{bin} \rangle$
domain of a list or function $\Box \langle n: \text{nat}. \ n+1 \rangle = \text{nat}$
selective union $2 \rightarrow [3;6;7;4] = [3;6;8;4]$
variable name
constant name
data name and evaluate data
the most recent data read on the channel
test for written but unread data on the channel
unit name, positive finite real number constant
conditional data, if data then data else data
named-data, defines dataname, data brackets
value-data, defines variablename
evaluation 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 ⊤ ⊥ ∞ ( ) [ ] { } ⦅ ⦆ ⦇ ⦈ ⦉ ⦊ ( ) value
1  list index function argument postfix % ? ?? infix _ @ &  left-to-right
2  prefix + – ⋆ $ ↔ # ~ ☐ *  → ^ ^^ right-to-left
3  infix × / ∧ ∨  left-to-right
4  infix + – ; ; ; ; ; ‘  left-to-right
5  infix , , ; ; ; | <=>  right-to-left
6  infix = ≠ < > ≤ ≥ ; : ∈  continuing
7  infix ⊨⫤  right-to-left

Evaluation brackets () can always be used to change the order of evaluation.

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)\&(b=c). Similarly a<b=c≤d means (a<b)\&(b=c)\&(c≤d).

Using ProTem

Following the prompt ⇧, key in a program. As you do so, keywords become bold, plain names become italic, and keyboard substitutes become the proper symbols. A program may stretch over many lines, including nl (new line) characters. You may make changes to a program using the delete (backspace) key and standard cut/copy/paste editing commands. When you are finished, send the end character by pressing [ct]., which is the simultaneous combination of the control key and the period (point) key. Then the program is checked for errors; if there are errors, you are told what the errors are, and invited to correct them; if there are no errors, your program is executed. For example, following the prompt ⇧, you can key in

! 2+2

The ! means output to the screen (see Output and Input). Then send end. Since there are no errors, the program is executed, 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

new temp := 2+2

followed by end, saves the result of the calculation 2+2 under the name temp, perhaps for use in further calculation. As we will see in Program Definition, the program

new myprogram []“2+2=”; temp]

followed by end, defines and saves a program named myprogram. The saved program is not immediately executed. To execute this saved program, key in

myprogram

followed by end. Saved definitions can be edited using the command [ct]e (see Edit).
Data

ProTem's basic data are numbers, characters, and binary values. ProTem's data structures are bunches, sets, strings, and lists. Also, there are functions, named-data, and value-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, and $-\infty$, less than all other numbers, included in the reals.

The one-operand postfix operator % means division by 100; for examples, 99.9%, x% and (x+y)%. There are two one-operand prefix operators + and −. There are nine two-operand infix operators + × / ∧ ∨ & . 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). 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). The complex number $x + iy$ can be written more briefly as $x\&y$. There are predefined function names such as abs, arc, arcacos, arcsin, arctan, ceil, cos, cosh, exp, floor, im, lb, ln, log, mod, randInt, randReal, re, round, sin, sinh, sqrt, tan, and tanh (see Predefined Names). Predefined names can be redefined.

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 character is sometimes useful as a sentinel at the end of a text. Predefined functions suc and pre give the successor and predecessor in the character order; “ ” (space) comes first and end comes last. Predefined functions charnat and natchar map between characters and their (possibly extended ASCII or unicode) numeric encodings. Some key combinations, such as [ctl]a and [ctrl]e, are characters and have numeric encodings.

Binary Values

The two binary values are ⊤ and ⊥. Negation is −, conjunction (minimum) is ∧, disjunction (maximum) is ∨. The infix two-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 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 data expression is a bunch expression, though not all are elementary.

Bunch union is denoted by a comma:

\[ A \cup B \]

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 characters that satisfy \( x \leq y \). Note that \( x \) is included and \( y \) is excluded. For example, \( 0 \ldots 3 \) consists of the first three natural numbers 0, 1, 2, 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 \( \varepsilon A \). For examples, \( \varepsilon(0, 1) = 2 \) and \( \varepsilon \text{null} = 0 \) and \( \varepsilon(a..b) = b-a \). The evaluation brackets \( ( ) \) are 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: \( 2^{\sqrt{2}} = 1.4142, -1.4142 \) approximately
- \text{com} all complex numbers. Examples: \( (-1)^{\sqrt{2}} = i, -i \ 3 \& 4 = 3 + 4i \)
- \text{char} all characters. Examples: “a” “ ” “delete “ ” “nl “ ” “end
- \text{bin} both binary values: \( \top, \bot \)
- \text{text} all texts (character strings). Examples: “abc” “Say “hi”.”
- \text{ord} the ordered type for which \( \wedge, \vee, <, >, \leq, \geq \) are defined
- \text{all} all ProTem data values

In ProTem, all operators whose precedence is before that of bunch union, except \( \varepsilon \) and \( \setminus \), 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 \( \text{nat}^2 \), the natural powers of two \( 2^n \text{nat} \), and many other things.

Sets

A set is formed by enclosing a bunch in set brackets. For examples, \( \{0, 2, 5\}, \{0..100\}, \{\text{null}\}, \{\text{nat}\} \). The inverse of set formation is the content operator ~. For example, ~\{0, 1\} = 0, 1. The size (or cardinality) of a set, traditionally written \( |S| \), is \( SS \) in ProTem. For examples, \$\{0, 1\} = 2, \$\{null\} = 0, and \$\{nat\} = \infty \. The element relation is \( x \in S \). For example, 1, 2 \( \in \{0, 1, 2, 3\} \).
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, $^*(0, 1) = \{\text{null}, \{0\}, \{1\}, \{0, 1\}$. In $^*(0, 1)$, the evaluation brackets ($()$) are needed due to operator precedence.

**Strings**

There is a predefined string name:

```
    nil  the empty string
```

Any number, character, binary value, set, 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  S join T
```

For example,

```
2; 3; 5; 7
```

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

```
x;..y  x to y (same pronunciation as x..y)
```

where $x$ and $y$ are integers or $\infty$ or characters that satisfy $x \leq y$. Again, $x$ is included and $y$ is excluded. For examples, $0;..3 = 0;1;2$ 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 evaluation 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, $3; 5; 9^{<2=>8} = 3; 5; 8$. This operator associates from left to right, so $3; 5; 9^{<2=>8^{<1=>7}} = ((3; 5; 9)^{<2=>8})^{<1=>7} = (3; 5; 8)^{<1=>7} = 3; 7; 8$. And $3; 5; 9^{<2=>8^{<2=>7}} = ((3; 5; 9)^{<2=>8})^{<2=>7} = (3; 5; 8)^{<2=>7} = 3; 7; 7$.

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” ; “” ; “”
```

```
“abcdefghij”_{(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 < 3; 5; 2 < 3; 6
(3; 5)\lor(3; 5; 2) = 3; 5; 2
```

A bunch of items is an item. Join distributes over bunch union, so

```
(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  n copies of S, 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;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, 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 of, 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 (LM)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
\( S_0, \{ S_1, [S_2; S_1]; S_0 \} \)
\( = 10, \{11, [12; 11]; 10\} \)

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

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

The list brackets \([\ ]\) distribute over bunch union. For example,
\[
[0, 1] = [0], [1]
\]
Thus \([10*nat]\) is all lists of length 10 whose items are natural, and \([4*[6*real]]\) is all 4 by 6 arrays of reals.

**Conditional Data**

The 3-operand expression \( x \models y \models z \), pronounced “if \( x \) then \( y \) else \( z \)”, has binary operand \( x \), but \( y \) and \( z \) are of arbitrary type. For example,
\[
y \neq 0 \models x/y \models \text{“nan”}
\]
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. For example,
\[
(a \models b \models c \models d \models e) = (a \models b = (c \models d \models e))
\]
If \( a \) has value \( \top \), then this expression has value \( b \), with no need to evaluate \( c, d \), or \( e \). If \( a \) has value \( \bot \), there is no need to evaluate \( b \).

**Functions**

A function defines a parameter; that is its only job. Let \( p \) (parameter) be any simple name, let \( D \) (domain) be any data expression (but not using \( p \)), and let \( B \) (body) be any data expression (possibly using \( p \) as a constant name for an element of \( D \)). Then \( \langle p; D, B \rangle \) is a function with parameter \( p \), domain \( D \), and body \( B \). For example,
\[
\langle n: 
\text{nat}. \ n+1 \rangle \quad \text{map } n \text{ in } \text{nat} \text{ to } n+1
\]
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**). Consequently, the parameter name can be any simple name, even one that has already been defined in the scope that encloses the function. The \( \Box \) operator gives the domain of a function. For example,
\[
\Box \langle n: 
\text{nat}. \ n+1 \rangle = \text{nat}
\]
The \( \# \) operator gives the size of the function, which is the size of its domain. For examples,
\[
\# \langle n: 0,..10. \ n+1 \rangle = 10
\]
\[
\# \langle n: \text{nat}. \ n+1 \rangle = \infty
\]
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
\[
\langle x: \text{rat}. \ y: \text{rat}. \ (x+y)/2 \rangle
\]
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 \( fxy \) 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 _realtext_ has four parameters. The first three parameters say how to format a number, and the last is the number to be formatted. For example, _realtext_ 4 10 pi = “3.1416^^0”.

We can define a new function

```
new myrealtext (realtext 4 1 10)
```

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

```
myrealtext pi = “3.1416^^0”
```

When the body of a function does not use its parameter, there is a syntax that omits the unused name. For example, $2 \rightarrow 3$ means $\langle n: 2.3 \rangle$ or choose any other parameter name. And $nat \rightarrow bin$ means $\langle n: nat. bin \rangle$ 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, $nat \rightarrow bin$ can be viewed in either of the following two ways: it is a function (with unused and omitted parameter) that maps each natural to $bin$; it is all functions with domain at least $nat$ and range at most $bin$. As an example of the latter view, we have

```
\langle i: int. i<10 \rangle: nat \rightarrow bin
```

If $f$ and $g$ are functions, then

```
f|g
```

“$f$ otherwise $g$”, “the selective union of $f$ and $g$”

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 \Rightarrow fx = g x)
```

The function $\langle f: nat \rightarrow rat. f2 \rangle$ is “higher order”, which means it has a function-valued parameter. It can be applied to any function with domain at least $nat$ and range at most $rat$.

Let $f$ and $g$ be functions such that $\neg(f: \square g)$ ($f$ 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)
(g f) x = g (f x)
```

**Named-Data**

Named-data has the form

```
simplename (| data |
```

Within the data, the simplename stands for the data recursively. The simplename begins its scope at the left data bracket (| and ends its scope at the corresponding right data bracket |) (see _Scope_). Consequently, the name can be any simple name, even one that has already been defined in the scope that encloses the named-data.

For example, here is a bunch of texts (a pattern or grammar).
This bunch includes the text “a+b+a–a” and many more texts. It is equivalent to
(a", "b"); *(("+", "–"); ("a", "b"))

Data is evaluated as needed. The preceding bunch is infinite, but it may appear in a context that does
not require its complete evaluation. For example, the binary expression
“a+b+a–a”; term ("a", "b"); term; term; term; term; term; term; term; term; term

is all binary trees with integer nodes.

Here is a named-data expressing the infinitely long text ∞❤” that is all hearts.

hearts ("❤"; hearts)

A named-data is equal to the data with all occurrences of the name replaced by the named-data. So
hearts ("❤"; hearts)
= "❤"; hearts ("❤"; hearts)
= "❤"; "❤"; hearts ("❤"; hearts)

and so on. Evaluation of hearts ("❤"; hearts) _ 5 gives “❤”.

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

value simplename : data := data [ program ]

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

value sum: rat:= 1
[new term: rat:= 1.
   for i: 1;..15 [term:= term/ i. sum:= sum+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.

All the ways of expressing data can be combined arbitrarily, without restriction. Here we define fun
as a function whose body is a value-data. It expresses the number of times 2 is a factor of n.

new fun {\(n: nat+1.\) value f: 0;..n:= 0
   [new m: 1;..n+1:= n.
      loop [if even m [f:= f+1. m:= m/2. loop]]]}

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

**Quote and Unquote**

The predefined function *quote* takes any data and produces a text representation of the data. Roughly speaking, it quotes its argument. For examples, *quote* 123 = “123”, *quote* ⊤ = “⊤”, *quote* “abc” = ““abc””, *quote* {0, [1; 2]} = “{0,[1;2]}”. The argument is evaluated before quoting; for examples, *quote* (2×3) = “6”, *quote* (0<1) = “⊤”. In a context where x=3, *quote* x = “3” and *quote* (x×4) = “12”. Function *quote* does not provide any control over the format of the resulting text. For real numbers, fine control over the format of the resulting text is provided by the predefined function *realtext*.

The predefined function *unquote* is a kind of inverse of *quote*. It applies to texts; roughly speaking, it unquotes its argument. For examples, *unquote* “123” = 123, *unquote* “⊤” = ⊤, *unquote* ““abc”” = abc, *unquote* “{0, [1; 2]}” = {0, [1; 2]}. The argument is evaluated after unquoting; for examples, *unquote* “2×3” = 6, *unquote* “0<1” = ⊤. In a context where x=3, *unquote* “x” = 3 and *unquote* “x×4” = 12. In a context where x is not defined, *unquote* “x” is not evaluated. If the argument does not represent a ProTem data expression, the function is not evaluated.

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

```plaintext
! 123
```

places a number where a text should be. So *quote* is applied automatically ( ! *quote* 123 ) resulting in a text ( ! “123” ) as required for output to the screen. If *quote* has been redefined (see Scope), the predefined *quote* is used.

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

```plaintext
“123” + 1 = *unquote* “123” + 1 = 123+1 = 124
```

If *unquote* has been redefined (see Scope), the predefined *unquote* is used.

**Scope**

A name is defined in these seven ways: by the keyword *new*, as a named-program, as a named-data, as a function parameter, as a plan parameter, as a for-index, or as a value-variable; we have already met function parameters and named-data and value-variables; we shall meet the others shortly. The scope of a name is the part of a program in which the name is defined. The scope of a name is limited by program brackets ⟦ ⟧, except that the scope of a function's parameter is limited by function brackets ⟨ ⟩, and the scope of the dataname of a named-data is limited by data brackets ⟨ ⟩.

A 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 \( \langle \rangle \) or \( (\mid ) \).

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.

A scope can be nested inside another scope, which can be nested inside another, and so on. Outside all scope limiters, \[ \] and \( \langle \rangle \) and \( (\mid ) \), is the persistent scope. A name defined by new in the persistent scope is called a persistent name. Persistent names serve as “files”. When you define a new name in the persistent scope, the name must differ from all names already in the persistent scope. 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. In the persistent scope, there is a dictionary named predefined that contains the predefined names.

Names must be defined before they are used (except for a Forward Definition). Whenever a name is used, it is looked up as follows: first, look in the most local scope (innermost \[ \] or \( \langle \rangle \) or \( (\mid ) \)); 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; finally, look in the predefined dictionary. The first occurrence found is the one that is used.

**Programs**

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

**Variable Definition**

Variable definition has the form

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

The name becomes a variable name. Here is an example variable definition.

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

This defines \( x \) to be a variable assignable to any element in 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. ProTem allows the type and initial value to be “static” (known at compile time), as in the first example (variable $x$), and it allows the type and initial value to be “dynamic” (not known until execution time), as in the second example (variable $y$).

Here are five more examples.

```plaintext
new s: 10*int:= 10*0
new t: text:= ""
new u: (0..20)*char:= “abcde”
new L: [*nat]:= [0;..10]
new A: [3*[3*bin]]:= [3*[3*⊤]]
```

In the first example, $s$ is defined as a variable that can be assigned to any string of ten integers, and is initially assigned to the string of ten zeroes. In the second example, $text$ is a predefined bunch equal to $*char$, so $t$ can be assigned to any text, and is initially assigned to the empty text. In the next 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 “abcde”. In the next example, $L$ is defined as a variable that can be assigned to any list of naturals, and is initially assigned to the first ten naturals. In the last example, $A$ is defined as a variable that can be assigned to a $3×3$ array of binary values, and is initially assigned to a $3×3$ array of $⊤$.

**Assignment**

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

```plaintext
variblename := data
```

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

```plaintext
x:= x+1 \quad \text{`now } x = 6
s:= s+2=8 \quad \text{`now } s = 0; 0; 8; 0; 0; 0; 0; 0; 0
u:= u_(0;..3) \quad \text{`now } u = “abc”
L:= 3→5 | 5→7 | L \quad \text{`now } L = [0; 0; 5; 0; 7; 0; 0; 0; 0]
A:= (1; 2)→⊥ | A \quad \text{`now } A = [[⊤; ⊤; ⊤]; [⊤; ⊤; ⊥]; [⊤; ⊤; ⊤]]
```

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

```plaintext
new newname := 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.

```plaintext
new size:= 10.
new piBy2:= pi / 2.
new range:= 0..size
```

where $pi$ is a predefined constant name.

A constant may use variables to express its value. For example

```plaintext
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,
\[\text{new } x: \text{nat} := 3. \quad \text{` } x \text{ has value } 3\]
\[\text{new } xplus1 := x + 1. \quad \text{` } x \text{ has value } 3 \text{ and } xplus1 \text{ has value } 4\]
\[x := 5 \quad \text{` } x \text{ has value } 5 \text{ and } xplus1 \text{ has value } 4\]

**Data Definition**

Data definition has the form
\[\text{new } \text{name} \{ \text{data} \}\]
The new name becomes a dataname. Data definition gives the data a name, but does not evaluate the data.
\[\text{new } xplus2 \{ x + 2 \}\]
makes the value of \(xplus2\) depend on the value of variable \(x\). As \(x\) changes value, \(xplus2 = x + 2\) 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.

\[\text{new } x: \text{nat} := 3. \quad \text{` } x \text{ assigns } 3\]
\[\text{new } xplus2 \{ x + 2 \}. \quad \text{` assigns } x \text{ to } 5\]
\[x := xplus2 \quad \text{` assigns } x \text{ to } 7\]

A data definition can depend indirectly on a variable. For example,
\[\text{new } twoxplus4 \{ 2 \times xplus2 \}\]
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.
\[\text{new } bad: 0..2 \times bad := bad \quad \text{` illegal}\]
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 example defines \(\text{div}\) to be the integer division function for natural numbers.
\[\text{new } \text{div} \{ \langle a: \text{nat}. \langle d: \text{nat} + 1. \quad a < d \models 0 = \text{even } a \models 2 \times \text{div } (a/2) \quad d \models 1 + \text{div } (a-d) \quad d \rangle \rangle\}\]

Here is a function that eats arguments until it is fed argument 0.
\[\text{new } \text{eat} \{ \langle n: \text{nat}. \quad n=0 \models 0 = \text{eat} \rangle \rangle\]
So \(\text{eat } 5 \ 2 \ 0 = 0\), and \(\text{eat } 4 \ 7 \ 3 \ 8 \ 0 = 0\), and \(\text{eat } 1 \ 2 = \text{eat}\) and \(\text{eat}: \text{nat} \rightarrow (0, \text{eat})\).

Here is a baseless recursion. If it is evaluated, its evaluation is nonterminating.
\[\text{new } \text{rec} \{ \text{rec} \}\]

**Named-Data versus Data Definition**

Since we have data definition, named-data is unnecessary. For example,
\[\text{new } t: \text{tree} \{ [\text{text}], [\text{tree}; \text{tree}] \} := [\text{“abc”}]\]
defines \(t\) to be a tree-valued variable (binary tree, text at the leaves). This example is almost
equivalent to
\[
\text{\texttt{new new tree t: tree:= ["abc"]}}.
\]
The difference occurs when \texttt{tree} has already been defined in the current scope; in that case, the named-data is still all right, but the data definition is not.

In the next example, variable \texttt{g} is assigned to the greatest common divisor of 10 and 15.
\[
g := \text{gcd} \langle \begin{array}{l} a: \text{nat} +1. \\ b: \text{nat} +1. \\ a=b \Rightarrow a = a < b \Rightarrow \text{gcd} a (b-a) \Rightarrow \text{gcd} (a-b) b \end{array} \rangle 10 15
\]
This example is exactly equivalent to
\[
\langle \begin{array}{l} \text{new gcd} \langle \begin{array}{l} a: \text{nat} +1. \\ b: \text{nat} +1. \\ a=b \Rightarrow a = a < b \Rightarrow \text{gcd} a (b-a) \Rightarrow \text{gcd} (a-b) b \end{array} \rangle \rangle \text{10 15}
\]
Named-data is a succinct way of recursively defining some data (in this example, the \texttt{gcd} function), and using the data once, immediately (in this example, the assignment of \texttt{g}). However, if you need to use the data (call \texttt{gcd}) more than once, you must make a data definition.

**Constant Definition 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:
\[
\begin{align*}
\text{\texttt{new five:=5}} \\
\text{\texttt{new five \{5\}}}
\end{align*}
\]
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.
\[
\begin{align*}
\text{\texttt{new six:=5+1}} \\
\text{\texttt{new six \{5+1\}}}
\end{align*}
\]
If the value of \texttt{six} is never required, the data definition \{\} is more efficient. If the value of \texttt{six} is required once, they are equally efficient. If the value of \texttt{six} is required two or more times, the constant definition := is more efficient. Here is a more interesting comparison.
\[
\begin{align*}
\text{\texttt{new double:=\{n: 0,..10. 2\times n\}}} \\
\text{\texttt{new double \{\{n: 0,..10. 2\times n\}\}}}
\end{align*}
\]
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 \texttt{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 \texttt{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.

**Output and Input**

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

Output has the form
\[
\text{\texttt{channelname ! data}}
\]
Channel \texttt{screen} accepts text, which is displayed on the screen. The program
\[
\text{\texttt{screen! "Hi there."}}
\]
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 the `delete` (backspace) character is output to the `screen` or `printer`, the previous character is deleted. If there are more `delete` characters than previous characters, the extra `delete` characters are ignored. When the `tab` character is output, some amount of space is substituted. When the `nl` character is output, further characters start on a new line.

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

```
mail! “To: hehner@cs.utoronto.ca”; nl;
“Hey Rick, have a look at the exec program: ”; nl;
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”. The `ctl .` combination is the single character `end`. The click button is just a key like any other; `click` is a character, and `doubleclick` is a character. Keyboard output is available as input on channel `keys`.

Input has two forms: with echo, and without echo. The form with echo is `channelname ? data ! channelname`

Five characters of input are received from channel `keys` and echoed to channel `screen` by saying `keys? 5*char !screen`

The first channelname is the input channel. The input read is the earliest input on that channel that has not yet been read. If input is not yet available, it is awaited. What comes between `?` and `!` is called the pattern. What follows `!` is the output channel for the echo.

The space, tab, and new line characters may be part of the input; they are just characters like any others. When execution asks for input from `keys`, you can use delete and cut/copy/paste to change what you have entered. The echo shows each character as it is entered, and each deletion and edit as it is made. When you are satisfied with the input, press `[ctl .]` to send the `end` character indicating that the input is in final form. The `end` character is not part of the input, but it may be part of the pattern. For example,

```
keys? text; end !screen
```

reads text until `end` is sent. The text is the input; `end` is not input.

The shortest input that fits the pattern is read. The program `keys? text; nl !screen`

reads text up to and including the first `nl` character, but `keys? text !screen`

just inputs the empty text. If the available input is shorter than the pattern, execution awaits further input. If the available input is longer than the pattern, the remaining input is future input.

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 by spaces, ending in a space or comma or new line or \texttt{end}, input
\begin{verbatim}
keys? *" "; numpat; (" ", ",", nl, end) !screen
\end{verbatim}
If (" ", ",", nl, end) were omitted, only leading spaces and an optional sign and the first digit would be read; subsequent digits, a point, and more digits would not be read.

When input is received, it is referred to by the channel name followed by \? . For example, after the input
\begin{verbatim}
keys? *digit; end !screen
\end{verbatim}
the digits can be referred to as \texttt{keys?} . Then we might have the assignment
\begin{verbatim}
x := unquote (keys?) + unquote (keys?)
\end{verbatim}
where \texttt{unquote} is a predefined function that converts from a text to the type required. Function \texttt{unquote} can be omitted (see \texttt{Quote and Unquote}), so we may write
\begin{verbatim}
x := keys? + keys?
\end{verbatim}
Both occurrences of \texttt{keys?} refer to the same input, and \texttt{keys?} continues to refer to the same input until the next time new input is read from channel \texttt{keys}.

If \texttt{c} is the name of an input channel, then \texttt{c??} is a binary expression with value \texttt{T} if there is written but unread data on the channel, and \texttt{\bot} if there is not. For example,
\begin{verbatim}
if keys?? [keys? char !screen] else [screen! “Are you still there?”]
\end{verbatim}
(See \texttt{if-Program}.) If \texttt{doc} is a text channel that reads from a document, \texttt{doc??} tells whether there is more to be read. 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 \texttt{c} is a channel to input text and \texttt{d} is a channel to output text, the program
\begin{verbatim}
c? “y”, “n” !d
\end{verbatim}
inputs one character, either “y” or “n”, from channel \texttt{c}, and echoes it to channel \texttt{d}. If the first available character on channel \texttt{c} is “a”, or more generally, if the input on the channel does not fit the pattern, what happens is not defined. Here are three options.
\begin{itemize}
\item The program cannot be executed, so execution ends.
\item An error message is sent to channel \texttt{d} to say that the input is unacceptable, and execution ends.
\item An error message is sent to channel \texttt{d} to say that the input is unacceptable, and the sender is given another opportunity to send an input that fits the pattern.
\end{itemize}
What happens depends on the implementation, on the channel, and on the number of attempts. Perhaps the last option is appropriate for channel \texttt{keys}, and the first is appropriate for a secure channel. Of course, you can read a character \texttt{c? char !d} and program what happens if it is neither “y” nor “n”.

The form of input without echo is
\begin{verbatim}
channelname ? data
\end{verbatim}
From the channel, data is read according to the pattern. But this data is not corrected by deletions and editing, and not terminated by \texttt{end}; instead, \texttt{delete} and \texttt{click} and \texttt{end} are just characters like any others. And the input is not echoed. This is useful, for example, when reading a password (see \texttt{Read Password}). It is useful for programming the deletions and editing and end-of-input that take place during program input and data input with echo. The two programs
\begin{verbatim}
in?pattern!out
in?pattern. out!in?
\end{verbatim}
differ. The first allows input editing, and is terminated by \texttt{end}, which is not included in \texttt{in?} . The second treats \texttt{delete} and \texttt{click} and \texttt{end} as ordinary characters being read.
An output channel name can be omitted, in which case the output channel is `screen`. For example, `! “Hello World”` prints `Hello World` on channel `screen`. And `! 2+2` prints `4` on channel `screen`. Thus ProTem can be used as a calculator. This program is short for `screen! quote (2+2)`.

An input channel name can be omitted, in which case the input channel is `keys`. For example, `? char!` reads one character from `keys` (possibly corrected, terminated by `end`), with echo to `screen`. The most recent text read on channel `keys` can be referred to as just `?`. And `??` is a binary expression saying whether there is written but unread data on channel `keys`. If the input channel is omitted, and the name `keys` has been redefined, the input channel is the predefined channel `keys`. If the output channel is omitted, and the name `screen` has been redefined, the output channel is the predefined channel `screen`.

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 implementation will complain that `unquote` is not a channel. Similarly for `quote (keys??)`. When `keys?` is shortened to `?` and used as an argument to a function or plan, it must be in evaluation brackets `(?). When `keys??` is shortened to `??` and used as an argument to a function or plan, it must be in evaluation brackets `(??)`.

In input with echo, the pattern can be omitted, in which case the pattern is `text; end`. The most common input program `?!` is short for `keys? text; end !screen` and means: from channel `keys`, read text, corrected by any deletions and editing, until the `end` character `ctl` is received. The value of `keys?` is the text read, not including `end`. The input is echoed, each character, each deletion, each editing change, on channel `screen`.

In summary, output and input are, respectively,
- `outchannel ! data`
- `inchannel ? pattern ! echochannel`

Input is correctable by deletion and editing until `end` is received. The input most recently read is referred to as `inchannel`.

The binary expression `inchannel ??` says whether there is written but unread data on the channel. If the channel name is `keys` or `screen` it can be omitted. If the pattern is `text; end`, it can be omitted. The input `inchannel ? pattern` reads data according to the pattern, including such characters as `delete`, `click`, and `end`, with no corrections and no echo.

**Sequential Composition**

Sequential composition is denoted by a period (point, dot).

`program . program`

It is an infix connective; in other words, the period comes between and joins programs.
Concurrent Composition

Concurrent composition has the form
\[ \text{program} \parallel \text{program} \]
The concurrent composition of programs \( P, Q, \) and \( R \) is \( P \parallel Q \parallel R \). A variable defined before the concurrent composition remains a variable in at most one component of the concurrent composition; in all the other components of the concurrent composition, it becomes a constant.

\[
\text{new } a : \text{nat} := 1 \parallel \text{new } b : \text{nat} := 2. \text{new } c : (a+b). \[ a := 4. A \] \parallel \[ b := 8. B \]. C
\]
In the concurrent composition \( [a := 4. A] \parallel [b := 8. B] \), variable \( a \) can be reassigned in one of the concurrent programs, but not in both. Likewise variable \( b \) can be reassigned in one of the concurrent programs, but not in both. 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.

\[
\text{new } a : \text{nat} := 1 \parallel a := 2 \quad \text{"illegal"}
\]
is not allowed because the use of \( a \) does not sequentially follow its definition. Concurrent programs cannot affect each other through assignments of variables. For co-operation, programs can communicate with each other on channels (see Channel Definition). A channel can be used for output in only one component of a concurrent composition. It can be used for input in all components, reading the same inputs independently.

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 \( [A. B] \parallel [C. D] \) because concurrent composition has precedence over sequential composition.

In summary: A name defined in one part of a concurrent composition cannot be used in the other parts, but it can be used in a sequentially following program. A variable defined before a concurrent composition remains a variable in at most one part of the composition, and is a constant in the other parts. A channel defined before a concurrent composition can be used for output in at most one part of the composition, and can be used for input in all parts.

if-Program

An if-program has the form
\[
\text{if } \text{data } \parallel \text{program }
\]
The if-program
\[
\text{if } b \parallel [P]
\]
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
\[
\text{if } \text{data } \parallel \text{program } \text{else } \parallel \text{program }
\]
The if-else-program
\[
\text{if } b \parallel [P] \text{ else } [Q]
\]
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. The program \( \text{if } b \parallel [P] \) is equivalent to \( \text{if } b \parallel [P] \text{ else } [\text{ok}] \) where \( \text{ok} \) is a predefined program whose execution does nothing and takes no time.
case-Program

A case-program has the form

```
  case data [] program []
```

in which the program is a sequence of cases. For example, in a case-program with three cases,

```
  case n [P] [Q] [R]
```

the programs, called cases, are numbered in order. Case 0 is [P], case 1 is [Q], and case 2 is [R]. It is executed as follows: natural expression n is evaluated; then one of the programs is executed. 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 equivalent to

```
  if n=0 [P] else if n=1 [Q] else if n=2 [R] else ["""Warning: case index too large."""]
```

Here is another example, also with three cases:

```
  case 2–n [ok] `case 0: all is well, nothing to do
  ["""Warning: don't do it again"]` case 1: warning
  ["""You're fired"]` case 2: firing
```

As the example illustrates, it is helpful to put a comment with each case to say the case index.

for-Program

A for-program has the form

```
  for simplename : data [] program []
```

The simplename becomes a constantname in the program. Here is a nest of for-programs that computes the transitive closure of array A: [n*[n*bin]]

```
  for j: 0;..n [for i: 0;..n [for k: 0;..n [if A i j ∧ A j k [A:= (i;k) → ⊤ | A]]]]
```

The if-program if A i j ∧ A j k [A:= (i;k) → ⊤ | A] can be restated as

```
  A:= (i;k) → (A i k v (A i j ∧ A j k)) | A
```

if you prefer. The name being defined by for is called a for-index. It is known only within the for-program, and it is known there as a constant, and so it is not assignable. In the example, each of the for-indexes j, i, and k takes values 0, 1, 2, and so on up to but excluding n.

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

```
  new n:= 1000. new prime: n*bin:= 2 *⊥; (n–2)*⊥.
  for i: 2;..ceil (sqrt n) [if prime i [for j: i;..ceil (n/i) [prime:= prime <i*j> ∨ A]]]]
```

A for-index is “by initial value”, so this example increases x by 1, not 2.

```
  for i: x; x [x:= i+1]
```

This next example prints the natural numbers forever.

```
  for n: 0;..∞ [""" n; ""]
```
After the `:` we can have any string expression; the `for`-index stands for each item in the string, in sequence. We can also have any bunch expression; the `for`-index stands for each element of the bunch, concurrently. As an example (note the use of ``, rather than `;` as earlier),

```
for i: 0..#L [L := i → 0 | L]
```

makes the items of `L` be `0`, concurrently. We could also write either of these:

```
for i: ☐ L [L := i → 0 | L]
```

```
L := [#L*0]
```

The domain of the `for`-index can also be a bunch of strings, or a string of 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

```
new [ program ]
```

The `new` name becomes a programname within the program. Program definition gives a program a name, but does not execute the program. For example,

```
new switchends [L := 0 → L 9 | 9 → L 0 | L]
```

Execution of this definition defines the program name `switchends` , but does not execute program `[L := 0 → L 9 | 9 → L 0 | L]` . 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,

```
new « x' > x » [x := x+1]
```

The specification `« x' > x »` means the final value of `x` is greater than its initial value. It 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,

```
new « x' = 0 » [if x ≠ 0 [x := x-1. « x' = 0 » ]]
```

In the program `[if x ≠ 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. Although the name is situated before a `[`, it begins its scope after `[` and ends its scope at the closing `]` . 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, \( A: [n^*[m*int]] \)).

\[
\begin{align*}
\text{new } i: \text{nat} &:= 0. \\
\text{tryThisI } \{\text{if } i=n [! x; "\text{ does not occur."}]
\text{else } \{\text{new } j: \text{nat} := 0. \\
\text{tryThisI } \{\text{if } j=m [i:= i+1. \text{tryThisI}]
\text{else } \{\text{if } A \text{ } i \text{ } j = x [! x; "\text{ occurs at "}; i; "\”; j]
\text{else } \{j:= j+1. \text{tryThisI}]}]}]
\end{align*}
\]

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.

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

\( N \{P\} \) is equivalent to \( \{P\} \) with occurrences of \( N \) replaced by \( N \{P\} \). So the fast remainder example means the same as

\[
\begin{align*}
r := a. \\
\text{if } r \geq d [\text{new } dd: \text{nat} := d. \\
\text{if } r < dd \text{ [outerloop] else [innerloop]}]
\end{align*}
\]

This process can be repeated. Although semantically there 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.

\[
\begin{align*}
\text{Fib } \{\text{if } n=0 [x:= 0. \text{ y}:= 1]
\text{else } \{\text{if } \text{odd } n [n:= (n-1)/2. \text{ Fib. } n:= x. \text{ x}:= x^2 + y^2. \text{ y}:= 2 \times n \times y + y^2]
\text{else } [n:= n/2 - 1. \text{ Fib. } n:= x. \text{ x}:= 2 \times x \times y + y^2. \text{ y}:= n^2 + y^2 + x]}]]
\end{align*}
\]

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

\[
\langle x' > x \rangle \{x := x+1\}
\]

The specification \( \langle x' > x \rangle \) is implemented (refined, implied) by the program \( \{x := x+1\} \). A prover is invoked by the [verify] 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,

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

Inside the program brackets, 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. (See Specified Blocks.)

Suppose a name is defined within a loop. For example, the name \( a \) in
\[
infiniteLoop \ [ \text{new } a:: \text{"a"}. \ !a. \ infiniteLoop \]
\]
Executing this loop prints an infinite sequence of the letter “a”. Replacing the call with the named-program, it is equivalent to
\[
[ \text{new } a:: \text{"a"}. \ !a. \ infiniteLoop \ ]
\]
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 \( name \) be a new name (not defined in the local scope), and let \( program \) be a program, possibly using the name \( name \). Then the following three lines are equivalent to each other.
\[
\begin{align*}
& \ [ \text{new } name \ [ \text{program} \] . \ name] \\
& \ [ \text{new } name \ [ \text{program} \] , \ name\ , \ old \ name]
\end{align*}
\]
Therefore named programs are unnecessary. For example
\[
loop \ [ \text{if } n > 0 \ [ n:: n-1. \ loop ]]
\]
is equivalent to
\[
[ \text{new } loop \ [ \text{if } n > 0 \ [ n:: n-1. \ loop ]], \ loop]
\]
A named-program is a succinct way of recursively defining a program, and using the program once. However, if you need to use (call) a program more than once, you must make a program definition.

**Plan**

A plan is a program with a parameter. There are five forms of plan. The first is
\[
\text{plan } \text{simplename : data} \ [ \text{program} ]
\]
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,
\[
\text{plan } y: \text{real} \ [ x:: xy ]
\]
A plan can be argumented by adjacency in the same way that lists are indexed and functions are argumented. The argument provides a value for the parameter. For example,
\[
\text{plan } y: \text{real} \ [ x:: xxy ] \ 3
\]
is the same as
\[
x:: xx3
\]
Commonly, a plan is named
\[
\text{new } P \ [ \text{plan } y: \text{real} \ [ x:: xxy ]]
\]
and then argumented \( P \ 3 \), but a plan is not required to have a name.

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
A plan can be named (in a program definition or named-program); a plan can be argumented; and a plan can be the body of a plan. A plan that is not fully argumented cannot be executed. A plan that has been fully argumented can be used wherever any program can be used. For examples,

\begin{verbatim}
plan x: int [plan y: int [z:= x+y ]] z:= 2 \text{ `this is not allowed}
plan x: int [plan y: int [z:= x+y ]] 3. z:= 2 \text{ `this is not allowed}
plan x: int [plan y: int [z:= x+y ]] 3 4. z:= 2 \text{ `this is allowed}
\end{verbatim}

Here is a named-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 \texttt{findmax \( i \) \( j \)} to find the maximum in the segment of \( L \) from (including) index \( i \) to (excluding) index \( j \), reporting the result as \( L \( i \), and then apply it to \( 0 \) (#L), which makes \( L \) 0 the maximum value of the initial list.

\begin{verbatim}
findmax [plan \( i: \square L \) [plan \( j: \square L+1 \)
\texttt{if} \( j−i\geq 2 \) [\texttt{findmax} \( i \) (\texttt{div} (\texttt{i+j} 2)) \| \texttt{findmax} (\texttt{div} (\texttt{i+j} 2)) \texttt{j}.
\texttt{L:= i \rightarrow L \ i \ ν \ L \ (\texttt{div} (\texttt{i+j} 2) \ | \ L)) \]} 0 (#L)
\end{verbatim}

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

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

assigns both \( x \) and \( y \) to the same value, one more than \( x \)’s initial value.

The second form of plan

\begin{verbatim}
plan \( \texttt{simplename := data [ program ]}
\end{verbatim}

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

\begin{verbatim}
plan x:= int [x:= 3]
\end{verbatim}

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 \( x \) (the argument) is nonlocal, and is not the local variable \( x \) (the parameter) appearing in the plan. But the plan

\begin{verbatim}
plan x:= int [x:= 3 \| y:= 4]
\end{verbatim}

cannot be applied to variable \( y \).

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

\begin{verbatim}
new \texttt{norm [plan num:= nat+1 [plan denom:= nat+1 \ ` normalize num/denom
\texttt{[new g:= gcd (a: nat+1. \ b: nat+1. ` greatest common divisor of \ a \ and \ b
a=b \ 至此 a \ a \ b \ 依\ gcd a (b\( a) \ 依\ gcd (a\−b) b)\]} \num denom.
\texttt{num:= num/g. \ denom:= denom/g]]]]}
\end{verbatim}

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

The next form of plan

\begin{verbatim}
plan \( \texttt{simplename} ! \texttt{data [ program ]}
\end{verbatim}

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

\begin{verbatim}
plan c! text [c! "abc"
\end{verbatim}

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 that receives text, even one named \( c \), because that \( c \) (the argument) is nonlocal, and is not the local channel \( c \) (the parameter) appearing in the plan. But
plan c! text [c! “abc” || d! “def”]
cannot be applied to channel d. The channel name screen cannot be omitted when used as an argument for an output channel parameter.

The next form of plan

plan simplename ? data [ program ]
creates a plan with an input channel parameter. For example.

plan c? text [c? 3*char !d]

This plan applies to an input channel that delivers text, but not to a channel appearing in the plan.

plan c? text [c?!d || d?!c]
cannot be applied to channel d. The channel name keys cannot be omitted when used as an argument for an input channel parameter.

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

new pps [plan a? rat [plan b? rat [plan c! rat
  [a? rat || b? rat. c! a?xb?.
      new a0:= a? || new b0:= b? || new d? rat !nil. `see Channel Definition
  pps a b d
  || [a? rat || b? rat. c! a0xb?+a?xb0.
      loop [a? rat || b? rat || d? rat. c! a0xb?+d?+a?xb0. loop]]]]]]]

The final form of plan

plan simplename \ [ program ]
creates a plan with a dictionary parameter. This plan can be applied to any dictionaryname that does not appear in the plan.

Dictionary Definition

Dictionaries are the way you organize your programs and data. There are two forms of dictionary definition. The first form is

new newname \ 
The newname becomes a dictionaryname. To create a new dictionary named abc, write

ew abc\ 
The newly created dictionary is empty. Now you can define names within this dictionary. For example,

new abc\x:= 2
defines x in dictionary abc to be the constant 2. This constant can then be used as abc\x. (It does not matter whether there are spaces before or after a backslash.) A name being defined in a dictionary must not already be defined in that dictionary in the current scope. If the current scope is a local scope, the name becomes undefined at the end of the scope, as usual. Each name in a dictionary is defined, using the keyword 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. 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\grammars\LL1.
A name within a dictionary can be undefined by `old` in the same scope where it was defined (see Name Removal). For example,

```
old abc
```
ends the definition of `x` in dictionary `abc`. In the scope where `abc` was defined,

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

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 \\ dictionaryname
```

We can create a dictionary named `parseStack` populated with the same definitions as `stack`.

```
new parseStack
```

It is equivalent to writing

```
new parseStack.
  new parseStack\$: *nat:= nil.
  new parseStack\$push [plan x: nat [parseStack\$:= parseStack\$; x]].
  new parseStack\$pop [parseStack\$:= parseStack\$\$(0;..;parseStack\$–1)].
  new parseStack\$top [parseStack\$(0;..;parseStack\$–1)].
old parseStack\$
```

Here is a recursive dictionary definition that is probably useless.

```
new d. new d\$c:= 2. new d\$d
```

Within `d` there is a dictionary named `d` with the same two definitions as in the outer `d`. Now `d\$c`, `d\$d\$c`, `d\$d\$c\$d`, `d\$d\$d\$d\$c`, and so on, are all the constant `2`.

There is a dictionary in the persistent scope 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×m/s for the speed 10 meters per second. And we can define

```
new km:= 1000×m
```
to make `km` be a kilometer, and

```
new h:= 60×60×s
```
to make `h` be an hour. So 1×m/s = 3.6×km/h evaluates to `T`. To assign a variable to a quantity with units attached, the variable's type must have compatible units attached. For example,

```
new speed: real×m/s:= 3.6×km/h
```

assigns `speed` to 1×m/s (which could be written `m/s×1` or `m×1/s` or `1/s×m` or just `m/s`). When the value 5×m/s is converted to text by `quote`, the result is “5 m/s” without the × sign and
without evaluating the unknown real value \( m/s \). And unquote “5 \( m/s \) = 5\( m/s \). Similarly for all units of measurement. One more example: quote (2\( \times \)3\( \times \)km/h) = “1.6667 \( m/s \).”

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

\[
\text{new \ quire := 25\times sheet.}
\]
\[
\text{new \ ream := 20\times quire}
\]

You can define a variable using the new units.

\[
\text{new \ order: \ nat\times sheet := 3\times ream}
\]

This assigns order to 1500\( \times \)sheet. Another example is a monetary unit, such as

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

**Forward Definition**

Forward definition has the form

\[
\text{new \ newname}
\]

The newname becomes either a dataname or a programname. For example

\[
\text{new \ mutual}
\]

is a notice that a definition of mutual 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

\[
\text{new \ f := 3. } \{ \text{new \ g } \mid \text{new \ f } \}
\]

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

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

The newname becomes a channelname. The first data is the type, and the second data is the initial value. The type and initial value cannot use the name of the channel being defined. The definition

\[
\text{new \ c? nat ! nil}
\]

defines c to be a new local channel that transmits values of type nat, and initially there are no values in the channel. Initially c?\(=\)nil because no input has yet been read. Initially c??\(=\)⊥ to say there is no written but unread data in the channel. Channel c can be used for output and input.

The definition

\[
\text{new \ Campbell? \ text !"Along the line of smoky hills"}
\]
creates a channel named Campbell that transmits text. Initially Campbell?=“” because no input has yet been read. Initially Campbell???=⊥ because there is the written but unread input “Along the line of smoky hills”

After the input program

\[
\text{Campbell? \ char}
\]

we have Campbell?=“A” . Then, after the output program
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Campbell! “the crimson forest stands”
the input available for reading on channel Campbell is
“long the line of smoky hills the crimson forest stands”
Now, after the input program with echo
Campbell? char !Campbell
we have Campbell?="l" , and the input available on channel Campbell is
“ong the line of smoky hills the crimson forest stands”

If we have a text document named report , we can create a channel to read from it like this:

new rpt? text /report
Initially rpt?="" . If the document is nonempty, then initially rpt?=?⊤ .

If channel c is defined to have type T , it holds a string of values of type T , which is a value of type *T . A string of values can be read together in one pattern, so c? also has type *T . For example,

new nn? nat !5; 3; 4
defines nn as a channel that transmits natural numbers. Then nn? 2*nat reads 2 items from the channel, after which nn? = 5; 3 . If the definition had been

new nn? *nat !5; 3; 4
the result is the same, because **T = *T . Since text = *char , channels Campbell and rpt could equally well have type char .

At the beginning of a session (see Session), all persistent channels are redefined (reinitialized). Before any keyboard input has been keyed in, keys?=“” and keys?=?⊥ .

To use a channel for communication between concurrent programs, define the channel before the start of the concurrent programs. Then one of the concurrent programs can write to the channel, and all the concurrent programs can read from the channel; they read the same inputs independently. If a program sequentially follows a concurrent composition, on each channel, the sequentially following program begins reading after all the inputs read by all concurrent programs. For example,

new c? nat! nil. AllB. D
On channel c , program D begins reading after the last input read by A or B .

new c? nat! nil. x:= c? ¯-assigns x to nil
new c? nat! nil. c? nat ¯-infinite wait for input
new c? nat! nil. c! 7. c? nat. x:= c? ¯-assigns x to 7
new c? nat! nil. [c? nat. x:= c?] || c! 7 ¯-assigns x to 7
new c? nat! nil. c! 7. [c? nat. x:= c?] || [c? nat. x:= c?] ¯-assigns x to 7 and y to nil

Name Removal

Names defined with the keyword new can become undefined with the keyword old . Name removal has the form

old oldname
Ironically, by saying 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, in predefined dictionary rand there are three names next , Int , and Real . They might be defined as:
new rand\var: 0..maxint:= 123456789. `will be hidden
new rand\next: [rand\var:= mod (rand\var × 5^13) maxint].
new rand\Int ⟨⟨from: int. ⟨to: int. floor (from + (to–from)×rand\var/maxint)⟩⟩⟩.
new rand\Real ⟨⟨from: real. ⟨to: real. from + (to–from)×rand\var/maxint)⟩⟩⟩.
old rand\var

Variable rand\var is now hidden; its name is undefined, but rand\next, rand\Int, and rand\Real still use it. And rand\Int 0 10 has the same value each time it is used until rand\Next is called. So rand\Int 0 10 + rand\Int 0 10 = 2 × rand\Int 0 10 has value ⊤. Similarly for rand\Real.

**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 x

shortens the name a \ b \ c \ d \ x 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 \ x to d \ x.

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

new b a. old a

The following sequence swaps the names p and q.

new t p. old p. new p q. old q. new q t. old t

**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.

\begin{verbatim}
A. B
or A. B
|-------------------|-------------------|
B

|-------------------|-------------------|
A ⊥ B
or A. B

|-------------------|-------------------|
if A [B] else [C]
or if A [B]
else [C]
|-------------------|-------------------|
or if A [B]
else [C]

|-------------------|-------------------|
plan x: A [B]
or plan x: A [B]

|-------------------|-------------------|
plan x: A [B]

|-------------------|-------------------|
\end{verbatim}
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. (Python uses indentation as part of the syntax; so in Python, indentation is not redundant and cannot be used 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. A command may be given at any time; it does not have to respect the grammatical structure of a program. Each command is the control key combined with one other key. The commands are:

- `ctl .` end of program or data
- `ctl p` pause or resume execution
- `ctl a` abort execution
- `ctl s` stop current session and start new session
- `ctl u` undo current session
- `ctl e` enter or exit editor for saved definitions
- `ctl d` display source or object code for saved definitions
- `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

**End**

Use `ctl .` to indicate the end of the program keyed in since the latest prompt. You will be asked whether execution should include checking that values assigned are in the variable's type. Type checking is useful for debugging and verification, but is redundant in a correct program. Execution is faster without type checking.

**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.

**Abort**

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

**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 program bracket 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 a text consisting of all keystrokes since the start of the current session. (This is quite practical: an hour of hard work produces only 10 kbytes of keystrokes.) This text can be saved as a record of work done, or for error recovery (see Undo).

Undo

The command \texttt{ctl u} undoes a session (except for inputs and outputs and \texttt{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 \texttt{session}, let us call it \texttt{recovery},

\begin{verbatim}
new recovery: text:= session
\end{verbatim}

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

Edit

The edit command \texttt{ctl e} is used to modify an existing persistent definition. It invokes a dialogue using keys and screen to determine which definition. It then invokes an editor. In the editor, \texttt{ctl e} exits the editor, and asks if you want to throw away the old definition and save the new definition. If you do want to save it, it is compiled. If you want to create a definition using the editor, first create the definition, for example, \texttt{new p [ok]}, and then invoke the editor to modify it. If you want to delete a persistent definition, use \texttt{old}.

Display

The command \texttt{ctl d} starts a dialogue using keys and screen to determine the name (simple or compound) of the persistent definition whose source or object code you want to view.

Names

The command \texttt{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 \texttt{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) \textbf{constant} \textit{The base of the natural logarithms.}

**Context**

The command \texttt{ctl c} starts a dialogue using \textit{keys} and \textit{screen} to determine the program, bracketed by \( [ ] \), 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.

\begin{quote}
`input: on these channels
`output: on these channels
`use: the values of these variables, constants, data names, units, and function names
`assign: these variables
`call: these program names and plan names
`refer: to these dictionaries
\end{quote}

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

\begin{quote}
`spec: specification
`pre: precondition
`post: postcondition
`inv: invariant
\end{quote}

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

**Verify**

The command \texttt{ctl v} starts a dialogue using \textit{keys} and \textit{screen} to determine the program, bracketed by program brackets \( [ ] \) 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 \textit{predefined} in the persistent scope (see Scope). 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 \textit{predefined\( i \)} (unless you have covered the name \textit{predefined} with a local definition). 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:

\begin{verbatim}
new i := predefined\( i \) \quad `'constant definition
new i := predefined\( i \) \quad `'synonym definition
new i := 0&1 \quad `'constant definition
\end{verbatim}

The command \texttt{ctl n} lists the names in the \textit{predefined} dictionary. The command \texttt{ctl m} gets a description of a predefined name. The collection of predefined names may change over time.

Each predefined name is one of:

\begin{verbatim}
variable at present, there are no predefined variables
custom evaluated; not assignable
data unevaluated; evaluation upon use; not assignable
program unexecuted; execution upon use
\end{verbatim}
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.

```protem
abs: com→real data Absolute value. \( abs \, x = \sqrt{re \, x + 2 + im \, x + 2} \).

all = com, char, bin, fall, *all, [all] data All ProTem data values.

arc: com → §(r: real. 0 ≤ r < 2pi) data The angle or arc of a complex number.

arccos: §(r: real. -1 ≤ r ≤ +1) → §(r: real. 0 ≤ r ≤ pi/2) data A trigonometric function.

arcsin: §(r: real. -1 ≤ r ≤ +1) → §(r: real. 0 ≤ r ≤ pi/2) data A trigonometric function.

arctan: real → §(r: real. 0 < r < pi/2) data A trigonometric function.

await program A plan with one constant parameter of type reals. 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 time and wait and s.

bin:= T, ⊥ constant The binary values.

bold: text→text data Same text but in bold font.

capital: char constant The English capital letters. See small and letter.

ceil: real→int data r ≤ ceil r < r+1

cchar data The characters.

charnat: char→nat data A one-to-one function with inverse natchar. The encoding might be extended ASCII or unicode. Character combinations, for example shift-option-a, also have numeric encodings.

click: char constant The click character.

com = real&real data The complex numbers.

cos: real → §(r: real. -1 ≤ r ≤ +1) data The trigonometric cosine function.

cosh: com→com data The hyperbolic cosine function.

ctx: char data The combination of the control and x characters.

cursor: nat; nat data A data name whose value is the current cursor position.

definition: text→text data If the argument is the name of a persistent definition, then the result is the textual definition. For example, if combo is defined as new combo:= "10-20-30", then definition “combo” = “combo:=” "10-20-30"”. Otherwise the result is the text “undefined”.

delete: char constant The delete or backspace character.

digit= “0”, “1”, “2”, “3”, “4”, “5”, “6”, “7”, “8”, “9” constant The decimal digits.

div: real → §(r: real. r>0) → int data div a d is the integer quotient when a is divided by d.

\(0 ≤ \mod a d < d) ∧ (a = \mod a d × d + \mod a d)\)

doubleclick: char constant The doubleclick character.

drain program A plan with one input channel parameter. Reads and discards any unread input.

e:= 2.718281828459045 (approximately) constant The base of the natural logarithms.

end: char constant The end-of-file character. It is greater than all other characters.

even: int→bin data A function that says whether its argument is even.

exec program 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 “x:= x+1”, the “x” refers to whatever x refers to at the location where exec “x:= x+1” occurs. If the argument does not represent a ProTem program, execution displays an error message. To evaluate data represented as text, for example “2+2”, use unquote.

ex: 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 \( \text{find} \ i \ S \) is the index of its first occurrence; if not, then \( \text{find} \ i \ S = \text{null} \).

fit: int→text→text data If \( i \geq 0 \) then \( \text{fit} \ i \ t \) is a text of length \( i \) obtained from \( t \) either by chopping off excess characters from the right end or by extending \( t \) with spaces on the right end. If \( i < 0 \) then \( \text{fit} \ i \ t \) is a text of length \( -i \) obtained from \( t \) either by chopping off excess characters from the left end or by extending \( t \) with spaces on the left end.

floor: real→int data floor \( r \leq r < 1 + \text{floor} \ r \) is 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? char! “” channel To the program that monitors key presses, it is an output channel; to all other programs, it is an input channel.

lb: $(r: real, r \geq 0) \rightarrow real data The binary (base 2) logarithm.

letter:= small, capital constant The English small and capital letters.

ln: $(r: real, r > 0) \rightarrow real data The natural or Napierian (base \( e \)) logarithm.

log: $(r: real, r > 0) \rightarrow 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 \( \text{match} \ \text{pattern} \ \text{subject} \) is the index of its first occurrence. If not, then \( \text{match} \ \text{pattern} \ \text{subject} = \text{null} \).

maxint: int constant The maximum representable integer (machine dependent).

maxreal: real constant The maximum representable real number (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 \rightarrow $(r: real, r > 0) \rightarrow real data \text{mod} \ a \ d \ \text{is the remainder when} \ a \ \text{is divided by} \ d \ . \ (0 \leq \text{mod} \ a \ d < d) \ \land \ (a = \text{div} \ a \ d \times d + \text{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 \( \text{charnat} \). 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 or next line or return or enter 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 \( \land \ \lor \ < \ > \leq \geq \) 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 of pixels in the vertical dimension, and \( z \) is the number of pixel values.

plain: text→text data Same text but not italic, not bold, and not underlined.

point data A function that applies to a list and gives its deep domain (a bunch of strings of indexes).

It is a signal to the implementation that the strings in it will be used only as indexes to the list. It can therefore be implemented as a memory address (pointer).
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 realtext.
rand\ dictionary containing three definitions.
next program Assigns a hidden variable to the next value in a random sequence.
Int: int→int→int data A function that is dependent on a hidden variable, and is reasonably uniform over the interval from (including) the first argument to (excluding) the second argument.
Real: real→real→real data A function that is dependent on a hidden variable, and is reasonably uniform 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 including ∞ and –∞.
realtext: nat→nat→nat→real→text data Format a real number. realtext 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.
realtext 4 1 10 pi = “3.1416^^0” realtext 2 0 6 (–pi) = “–3.14”
realtext 0 0 3 5 = “5” realtext 0 0 3 (–5) = “–5” realtext 0 0 2 123 = “• •”
See quote.
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: text data The join of 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. –1 ≤ r ≤ +1) data The trigonometric sine function.
sinh: com→com data The hyperbolic sine function.
small: char constant The English small letters. See capital and letter.
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.
suc: char→char constant The character successor function.
s: constant The tab character.
tan: real→real data The trigonometric tangent function.
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\text{tanh: \text{com} \rightarrow \text{com} \ data} \  \text{The hyperbolic tangent function.}
\text{text = *\text{char} \ data} \  \text{The character strings.}
\text{time: \text{real}\times\text{s} \ data} \  \text{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). Times before then are negative. For example,} \text{time} \ “1947 September 16 at 14:24:32.5 UTC–5” = \text{–68675727.5s} \  \text{Otherwise the result is \text{–}\infty \times\text{s}. See \text{timetext}.}
\text{timetext: (\text{real}\times\text{s}) \rightarrow (–12,..12) \rightarrow \text{text} \ data} \  \text{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} \ (–68675727.5\times\text{s}) \ (–5) = “1947 September 16 at 14:24:32.5 UTC–5”
\text{trim: \text{text} \rightarrow \text{text} \ data} \  \text{A text formed from the argument by removing all leading and trailing space, tab, and new line characters.}
\text{true}:= \top \  \text{constant} \  \text{A binary value.}
\text{underline: \text{text} \rightarrow \text{text} \ data} \  \text{Same text but underlined. Any part of the text that is already underlined is underlined again.}
\text{unquote: \text{text} \rightarrow \text{all} \ data} \  \text{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 function is not evaluated. See \text{quote}.}
\text{wait \ program} \  \text{A plan with one constant parameter of type \text{real}\times\text{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}.}

\textbf{Miscellaneous}

The ProTem equivalent of enumerated type is shown here.
\text{new color:=} \ “red”, “green”, “blue”.
\text{new brush: color:=} \ “red”

The ProTem equivalent of the record type (structure type) is as follows.
\text{new person:=} \ “name” \rightarrow \text{text} \ | “age” \rightarrow \text{nat}.
\text{new p: person:=} \ “name” \rightarrow “Josh” \ | “age” \rightarrow 16

The fields of \text{p} can be selected by data that evaluates to text, for example
\text{p “name”}

is the text “Josh”. The value of \text{p} can be changed using a function arrow and selective union.
\text{p:=} “age” \rightarrow 17 \ | \ p.
\text{p:=} “name” \rightarrow “Amanda” \ | “age” \rightarrow 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:= file; p}

When the predefined function \text{point} is applied to a list argument, it yields the deep domain of the list. For example,
\text{point \ [10; [11; 12]; 13] = 0, 1; (0, 1), 2 = 0, 1; 0, 1; 1, 2}

When used as a type or as part of a type, \text{point} is unusual; it does not quite obey the language rules. For example, we can define a linked list \text{G} as follows.
new \( G \): \[\{\text{name} → \text{text} | \text{next} → \text{point} \}\] := \[\{\text{name} → \text{“Alice”} | \text{next} → 0 \}\].

new current: point \( G \) := 0

Contrary to the rule, the type mentions \( G \), the variable being defined. The occurrences of \( point \ G \) are the deep indexes of \( G \) at all times, not just at the time the definition is executed. The use of \( point \) is a signal to the implementation that its strings of natural numbers will be used only as indexes into \( G \) (and the implementation will check that this is so). Therefore they can be implemented as memory addresses, giving us the efficiency of pointers. The initial value of \( G \) is a list of length 1, so initially the only possible value of \( G \) 0 “next” is 0, and the only possible value of \( current \) is 0. Now suppose \( G \) is reassigned as follows;

\( G \) := \[\text{name} → \text{“Bob”} | \text{next} → 1 \];

Then \( G \) has length 2, so \( G \) 0 “next” can have value 0 or 1. Similarly \( current \) can have value 0 or 1, so the assignment \( current := current + 1 \) can now be made, but the assignment \( current := current + 2 \) cannot be made at this time.

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

new \( t \): tree \( \{[\text{nil}], [\text{tree}; \text{nat}; \text{tree}]\} := [\text{nil}].

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

If tree \( t \) gains some branches, for example,

\( t := [[\text{nil}]; 2; [\text{nil}]; 5; [\text{nil}]]; 3; [[\text{nil}]; 7; [\text{nil}]])\)

we can move \( p \) down to the left in the tree with the assignment

\( p := p; 0 \)

and move it down to the right with the assignment

\( p := p; 2 \)

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

\( t := p → s | t \)

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

\( t@p \) 1 or \( t@(p; 1) \)

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

\( t := (p; 1) → 6 | t \)

To move up in the tree, we just remove the final item of \( p \)

\( p := p_(0;..↔p−1) \)

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

new transform \[\{\text{plan} \text{magnification: real} | \text{plan} \text{translation: real} | \[\text{x := magnification}×x + \text{translation}]\}\]

Here is a definition of a plan with one parameter

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

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.

new magnify \[\{\text{plan} \text{magnification: real} | \text{transform} \text{magnification} 0\]\]

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

\( \text{magnify} 3 \) or \( \text{transform} 3 \ 0 \)

In some other programming languages, the “function” is a combination of naming, scope, parameter(s), and value-data. For example,

new factorial \( \{(n: \text{nat}. \text{value} f: \text{nat} := 1 | \text{for} i: 1..n+1 \{f := f\times i\}\}\)
Exception handling is provided by | or if or =~=. For example,

\[
\text{new} \ divide \ (\langle \text{dividend: com.} \ \langle \text{divisor: com.} \ \text{divisor}=0 \implies \text{“zero divide”} \implies \text{dividend/divisor} \rangle) \]

Then

\[
\text{divide: com } \rightarrow \text{com } \rightarrow (\text{com, “zero divide”})
\]

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

\[
\text{new} \ \text{weekday}:= \langle d: 0,..7. \ 1 \leq d \leq 5 \rangle
\]

Then if \(i\) fails to be an integer in the range \(0,..7\) in the expression

\[
(\text{weekday} \ | \ all \implies \text{“domain error”}) \ i
\]

the left side of | “catches” the exception and “throws” it to the right side, where it is “handled”.

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

\[
\text{inputchoice} \ [\text{if} \ c?? [c?? \ numpat; \ end. \ P] \ \text{else} \ [\text{if} \ d?? [d?? \ numpat; \ end. \ Q] \ \text{else} \ [\text{inputchoice}]])
\]

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 old. Unix mv is a synonym definition followed by old. Unix Is and man commands are [ctrl n] and [ctrl m]. The effect of Unix pipes is obtained by channel parameters. For example, suppose trimmer is a plan to trim off leading and following blanks and tabs from lines of text, and enumerate is a plan to number lines.

\[
\text{new} \ \text{trimmer} \ [\text{plan in? text} \ [\text{plan out! text} \ [\text{loop} \ [\text{if} \ in?? \ [\text{in? text}; \ \text{nl. out! trim} \ (\text{in?}-(0;.. \leftrightarrow \text{in?})-1)); \ \text{nl. loop}]])]]
\]

\[
\text{new} \ \text{enumerate} \ [\text{plan in? text} \ [\text{plan out! text} \ [\text{new} \ n: \ \text{nat:=} \ 0. \ \text{loop} \ [\text{if} \ in?? \ [\text{in? text}; \ \text{nl. out! n; “”; in?}. \ n:= n+1. \ \text{loop}]])]]
\]

We can feed the output from trimmer to the input of enumerate by defining a channel for the purpose. If the original input comes from keys, and the final output goes to screen, then

\[
\text{new pipe? text! “”}. \ \text{trimmer} \ \text{keys pipe. enumerate pipe screen. old pipe}
\]

Even better:

\[
\text{new pipe? text! “”}. \ \text{trimmer} \ \text{keys pipe | enumerate pipe screen. old pipe}
\]

If enumerate wants input before it is available from trimmer, enumerate waits. If trimmer sends output before enumerate wants it, it is buffered.

Unix mail is ProTem’s mail channel. If you are the creator of the definition of something in the persistent scope, and you want to send it to someone for them to make changes, then

\[
\text{mail! “To: someone@address.domain”; nl; definition “something”}
\]

(see predefined definition). When someone sends back the changed definition, receive it, delete your old definition, and then redefine it (see predefined exec) by

\[
\text{mail? text; end. old something. exec (“new”; mail?)}
\]

An implementation may provide plans for a variety of languages. For example, it may provide a plan named Python, with one text parameter, whose execution is that of the Python fragment represented by the argument. It may provide 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 \(\backslash\) (see parseStack 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.

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 it is, the ordering symbols ∨ ∧ < > ≤ ≥ are nicely related.

In ProTem, a text is written with quotation marks. An attractive alternative to quotation marks is underlining. For example, the text “abc” would instead be written abc. It is a good-looking syntax, but awkward to key in, so quotation marks could be the keyboard substitute. (The empty text would be nil, string indexing would not be underscore, and quote and unquote would be renamed textify and untextify.) I have used underlining in ProTem just for quotation marks within a text; for example, “Just say “no”.” This would become Just say “no” . , with no exception needed for quotation marks within a text. In ProTem, if you want an underlined quotation mark within a text, you have to underline it again. And so on. Thus every character can occur within a text. In the alternative notation, no special rule is needed. Underlining presents a theoretical (but not practical) limitation: we cannot write a self-reproducing text (try). We can write a self-reproducing text with quotation marks, repeating the left and right quotation marks as characters within a text. For example, “Just say ““no””.” Using this convention, here is a self-reproducing text:

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

Perform the indexing to see what you get.

In the Presentation Grammar, the case-program has the form

```plaintext
case data [ program ]
```

with the program form

```plaintext
program [ program ]
```

to make more cases. Although it is correct, it is not a clear presentation of

```plaintext
case data [ program ] [ program ] [ program ]
```

and so on. A clear presentation requires another nonterminal, as in the LL(1) Grammar and LR(0) Grammar. My principle is that the Presentation Grammar has only two nonterminals (program and data), but the case-program stretches that principle rather thin. Furthermore, the program form

```plaintext
program [ program ] [ program ]
```

is the only program or data form whose use is confined to a single context, and I am unhappy to have any program or data form that cannot be used more generally.

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. Channel screen must be modified so pictures
can be output on channel *screen*.

Suppose we want to input 10 characters with echo

? 10*char!

except that we want any space, tab, delete, and new line input characters to appear visibly in the echo, rather than causing spaces, tabs, deletions, and new lines. Then we must do so one character at a time.

```plaintext
for i: 0..10 [? char. if ?=" " [!"\rightarrow"]
  else [if ?=tab [!"\rightarrow"]
    else [if ?=nl [!"\leftarrow"]
      else [if ?=delete [!"\leftarrow"]
        else [!?]]]]
```

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**

```plaintext
assert x≤y
```

means

```plaintext
if –(x≤y) [! “assert failure”. stop]
```

**Name grouping**

```plaintext
new x, y: int:= 0
old x, y
x, y:= 0
(a, b: nat. a+b)
plan a, b: nat [x:= a+b]
```

**Item assignment**

```plaintext
S_3:= 5
L 3:= 5
A 3 4:= 5
```

**Loop constructs**

```plaintext
while n>0 [n:= n−1] means while [if n>0 [n:= n−1. while]]
repeat [n:= n−1] n=0 means repeat [n:= n−1. if –(n=0) [repeat]]
loop [n:= n−1. if n=0 [exit 1]. loop [m:= m−1. if m=0 [exit 2] else [exit 1]]] means loop [n:= n−1. if –(n=0) [m:= m−1. if –(m=0) [loop]]]
```

**Return from named-program**

```plaintext
name [if n=0 [return name]. more] means name [if –(n=0) [more]]
```

The assignment `L:= 3→5|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

```plaintext
while [if n>0 [n:= n−1. while]]
```

the last-action (tail recursive) call should be compiled as a branch instruction, with no stack activity, the same as a while-loop would be if it were included. The same for other loop constructs. Omitting item assignment and looping constructs should not cost execution time or space.
Plans with parameters and arguments of type program

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

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

were considered and rejected due to syntactic and semantic ambiguities.

As a counterpart to the Unix \text{cd} command, I considered

\[
\text{open dictionaryname}
\]

\[
\text{close dictionaryname}
\]

to allow names in that dictionary to be referred to without stating the dictionary. For example, if we have dictionary \text{abc}, and within it names \text{x} and \text{y}, we refer to these names as \text{abc}\text{x} and \text{abc}\text{y}. By saying \text{open abc} we can then refer to them as just \text{x} and \text{y}. But the interaction between \text{open} and scope is complex, we can already refer to names within \text{predefined}, and we can shorten names by synonym definition, so I left out \text{open} and \text{close}.

The syntax

\[
\text{new abc}\text{def}
\]

defines a new dictionary \text{abc} populated with the definitions from existing dictionary \text{def}. Perhaps it should instead add the definitions of existing dictionary \text{def} to existing dictionary \text{abc}. At present, there is no way to do that. If I were to make this change, there would still be a way to define a new dictionary populated with definitions from an existing dictionary:

\[
\text{new abc\ new abc}\text{def}
\]

But I would have to decide how to resolve duplicate definitions. I am guessing that we always want to populate a new dictionary, not further populate an existing one.

There is no frame construct in ProTem, but \text{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 a personal identity type and a scheme of permits to say who can use and change what. The scheme was more flexible than Unix \text{chmod}, and I was quite pleased with it. But with sharing, all mathematical reasoning is invalid; \text{x=x} might evaluate to \text{⊥}. And with sharing, locks are required so that assignments do not interfere with uses, and assignments do not interfere with other assignments. Sharing problems are solved by the use of channels: anyone can email anything to anyone else; any program can send anything to any other program on a channel. So, even though it hurts to leave out something I worked hard on, identities and shared variables are intentionally omitted.

Two binary operators \text{Δ} (nand) and \text{∇} (nor) are missing. They are not wanted very often, there are no good keyboard substitutes for them, and they are easily synthesized:

\[
x\Delta y = -(x\land y) \quad x\nabla y = -(x\lor y)
\]

The empty program, denoted by nothing, whose execution does nothing and takes no time, is easy to add to ProTem. With it, we can almost always consider the period ( . ) to be a program terminator, rather than an infix connective. But there is one context where it causes confusion.

\[
A. || B.
\]

looks like program \text{A} (terminated with a period) is in parallel with program \text{B} (terminated with a period). But, following \text{A}, the empty program is in parallel with \text{B}, as in

\[
A. [ || B].
\]

So I have not included the syntactically empty program in ProTem, providing instead the predefined program \text{ok} whose execution does nothing and takes no time (as in \text{aPToP}).
**Implementation Philosophy**

An implementation checks whether the text presented to it represents a program, and issues an error message if it does not. Using \( \texttt{ctl} \), we are asked whether 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. When we are satisfied that all assignments are always to values included in their types, we can choose not to check types, resulting in faster execution.

Some expressions do not need to be evaluated, and some cannot be evaluated. For examples,

\[
\begin{align*}
! -3 & \quad \text{prints } -3 \\
! [0; 1] 2 & \quad \text{should print } [0; 1] 2 \\
! [0; 1] 2 = [0; 1] 2 & \quad \text{should print } T \\
! 4^{(1/2)} & \quad \text{should print } 2, -2 \\
! 1/0 & \quad \text{might print } \infty, -\infty \text{ or might print } 1/0 \\
! 0/0 & \quad \text{might print } \texttt{real} \text{ or might print } 0/0 \\
! 1/0 = 1/0 & \quad \text{should print } T \\
! (r: \texttt{rat}. 5) (1/0) & \quad \text{should print } 5
\end{align*}
\]

ProTem does not evaluate the application of the negation operator \( \neg \) to the operand 3 (see Number Representation); it just prints the operator and operand. Depending on the axioms of arithmetic being used, 1/0 might be evaluated as \( \infty, -\infty \) and 0/0 might be evaluated as \( \texttt{real} \). Due to the difficulty of implementation, it is permissible for an implementation to behave differently.

No programming language has ever been, nor will ever be, implemented entirely. Every programming language is finite; 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, the 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

```
int rat bin text [n*type]
```

where \( n \) is a natural number and \( type \) 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**

```
new simport ` a program to simulate portation
[ `input: keys
  `output: screen
  `use: ceil m nat nil nl point 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/s². ` 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" → (realxs) ` arrival time at this box
| "speed" → (realxs)))] ` 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”) → ? | (?; “behind left”) → b | box.
! "What box is ahead-right of box "; b; “?” . ?!
  box:= (b; “ahead right”) → ? | (?; “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”].

` 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: realxs:= ∞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; natxs]:= 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\times m]].

boxesToDo:= boxesToDo; [box b “ahead left”; 1\times m].
if box b “ahead left” ≠ box b “ahead right” [boxesToDo:= boxesToDo; [box b “ahead right”; 1\times m]].
old b. old bb.

new accel: real\times m/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_0(1;\leftrightarrow boxesToDo).
if d=maxdistance
[new desiredspeed ` according to porter pa

\$\langle \text{pa: point porter, numporters.}
\text{pa=numporters \models speedlimit}
\text{=} (\text{sqrt (porter pa “speed”}\times2 + 2\times maxaccel\times d
+ (maxaccel\times cushion)\times2)

- maxaccel\times cushion) \land speedlimit\rangle$. accel:= ( ( ( desiredspeed (box b “above”)

\land desiredspeed (porter (box b “beside”) “above”))

- porter p “speed”)

\times impatience)

\lor -maxaccel) \land 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\times m].
if box b “ahead left” ≠ box b “ahead right”
[boxesToDo:= boxesToDo; [box b “ahead right”; d+1\times m]].
nextBox]
else [if \leftrightarrow boxesToDo > 0 [nextBox]]].
old boxesToDo.

` using accel, move porter p ahead one box
new b: point box:= porter p “below”.
box:= (b; “porter”) \rightarrow numporters \parallel box. draw b “grey”.
rand\next. b:= box b (randInt 0 2 = 0 ⇒ “ahead left” = “ahead right”).
if box b “porter” < numporters [draw b “red”. stop]. ` crash
porter:= (p; “below”) \rightarrow b \parallel porter. box:= (b; “above”) \rightarrow p \parallel box. draw b “blue”.
old b.

new speed:= sqrt (porter p “speed”\times2 + 2\times accel\times m) \land speedlimit.
porter:= (p; “arrival time”) \rightarrow (porter p “arrival time” + 2\times m/(porter p “speed” + speed))
\parallel (p; “speed”) \rightarrow speed
\parallel 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 \langle n: nat. \langle m: nat. ` shift n left m places; n×2^m
value r: nat:= n \[for i: 0;..m \[r:= r×2]]\].

new shr \langle n: nat. \langle m: nat. ` shift n right m places; floor (n×2^m) or div n (2^m)
value r: nat:= n \[for i: 0;..m \[r:= div r 2]]\].

new gcd \langle a: nat+1. \langle b: nat+1. ` greatest common divisor of a and b
a=b \iff a = a×b \iff gcd a (b–a) = gcd (a–b) b\rangle.

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)) \neq even (shr string (quote–1)) ` roll-normalized
\[if ` repeat-normalized
value repeatnorm: bin:= \[\top
\[new len: nat:= div (length–quote) 2. ` the length of the possibly repeating part
trythislen \[if len>0 \[\top 1 \leq len \leq (length–quote)/2
\[new extract \langle (i: nat. \langle l: nat. ` index i length l
shr string i – shl (shr string (i+l) l) \rangle\].
new ex:= extract quote len.
if ` the negative part is a repetition (twice or more) of ex
value b: bin:= \[\bot
\[new i: nat:= quote+len. ` i+length
iloop \[new ey:= extract i len.
if ex=ey \[i:= i+len. ` i\leq length
if i+len \leq length \[iloop
else \[\[b:= \[\bot\]\]\]
else \[\[b:= \[\bot\]\]\]]
\[repeatnorm:= \[\bot\]} else \[\[len:= len–1. trythislen\]]]\]]
\[for point: 0;..length+1 ` each point position (right end, interior, left end)
\[if ` the rightmost bit is 1 or it is to the left of quote or point
odd string v (quote=0) v (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: end find nat nil nl point real text

new forest: *[real; tree ([text], [tree; tree])]:= nil. `The data structure is a string of lists.
  `Each list is a pair of real and tree; the real is the frequency of the tree.
  `Each tree is binary with texts at the leaves.

inputstart
[! “Enter a frequency, then a colon, then a message, then end, and repeat. ”;
  “To end, just enter end.”; nl.
readloop
[?!.
  if ↔? = 0 ` Just end 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=→∞ [[! “Bad frequency format. Try again.”. readloop].
    new message:= ?_(c+1;..↔?).
  ` find where the new data goes in forest and put it there.
  new i: nat:= 0.
  findloop [if i = ↔forest ∨ (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; [“c”]]; [4; [“a”]]; [9; [“f”]]; [12; [“b”]]; [15; [“e”]]; [20; [“d”]]

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  
\[
\text{new } t := \{ (\text{forest}_0)_0 + (\text{forest}_1)_0; \{ (\text{forest}_0)_1 ; (\text{forest}_1)_1\} \}.
\]
` remove those first two trees from the forest  
\[
\text{forest} := \text{forest}_2; \ldots \leadsto \text{forest}.
\]
` put tree  \( t \) into its place in the forest  
\[
\text{innerloop} \begin{cases} 
\text{if} \ here = \leadsto \text{forest} \lor (t_0 < (\text{forest}_{\text{here}})_0) \text{ we have found where it goes} \\
\{ \text{forest} := \text{forest}_{\text{here}} ; t ; \text{forest}_{\text{here}} ; \ldots \leadsto \text{forest}. \ loop \} \\
\text{else} \{ \text{here} := \text{here} + 1. \ \text{innerloop} \} \end{cases}.
\]
` forest  is now a single pair consisting of the total of all frequencies and a code tree.  
\[
\text{new } t := \text{forest}_1. \ ` the code tree  
\]
` Walk the tree, depth-first, printing leaves and their codes  
\[
\text{new } p: \text{point } t := \text{nil}. \ ` a path within  \( t \) starting at the root  
\text{new } \text{pt}: \text{text} := \text{""}. \ ` \text{same path as } p \text{ but as a text for printing}  
\text{new } \text{back} \[ \begin{array}{l}
\text{plan } p := * \text{nat} \[ p := p_{(0; \ldots \leadsto p – 1)} \]. \\
\text{loop} \begin{cases} 
\text{if} \ ~(t; p): \text{text} \ ` \text{we are at a leaf} \\
\{ \text{! \text{"code}: \}; pt; \text{"; message: \}; \sim(t; p); \text{nl} \} \\
\text{else } \{ p := p_0; pt := pt; \text{"0"}. \ \text{loop. back } p. \ \text{back } pt. \\
\quad p := p_1; pt := pt; \text{"1"}. \ \text{loop. back } p. \ \text{back } pt \} \end{cases} \] \] end of MRC

Read Password

` program to read a password, allowing corrections, displaying blobs  
\` input: keys  
\` output: screen  
\` use: char delete end text  
\text{new } \text{password}: \text{text} := \text{""}.  
\text{pswd} \begin{cases} \text{!\text{"Please enter password followed by \text{ end : \"}.} \\
\text{read } \text{? char}. \\
\quad \text{if } ? = \text{end} \{ \text{if } \text{password} = \text{"\"} \{ \text{!\text{"Empty password. Try again."}; \text{nl. pswd} \} \\
\quad \text{else} \{ \text{nl} \} \} \\
\text{else } \{ \text{if } ? = \text{delete} \{ \text{if } \text{password} \neq \text{"\"} \{ \text{password} := \text{password}_{(0; \ldots \leadsto \text{password} – 1)}. \text{!delete} \} \\
\text{else } \{ \text{password} := \text{password}; ?; \text{!\text{"\"} \}. \text{read} \} \} \end{cases}
\]

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 \( 33 – 8 = 25 \) nonterminals.
moresequents . program
empty

sequent phrase parallelphrases

parallelphrases || sequent
empty

phrase

\textbf{new} simplename afternewname
\textbf{old} simplename compounder
[ program ]
\textbf{if} data [ program ] elsepart
\textbf{case} data [ program ] morecases elsepart
\textbf{for} simplename : data [ program ]
\textbf{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
\afterbackslash simplename compounder
empty

compounder \ simplename compounder
empty

elsepart \textbf{else} [ program ]
empty

morecases [ program ] morecases
empty

parameterkind : data
:= data
! data
? data
\afterbackslash

aftersimplename [ program ]
compounder aftername
aftername := data
! data
? inputafterq
arguments

inputafterq ! echo
data afterpattern

afterpattern ! echo
empty

echo
   simplename compounder
   empty

arguments
   number arguments
   \infty arguments
   text arguments
   \top arguments
   \bot arguments
   value simplename : data := data [ program ] arguments
   \{ data \} arguments
   [ data ] arguments
   ( data ) arguments
   \{ simplename : data . data \} arguments
   simplename specificand arguments
   empty

data
data6 moredata

moredata
   \models data = \models data
   empty

data6
data5 moredata6

moredata6
   = data5 moredata6
   \neq data5 moredata6
   < data5 moredata6
   \geq data5 moredata6
   \leq data5 moredata6
   \geq data5 moredata6
   : data5 moredata6
   :: data5 moredata6
   \in data5 moredata6
   empty

data5
data4 moredata5

moredata5
   , data4 moredata5
   .. data4 moredata5
data4

moredata4
+ data3 moredata4
− data3 moredata4
;; data3 moredata4
; data3 moredata4
;.. data3 moredata4
` data3 moredata4
empty

data3

data2

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

data2
# data2
− data2
~ data2
+ data2
□ data2
≠ data2
* data2
ε data2
$ data2
↔ data2
data1 moredata2

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

data1

data0 moredata1

moredata1
%
moredata1
?
moredata1
?? moredata1
_ data0 moredata1
@ data0 moredata1
& data0 moredata1
arguments
data0 number
\infty
text
\top
\bot
\?
??

value simplename : data := data ![ program ]
{ data }
[ data ]
( data )
⟨ simplename : data . data ⟩
simplename specificand

specificand ⟨ data ⟩
componder

**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.

program sequent
  program . sequent

sequent phrase
  sequent || phrase

phrase
  **new** name : data := data
  **new** name := data
  **new** name ⟨ data ⟩
  **new** name ![ program ]
  **new** name ? data ! data
  **new** name #1
  **new** name \n
  **new** name \ name
  **new** name name
  **new** name
  **old** name
  name := data
  name ! data
  ! data
  name ? data ! name
  ? data ! name
  name ? ! name
  name ? data !
? ! name
? data !
nname ?!
? !
nname ? data
? data
simplename [ program ]
 if data [ program ]
 if data [ program ] else [ program ]
case data cases
 case data cases else [ program ]
for simplename : data [ program ]
[ program ]
plan

cases
[ program ]
cases [ program ]

plan
plan simplename : data [ program ]
plan simplename := data [ program ]
plan simplename ? data [ program ]
plan simplename ! data [ program ]
plan simplename \ [ program ]
plan data0
name

data
data6 ⊨ data = data
data6

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

data5
data5 , data4
data5 .. data4
data5 \ data4
data5 | data4
data5 ⊲ data
data4 ⊳ data4
data4

data4
data4 ; data3
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

data1 data0
data1 _ data0
data1 @ data0
data1 %
data1 & data0
name ?
name ??
?
??
data0

number
∞
text
T
⊥
[ data ]
{ data }
( data )
⟨ simplename : data . data ⟩
value simplename : data := data [ program ]
name
simplename \ data
Acknowledgements

The first public mention of ProTem was
E.C.R.Hehner, T.S.Norvell: “ProTem: a Programming System”, University of Toronto,
Computer Systems Research Group, technical report CSRG213, 1988 September
On 1991 April 16, Eric Hehner gave a talk at the University of Waterloo titled “the ProTem
Programming System”.

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.