**ActorScript™ extension of C#®, Java®, Objective C®, JavaScript®, and SystemVerilog using iAdaptive™ concurrency for antiCloud™ privacy and security**

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*This article is dedicated to Ole-Johan Dahl and Kristen Nygaard.*

**Message passing using types is the foundation of system communication:**
- Messages are the unit of communication
- Types enable secure communication Actors

ActorScript™ is a general purpose programming language for implementing iAdaptive™ concurrency that manages resources and demand. It is differentiated from previous languages by the following:
- Universality
  - Ability to directly specify exactly what Actors can and cannot do
  - Everything is accomplished with message passing using types including the very definition of ActorScript itself.
  - Messages can be directly communicated without requiring indirection through brokers, channels, class hierarchies, mailboxes, pipes, ports, queues *etc.* Programs do not expose low-level implementation mechanisms such as threads, tasks, locks, cores, *etc.* Application binary interfaces are afforded so that no program symbol need be looked up at runtime. Functional, Imperative, Logic, and Concurrent programs are integrated.
  - A type in ActorScript is an interface that does not name its implementations (contra to object-oriented programming languages beginning with Simula that name implementations called “classes” that are types). ActorScript can send a message to any Actor for which it has an (imported) type.
Concurrency can be dynamically adapted to resources available and current load.

- Safety, security and readability
  - Programs are *extension invariant*, i.e., extending a program does not change the meaning of the program that is extended.
  - Applications cannot directly harm each other.
  - Variable races are eliminated while allowing flexible concurrency.
  - Lexical singleness of purpose. Each syntactic token is used for exactly one purpose.

- Performance
  - Imposes no overhead on implementation of Actor systems in the sense that ActorScript programs are as efficient as the same implementation in machine code. For example, message passing has essentially same overhead as procedure calls and looping.
  - Execution dynamically adjusted for system load and capacity (e.g. cores)
  - Locality because execution is not bound by a sequential global memory model
  - Inherent concurrency because execution is not limited by being restricted to communicating *sequential* processes
  - Minimize latency along critical paths

ActorScript attempts to achieve the highest level of performance, scalability, and expressibility with a minimum of primitives.

*C#* is a registered trademark of Microsoft, Inc.
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*Objective C* is a registered trademark of Apple, Inc.
*Computer software should not only work; it should also appear to work.*

**Introduction**

ActorScript is based on the Actor mathematical model of computation that treats “Actors” as the universal primitives of concurrent digital computation

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1 Performance can be tricky as illustrated by the following:

- “Those who would forever give up correctness for a little temporary performance deserve neither correctness nor performance.” [Philips 2013]
- “The key to performance is elegance, not battalions of special cases” [John Bentley]
- “If you want to achieve performance, start with comprehensible.” [Philips 2013]
- Those who would forever give up performance for a feature that slows everything down deserve neither the feature nor performance.
Actors have been used as a framework for a theoretical understanding of concurrency, and as the theoretical basis for several practical implementations of concurrent systems.

**ActorScript**
ActorScript is a general purpose programming language for implementing massive local and nonlocal concurrency.

This paper makes use of the following typographical conventions that arise from underlying namespaces for types, messages, language constructs, syntax categories, etc.:
- type identifiers (e.g., `Integer`)
- program variables (e.g., `aBalance`)
- message names (e.g., `getBalance`)
- reserved words for language constructs (e.g., `Actor`)
- structures (e.g., `[ ] and `)
- argument keyword (e.g., `to`)
- logical variables (e.g., `x`)
- comments in programs (e.g., `/* this is a comment */`)

There is a diagram of the syntax categories of ActorScript in an appendix of this paper in addition to an appendix with an index of symbols and names along with an explanation of the notation used to express the syntax of ActorScript.

**Actors**
ActorScript is based on the Actor Model of Computation [Hewitt, Bishop, and Steiger 1973; Hewitt 2010a] in which all computational entities are Actors and all interaction is accomplished using message passing.

The Actor model is a mathematical theory that treats “Actors” as the universal primitives of digital computation. The model has been used both as a framework for a theoretical understanding of concurrency, and as the theoretical basis for several practical implementations of concurrent systems. Unlike previous models of computation, the Actor model was inspired by physical laws. The advent of massive concurrency through client-cloud computing and many-core computer architectures has galvanized interest in the Actor model.

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1 The choice of typography in terms of font and color has no semantic significance. The typography in this paper was chosen for pedagogical motivations and is in no way fundamental. Also, only the abstract syntax of ActorScript is fundamental as opposed to the surface syntax with its many symbols, e.g., `↦`, etc.
An Actor is a computational entity that, in response to a message it receives, can concurrently:
- send messages to addresses of Actors that it has
- create new Actors
- for a serialized Actor, designate how to handle the next message it receives.

There is no assumed order to the above actions and they could be carried out concurrently. In addition two messages sent concurrently can be received in either order. Decoupling the sender from communication it sends was a fundamental advance of the Actor model enabling asynchronous communication and control structures as patterns of passing messages.

The Actor model can be used as a framework for modeling, understanding, and reasoning about, a wide range of concurrent systems. For example:
- Electronic mail (e-mail) can be modeled as an Actor system. Mail accounts are modeled as Actors and email addresses as Actor addresses.
- Web Services can be modeled with endpoints modeled as Actor addresses.
- Object-oriented programming objects with locks (e.g. as in Java and C#) can be modeled as Actors.

Actor technology will see significant application for integrating all kinds of digital information for individuals, groups, and organizations so their information usefully links together. Information integration needs to make use of the following information system principles:
- **Persistence**: Information is collected and indexed.
- **Concurrency**: Work proceeds interactively and concurrently, overlapping in time.
- **Quasi-commutativity**: Information can be used regardless of whether it initiates new work or becomes relevant to ongoing work.
- **Sponsorship**: Sponsors provide resources for computation, i.e., processing, storage, and communications.
- **Pluralism**: Information is heterogeneous, overlapping and often inconsistent. There is no central arbiter of truth.
- **Provenance**: The provenance of information is carefully tracked and recorded.

The Actor Model is designed to provide a foundation for inconsistency robust information integration.
Syntax
To ease interoperability, ActorScript uses an intersection of the orthographic conventions of Java, JavaScript, and C++ for words and numbers.

Expressions
ActorScript makes use of a great many symbols to improve readability and remove ambiguity. For example the symbol “▮” is used as the top level terminator to designate the end of input in a read-eval-print loop. An Integrated Development Environment (IDE) can provide a table of these symbols for ease of input as explained below:

Expressions evaluate to Actors. For example, \(1+3\)\(^i\) is equivalent\(^iv\) to \(4\).

Parentheses “(” and “)” can be used for precedence. For example using the usual precedence for operators, \(3*(4+2)\) is equivalent to \(18\), while \(3*4+2\) is equivalent to \(14\).

Identifiers, e.g., \(x\), are expressions that can be used in other expressions. For example if \(x\) is 1 then \(x+3\) is equivalent to \(4\). The formal syntax of identifiers is in the following end note: 4.

Types
Types are Actors. In this paper, Types are shown in green, e.g., Integer.

The formal syntax for types is in the following end note: 5.

Definitions, i.e., ≡
A simple definition has the name to be defined followed by “≡” followed by the definition. For example, \(x: Integer ≡ 3\) defines the identifier \(x\) to be of type Integer with value 3.

The formal syntax of a definition is in the end note: 6.

\(^i\) sometimes called "names"
\(^iv\) in the sense of having the same value and the same effects
Interfaces for procedures, i.e., Interface { | |→ }

A procedure interface is used to specify the types of messages that a procedure Actor can receive. The syntax is “Interface” followed by an interface identifier, and procedure signatures in parentheses separated by commas. A procedure signature consists of a message signature with argument types delimited by “[” and “]”, followed by “→”, and a return type. An alternative syntax (which is more like Java) is that a procedure signature can be written as a return type followed by “↤”, and message signature with argument types delimited by “[” and “]”.

For example, the interfaceii for the overloaded procedure type IntegerToIntegerAndVectorToVector that takes an Integer argument to return an Integer value and a Vector argument and to return a Vector can be constructed as follows:vi

\[
\text{Interface IntegerToIntegerAndVectorToVector} \\
\quad \{ [\text{Integer}] \rightarrow \text{Integer}, \quad \text{// equivalently } [\text{Integer}] \rightarrow \text{Integer} \\
\quad \{ [\text{Vector}] \rightarrow \text{Vector} \}
\]

For security reasons, the type IntegerToIntegerAndVectorToVector is different from the type constructed below:vii

\[
\text{Interface VectorToVectorAndIntegerToInteger} \\
\quad \{ [\text{Vector}] \rightarrow \text{Vector}, \\
\quad \{ [\text{Integer}] \rightarrow \text{Integer} \}
\]

The formal syntax of a procedure interface is in the following end note: 9.

Procedures, i.e., Actor implements | |→ , ¶ and §

A procedure has message formal parameters delimited by “[” and “]” followed by “→” and then the expression to be computed.vi For example,

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i Since communicating using messages is crucial for Actor systems, messages are shown in red in this article. The choice of color has no semantic significance.

ii Every interface is a type.

iii Merely, having procedures with the same signatures does not make IntegerToIntegerAndVectorToVector the same type as VectorToVectorAndIntegerToInteger.

iv Note the following crucial differences (recalling that font, color, and capitalization are of no semantic significance for identifiers although words with different capitalization are different identifiers):
[n:Integer]→n+n ▮ is a (unnamed) procedure that given a message with an integer number, n, returns the number plus itself.

Procedures can be overloaded using “Actor implements”, followed by a type, followed by “using”, followed by a list of procedures separated by “¶” and terminated by “§”. For example, in the following Double is defined to implement IntegerToIntegerAndVectorToVector.

Double ≡ Actor implements IntegerToIntegerAndVectorToVector using

[n:Integer]→ n+n ▮ // integer addition
[v:Vector]→ v+v § ▮ // vector addition

The formal syntax of procedures is in the end note: 10.

Sending messages to procedures, i.e., ❍[ ]

Sending a message to a procedure (i.e. “calling” a procedure with arguments) is expressed by an expression that evaluates to a procedure followed by “✱” followed by a message with parameter expressions delimited by “[” and “]”.

For example, Square✱[2+1]▮ means send Square the message [3]. Thus Square✱[2+1]▮ is equivalent to 9▮.

The formal syntactic definition of procedural message sending is in the end note: 12.

• [Integer]→Integer is a procedure signature type and not a procedure. It is a procedure type for a procedure that takes an Integer argument and returns an Integer.

• [Integer]→Integer is a procedure and not a type. It is the “identity” procedure of one argument that always returns the argument.

Since both procedures and implementations can be quite large, an IDE can use these special symbols to provide additional help.

As a convenience, the procedure Square can be defined to implement the type [Integer]→Integer as follows: Square✱[x:Integer]:Integer ≡ x*x▮
Patterns

Patterns are fundamental to ActorScript. For example,

- 3 is a pattern that matches 3
- “abc” is a pattern that matches “abc”.
- _ is a pattern that matches anything\(^{i}\)
- _:Integer is a pattern that matches any Integer
- $$x$$ is a pattern that matches the value of x.
- $$x+2$$ is a pattern that matches the value of the expression x+2.
- < 5 is a pattern that matches an integer less than 5
- x suchThat Factorial\([x]>120\) is a pattern that matches an integer whose factorial is greater than 120

Identifiers\(^{ii}\) can be bound using patterns as in the following examples:

- x is a pattern that matches “abc” and binds x to “abc”
- x:Integer is a pattern that does not match “abc” because “abc” is not an integer
- x:Integer is a pattern that matches 3 and binds x to 3

Cases, i.e., \(\therefore \overset{?}{3}, 3 \overset{?}{\therefore}\)

Cases are used to perform conditional testing. In a Cases Expression, an expression for the value on which to perform case analysis is specified first followed by “\(\therefore\)”\(^{iii}\) and then followed by a number of cases such that each case is separated from the next by “;” and cases are terminated by “\([?]\)”\(^{iv}\). A case consists of

- a pattern followed by “\(\overset{?}{;}\)” and an expression to compute the value for the case. All of the patterns before an else case must be disjoint; i.e., it must not be possible for more than one to match.
- optionally (at the end of the cases) one or more of the following cases: “else” followed by an optional pattern, “\(\overset{?}{;}\)” and an expression to compute the value for the case. An else case applies only if none of the patterns in the preceding cases\(^{iv}\) match the value on which to perform case analysis.

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\(^{i}\) e.g., _ matches 7

\(^{ii}\) An identifier is a name that is used in a program to designate an Actor

\(^{iii}\) “\(\therefore\)” is fancy typography for “?”,

\(^{iv}\) including patterns in previous else cases
As an arbitrary example purely to illustrate the above, suppose that the procedure Random is of type [ ]→\text{Integer} in the following example:

\begin{verbatim}
Random[ ]  |
  0  %  // Random[ ] returned 0
      Throw RandomNumberException[ ],          // throw an exception because Fibonacci[0] is undefined
  1  %  // Random[ ] returned 1
  6,   // the value of the cases expression is 6
  else y thatIs < 5  %  // Random[ ] returned y that is not 0 or 1 and is less than 5
      Fibonacci[ y], // return Fibonacci of the value returned by Random[ ]
  else z  %  // Random[ ] returned z that is not 0 or 1 and is not less than 5
      Factorial[ z], // return Factorial of the value returned by Random[ ]
\end{verbatim}

The formal syntax of cases is in the following end note: 14.

\textbf{Binding locals, \textit{i.e.}, Let {← } }

Local identifiers can be bound using \texttt{“Let”} followed by a pattern, \texttt{“←”}, an expression for the Actor to be matched, \texttt{“,”}, and an expression in which the identifiers can be used to compute an Actor. For example, \texttt{[“G”, “F”, “F”]} could be written as follows:

\begin{verbatim}
Let x ← “F”,  // x is “F”
[“G”, x, x]
\end{verbatim}

– As is standard, ActorScript uses the token \texttt{//} to begin a one-line comment. In this article, comments are depicted in gray font.
– Reserved words are shown in bold font.

\footnote{As is standard, ActorScript uses the token \texttt{//} to begin a one-line comment. In this article, comments are depicted in gray font.}
\footnote{Reserved words are shown in bold font.}

9
Dependent bindings (in which each can depend on previous ones) can be accomplished using "[" followed by bindings separated using "," terminated by "]". Also, a binding can be accomplished using a list pattern. For example, ["L", ["H", "F"], ["K", "F"]] could be written as follows:

```latex
\begin{align*}
\text{Let } & \langle x \leftarrow "F", \quad // \; x \text{ is } "F" \\
 & y \leftarrow ["G", x, x], \quad // \; y \text{ is } ["G", "F", "F"] \\
 & [u, v] \leftarrow ["H", x, ["K", x]], \quad // \; u \text{ is } ["H", "F"] \text{ and } v \text{ is } ["K", "F"] \\
 & ["L", u, v]\end{align*}
```

Also, multiple results can be bound. For example

```latex
\begin{align*}
\text{Let } & \langle \text{[quotient, remainder]} \leftarrow \text{QuotientRemainder }7/3, \quad // \; \text{quotient is } 2 \text{ and remainder is } 1 \\
 & \text{quotient }-\text{remainder}\end{align*}
```

The formal syntax of bindings is in the following end note: 15.

**Actor expressions with Assignable Variables, i.e., Actor and :=**

Using the expressions introduced so far, actors do not change. Mutable Actors are introduced below.

An Actor can be created using "Actor" optionally followed by the following:
- constructor name with formal arguments delimited using brackets
- declarations of variables\(^1\)
- implementations of interface(s).

Reserved words (e.g., Actor) are case sensitive. Furthermore, an infix reserved word is always lower case.

Message handlers in an Actor execute mutually exclusively. In this paper assignable variables are colored orange, which by itself has no semantic significance, i.e., printing this article in black and white does not change any meaning. The use of assignments is strictly controlled in order to achieve better structured programs.\(^{16}\)

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\(^1\) each variable declaration followed by a comma

\(^{16}\)
Below is an example of an account which provides the ability to get the current balance, deposit an amount, and withdraw an amount:

\[
\text{Actor SimpleAccount[startingBalance:Euro]}
\]

\[
\text{myBalance \equiv startingBalance,}
\quad // \text{myBalance is an assignable variable initialized with startingBalance}
\]

\[
\text{implements Account\! using}
\]

\[
\text{getBalance[ ] \rightarrow myBalance \}
\]

\[
\text{deposit[anAmount:Euro] \rightarrow Void} \quad // \text{return Void afterward myBalance \equiv myBalance+anAmount}]
\]

\[
\text{withdraw[anAmount:Euro] \rightarrow (amount > myBalance) \quad True \; \text{\r{\textbf{\uparrow}} \!\text{Throw OverdrawnException[ ],}}
\]

\[
\text{False \; \text{\r{\textbf{\uparrow}} \!\text{Void} \quad // \text{return Void afterward myBalance \equiv myBalance-anAmount}]}\]
\]

The formal syntax of \textit{Actor} expressions is in the following end note: \textbf{18}.

A message handler signature consists of a message name followed by argument types delimited by “\[” and “\]”, “\rightarrow”, and a return type. An alternative syntax (which is more like Java) is that a message handler signature can be written as a return type followed by “\r{\textbf{\uparrow}}”, message name, and argument types delimited by “\[” and “\]”.

The formal syntactic definition of named-message sending is in the following end note: \textbf{19}

**Continuations**

Continuations are used in ActorScript to linearize computation and to increase referential transparency of variables.\textsuperscript{20} Regions highlighted in yellow above are continuations.

\[
\text{1 Interface Account{getBalance[ ]\rightarrow Euro,}
\quad // equivalently Euro \r{\textbf{\uparrow}} \!\text{getBalance[ ]}
\quad \text{deposit[Euro] \rightarrow Void,}
\quad \text{withdraw[Euro] \rightarrow Void})}
\]
For example, the following sub-continuation in the `withdraw` handler

```plaintext
Void afterward myBalance := myBalance + anAmount
returns Void and updates myBalance for the next message received.
```

By linearizing computation, a continuation prevents default concurrency and consequently variable data races are impossible.

The formal syntax of continuations is in the following end note: 21.

**Antecedents, Preparations, and Concurrency, i.e., ; and ⦷**

An expression can be annotated for concurrent execution by preceding it with “⦷” indicating that the following expression should be considered for concurrent execution if resources are available. For example

```plaintext
⦷ Factorial₄[1000] + ⦷ Fibonacci₄[2000] ⦷
```

is annotated for concurrent execution of `Factorial₄[1000]` and `Fibonacci₄[2000]` both of which must complete execution. This does not require that the executions of `Factorial₄[1000]` and `Fibonacci₄[2000]` actually overlap in time.

The formal syntax of explicit concurrency is in the following end note: 22.

Concurrency can be controlled using preparation that is expressed in a continuation using “Do” followed by a preparatory expressions, “⦷” and an expression that proceeds only after the preparations have been completed.

The following expression creates an account `anAccount` with initial balance €5 and then concurrently withdraws €1 and €2 in preparation for reading the balance:

```plaintext
Let anAccount ← SimpleAccount₄[€6], // € is a reserved prefix operator
Do ⦷ anAccount.withdraw[€1],
    ⦷ anAccount.withdraw[€2] ⦷ ⦷
    // proceed only after both of the
    // withdrawals have been acknowledged

anAccount.getBalance[ ]
```

The above expression returns €3.

Operations are quasi-commutative to the extent that it doesn’t matter in which order they occur. Quasi-commutativity can be used to tame indeterminacy.

The formal syntax of compound expressions is in the following end note: 23
Swiss cheese

Swiss cheese [Hewitt and Atkinson 1977, 1979; Atkinson 1980] is a generalization of mutual exclusion with the following goals:

- **Generality:** Ability to conveniently program any scheduling policy
- **Performance:** Support maximum performance in implementation, e.g., the ability to minimize locking and to avoid repeatedly recalculating a condition for proceeding.
- **Understandability:** Invariants for the variables of a mutable Actor should hold whenever entering or leaving the cheese.
- **Modularity:** Resources requiring scheduling should be encapsulated so that it is impossible to use them incorrectly.

Message handlers in an Actor execute mutually exclusively while in the “cheese”, *i.e.*, at most one activity can execute in the cheese at a time. However, there can be “holes” in the cheese to permit other activities to happen and then continue execution. This is achieved using “string bean style” to control visibility of effects (e.g. assignments) and to enforce sequencing moving in and out of the cheese.

In the examples below, holes in the cheese are highlighted in grey and queues are shown in orange. The color has no semantic significance. In addition to reserved words being case sensitive, if a reserved word begins a phrase (*e.g. Enqueue*) then it always capitalized and infix reserved words within the phrase (*e.g. for, permit, afterward*, etc.) are lower case.

A variable can change only as follows:

- just after leaving the cheese or after an internal delegated operation.
- when cheese is (re-)entered, a variable has the value when the cheese was last left.

---

1 Consequently, variable races are impossible.
Below is an implementation of a Gate that suspends those who send a passThru[] and whenever the gate receives an open[] message, then those already waiting are allowed to pass through.

**Actor** PassThruWhenOpenedGate[]

```plaintext
queue aQueue
    // declare aQueue to be a queue for activities, which is initially empty
implements Gate using
    passThru[] →
        Enqueue aQueue
            // Enqueue this activity in aQueue and then leave cheese
        Void
            // when resumed return Void and
        permit aQueue
            // permit the first of aQueue
open[] → Void
    // return Void
    permit aQueue
        // resume the first of aQueue
```

The formal syntax of the above is in the following end note: 

The following is a state diagram of the above implementation PassThruWhenOpenedGate:
Below is an implementation of a Gate\(^1\) that suspends those who send a passThrough[] until the gate is opened by receiving an open[] message and thereafter remains open:

```java
Actor OnetimeGate[]
  queue aQueue,
  opened := False,
  // opened is a local assignable variable that is initially False
implements Gate using
  passThru[] →
  Do opened ≠ False \ Brand \ Enqueue aQueue \ BRAND \ Void,
    // if opened is False, then join aQueue and leave cheese
  True \ Void \ BRAND \ Void,
    // if opened is True
  \ BRAND \ then proceed immediately without leaving cheese

Precondition\(^2\) opened,
  // opened must be True or an exception is thrown\(^3\)
Void
  // return Void and
open[] → Void
  // return Void and
  permit aQueue \ BRAND \ // resume the first of aQueue\(^4\)
  // also
always opened := True \ BRAND \ // opened always assigned True
```

The following is a state diagram of the above implementation OnetimeGate:

```
```

The formal syntax of the above is in the following end note: 33

\(^1\) Interface Gate \{passThru[] → Void, opened[] → Void\} \^
By contrast with the nondeterministic lambda calculus, there is an always-halting Actor that when sent a start message can compute an integer of unbounded size. This is accomplished by sending a counter that it creates both a stop message and a go message. The counter is created with an integer variable currentCount initially 0 and a Boolean variable continue that is initially True with the following behavior:

- When a stop message is received, set continue to False and return currentCount.
- When a go message is received:
  1. if continue is True, increment currentCount by 1 and send the counter a go message.
  2. if continue is False, return Void

By the Actor Model of Computation [Clinger 1981, Hewitt 2006], the above Actor will eventually receive the stop message and return an unbounded number.

As a convenience, a message can be delegated to this Actor by prefixing the message with “∎”.

Unbounded ≡

```
start [] → // a start message is implemented by
Let aCounter ← SimpleCounter [] // let aCounter be a new Counter
Do [aCounter.go [], // send aCounter a go message and concurrently
   aCounter.stop []] // return the result of sending aCounter a stop message
```

Actor SimpleCounter []

```plaintext
count ≔ 0, // the variable count is initially 0
continue ≔ True,
implements Counter using
stop [] →
   count // return count
   afterward continue ≔ False // continue is updated to False for the next message received
   go [] →
      continue ⊢
      True ≔ Hole go [], // send go to this counter after
      after count ≔ count + 1, // incrementing count
      False ≔ Void ⊢, // if continue is False, return Void
```

The formal syntax of the above is in the following end note: 35
A barbershop\textsuperscript{36} with two barbers can be implemented as follows:

\begin{verbatim}
Actor SimpleShop[waitingRoomCapacity: Integer,
firstBarber: Barber,
secondBarber: Barber]
queue aQueue,
firstBarberIsShaving \equiv False,  // initially neither barber is shaving
secondBarberIsShaving \equiv False,
implements BarberShop\textsuperscript{37} using
visit[aClient: Client] →
Do (Length aQueue) > waitingRoomCapacity \rightarrow
  True \wedge Throw WaitingRoomFull[],  // waiting room is full
  False \rightarrow (firstBarberIsShaving \land secondBarberIsShaving) \rightarrow
    True \rightarrow Enqueue aQueue \rightarrow Void,
    // if both barbers are shaving then enqueue in aQueue
False \rightarrow Void,  // one of the barbers must be free or an exception is thrown\textsuperscript{38}

Precondition \neg firstBarberIsShaving \lor \neg secondBarberIsShaving,
  // one of the barbers must be free or an exception is thrown\textsuperscript{38}
\neg firstBarberIsShaving \rightarrow
  True \rightarrow
    // first barber is always preferred
    Hole firstBarber.shave[aClient]
    // leave cheese while shaving
    // after recording that first barber is shaving
    after firstBarberIsShaving \equiv True
    returned\rightarrow aTip \rightarrow
      Do firstBarber.giveTip[aTip],
      Void permit aQueue \rightarrow
        always firstBarberIsShaving \equiv False,
        threw permit aQueue
        always firstBarberIsShaving \equiv False.
False \rightarrow
    Hole secondBarber.shave[aClient]\rightarrow
    after secondBarberIsShaving \equiv True
    returned\rightarrow aTip \rightarrow
      Do secondBarber.giveTip[aTip],
      Void permit aQueue \rightarrow
        always secondBarberIsShaving \equiv False,
        threw permit aQueue
        always secondBarberIsShaving \equiv False.
\end{verbatim}
The following is a state diagram of the above implementation Shop:

Concurrence control for readers and writers in a shared resource is a classic problem. The fundamental constraint is that multiple writers are not allowed to operate concurrently and a writer is not allowed operate concurrently with a reader.

Swiss cheese with holes
Below are two implementations of readers/writer guardians for a shared resource that implement different policies:

1. ReadingPriority: The policy is to permit maximum concurrency among readers without starving writers.
   a. When no writer is waiting, all readers start as they are received.
   b. When a writer has been received, no more readers can start.
   c. When a writer completes, all waiting readers start even if there are writers waiting.

2. WritingPriority: The policy is that readers get the most recent information available without starving writers.
   a. When no writer is waiting, all readers start as they are received.
   b. When a writer has been received, no more readers can start.
   c. When a writer completes, just one waiting reader is permitted to complete if there are waiting writers.

The interface for the readers/writer guardian is the same as the interface for the shared resource:

```
Interface ReadersWriter {read[Query]→ QueryResult,
                          write[Update]→ Void}
```
State diagram of **ReadersWriter** implementations:

Note:
1. At most one activity is allowed to execute in the cheese.\(^i\)
2. The cheese has holes.\(^ii\)
3. The value of a variable\(^iii\) changes only when leaving the cheese or after an internal delegated operation.\(^iv\)

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\(^i\) Cheese is yellow in the diagram
\(^ii\) A hole is grey in the diagram
\(^iii\) A variable is orange in the diagram
\(^iv\) Of course, other external Actors can change.
Actor ReadingPriority [theResource: ReadersWriter]

queues {readersQ, writersQ} // readersQ and writersQ are initially empty
writing ≔ False,
numberReading:(Integer thatIs ≧ 0) ≔ 0,

implements ReadersWriter using

read[query]→
  Do (writing ∨ ¬IsEmpty writersQ) ◊
  True ≔ Enqueue readersQ ◊ Void // leave cheese while in readersQ
  backout (¬writing ∧ numberReading=0 ∧ ¬IsEmpty readersQ) ◊
  True $\Downarrow$ Void permit writersQ,
  False $\Downarrow$ Void,
 False $\Downarrow$ Void,
  Precondition ¬writing,45
  Hole theResource, read[query] // leave cheese while
  after permit readersQ always numberReading++ 46
  afterward
  (IsEmpty writersQ) ◊
  True ≔ permit readersQ always numberReading— 47
  False ≔ numberReading ◊
  1 $\Downarrow$ permit writersQ always numberReading—,
  else $\Downarrow$ also numberReading— 48

write[update]→
  Do numberReading>0 ∨ ¬IsEmpty readersQ ∨ writing ∨ ¬IsEmpty writersQ ◊
  True ≔ Enqueue writersQ ◊ Void // leave cheese while in writersQ
  backout (isEmpty writersQ ∧ ¬writing) ◊
  True $\Downarrow$ Void permit readersQ,
  False $\Downarrow$ Void,
  False $\Downarrow$ Void,
  Precondition numberReading=0 ∨ ¬writing,48
  Hole theResource, write[update] // leave cheese while writing after
  after writing $\Downarrow$ True // recording that writing is happening
  afterward (IsEmpty readersQ) ◊
  True ≔ permit writersQ always writing $\Downarrow$ False,
  False ≔ permit readersQ always writing $\Downarrow$ False,48
Illustration of writing-priority:

Actor WritingPriority [theResource: ReadersWriter]
queues readersQ, writersQ.
writing := False.
numberReading: (Integer that satisfies \(\geq 0\)) := 0,
implements ReadersWriter using
read[query] →

Do (writing \(\lor\) Empty writersQ) ♦
  True := Enqueue readersQ ♦ Void // leave cheese while in readersQ,
   backout (writing \(\land\) numberReading=0 \(\land\) isEmpty readersQ)
   True := Void permit writersQ,
   False := Void [7],
False := Void [7],

Precondition \(\neg\)writing.

Hole theResource, read[query]

after isEmpty writersQ ♦
  True := permit readersQ always numberReading++,
  False := Also numberReading++ [7],
  afterward
  (isEmpty writersQ) ♦
  True := permit readersQ always numberReading--,
  False := numberReading ♦
  True := permit writersQ always numberReading--
else := numberReading-- [7] [7]

write[update] →

Do numberReading>0 \(\lor\) isEmpty readersQ \(\lor\) writing \(\lor\) isEmpty writersQ ♦
  True := Enqueue writersQ ♦ Void // leave cheese while in writersQ,
   backout (isEmpty writersQ \(\land\) writing) ♦
   True := Void permit readersQ,
   False := Void [7],
False := Void [7],

Precondition numberReading=0 \(\land\) \(\neg\)writing.

Hole theResource, write[update]

after writing := True

afterward
  (isEmpty readersQ) ♦
  True := permit writersQ always writing := False,
  False := permit readersQ always writing := False [7] [7]

The formal syntax of queue management in cheese is in the following end note: 49.
Conclusion

Before long, we will have billions of chips, each with hundreds of hyper-threaded cores executing hundreds of thousands of threads. Consequently, GOFIP (Good Old-Fashioned Imperative Programming) paradigm must be fundamentally extended. ActorScript is intended to be a contribution to this extension.

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ActorScript is intended to provide a foundation for information integration in privacy-friendly client-cloud computing [Hewitt 2009b].

\(^1\) In the sense that the implementation never spins on a hardware lock.
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Appendix 1. Extreme ActorScript

Parameterized Types, i.e., `<`, `>`

Parameterized Types are specialized using other types delimited by “<” and “>”:

```
Double< #Type > ≡
Actor implements [ #Type ]→#Type using
[ x ]→ x+x §  // addition for #Type
```

The formal syntax of parameterized types is in the following end note: 50.

Structures, i.e., Structure

A structure can be defined using a structure identifier followed a list of the parts enclosed by “[“ and “]”.

For example, the structure Leaf can be defined as follows to extend Tree:

```
Structure Leaf< #Type >[ #Terminal: #Type ] extends Tree< #Type >
// a terminal must be of type #Type
```

For example,
- The expression Let xᵢ ← 3, Leaf< Integer >[x] is equivalent to Leaf< Integer >[3]
- The pattern Leaf< Integer >[x] matches Leaf< Integer >[3] and binds x to 3.

The formal syntax of structures is in the following end note: 51

Structures with named fields, i.e., ⇢ and ↳

The structure Fork can be defined as follows:

```
Structure Fork< #Type >[ left ⇢ Tree, right ↳ Tree ]
extends Tree< #Type >
```

\[x\] is of type Integer
For example,

- The expression
  \[
  \text{Let } x \leftarrow 3, \quad \text{Fork} \langle \text{Integer} \rangle [\text{left} \Leftarrow \text{Leaf} \langle \text{Integer} \rangle [x], \\
  \text{right} \Leftarrow \text{Leaf} \langle \text{Integer} \rangle [x+1])
  \]
  is equivalent to the following:
  \[
  \text{Fork} \langle \text{Integer} \rangle [\text{Leaf} \langle \text{Integer} \rangle [\text{left} \Leftarrow 3], \\
  \text{right} \Leftarrow \text{Leaf} \langle \text{Integer} \rangle [4])
  \]
- The pattern \text{Fork} \langle \text{Integer} \rangle [\text{left} \Leftarrow x, \text{right} \Leftarrow y] matches \text{Fork} \langle \text{Integer} \rangle [\text{Leaf} \langle \text{Integer} \rangle [6], \text{Leaf} \langle \text{Integer} \rangle [6]] and binds x to \text{Leaf} \langle \text{Integer} \rangle [5] and y to \text{Leaf} \langle \text{Integer} \rangle [6].

The formal syntax structures with named fields is in the following end note: 52.

**Processing Exceptions, i.e., Try catch, & Try cleanup**

It is useful to be able to catch exceptions. The following illustration returns the string “This is a test.”:

\[
\text{Try Throw Exception} ["This is a test."] \text{ catch Exception}[a\text{String}: a\text{String}]
\]

The following illustration performs \text{Reset} \[\] and then rethrows \text{Exception} ["This is another test."]:

\[
\text{Try Throw Exception} ["This is another test."] \text{ cleanup Reset} [\]
\]

The formal syntax of processing exceptions is in the following end note: 53.

**Runtime Requirements, i.e., Precondition ; and postcondition**

A runtime requirement throws exception an exception if does not hold. For example, the following expression throws an exception that the requirement \( x \geq 0 \) doesn't hold:

\[
\text{Let } x \leftarrow -1, \\
\text{Precondition } x \geq 0, \\
\text{SquareRoot} [x]
\]

Post conditions can be tested using a procedure. For example, the following expression throws an exception that \text{postcondition} failed because square root of 2 is not less than 1:

\[
\text{SquareRoot} [2] \text{ postcondition } [y: \text{Float}] \rightarrow y < 1
\]

The formal syntax requirements is in the following end note: 54.
Polymorphism

Polymorphism provides for multiple implementations of a type. For example, Cartesian Actors that implement Complex can be defined as follows:

Actor Cartesian[myReal: Float default 0, myImaginary: Float default 0]

implements Complex using

// construct a Cartesian of type Complex
realPart[] → myReal¶
imaginaryPart[] → myImaginary¶
magnitude[] →
SquareRoot.[myReal*myReal + myImaginary*myImaginary]¶
angle[] →
Let theta ← Arcsine.[myImaginary/ magnitude[]], // magnitude[] is the result of sending magnitude[] to this Actor
myReal>0 ¶
True ⚫ theta,
False ⚫ myImaginary >0 ¶
True +180°-theta,55
False +180°+theta ¶¶

plus[argument]→
Let argumentRealPart ← argument.realPart[],
argumentImaginaryPart ← argument.imaginaryPart[],
Cartesian[myReal+argumentRealPart,
myImaginary+argumentImaginaryPart]¶

times[argument]→
Let {argumentRealPart ← argument.realPart[],
argumentImaginaryPart ← argument.imaginaryPart[]},
Cartesian[myReal*argumentRealPart
- myImaginary*argumentImaginaryPart,
myImaginary*argumentRealPart
+ myReal*argumentImaginaryPart]¶
equivalent[x] → // test if x is an equivalent complex number
myReal=zx.realPart[] ∧ myImaginary=zx.imaginaryPart[]¶81

\[1\] Interface Complex {realPart[] → Float,
imaginaryPart[] → Float,
magnitude[] → Float,
angle[] → Degrees,
plus[Complex] → Complex,
times[Complex] → Complex,
equivalent[Complex] → Boolean}
Consequently,
- Cartesian,[1, 2].realPart[] is equivalent to 1
- Cartesian,[3, 4].magnitude[] is equivalent to 5.0
- Cartesian,[0, 1].times[Cartesian,[0, 1]] is equivalent to Cartesian,-1, 0]
- Cartesian,[1, 2].Complex[] is equivalent to True
- Cartesian,[1, 2].Cartesian[] is equivalent to False because the constructor returns Actors of type Complex

Arguments with named fields, i.e., and :

Polar Actors that implement Complex with named arguments angle and magnitude can be defined as follows:

```
Actor Polar[angle Degrees default 0],
    // angle of type Degrees is a named argument of Polar with // default 0°
    magnitude Length]
implements Complex using
    angle[]→ angle[]
    realPart[]→ magnitude*Sine.[angle][]
    imaginaryPart[]→ magnitude*Cosine.[angle][]
    plus[argument]→
        Cartesian,[argument,realPart[] + ×realPart[],
            // ×realPart[] is the result of sending realPart[] to this Actor argument,imaginaryPart[] + ×imaginaryPart[]][]
    times[argument]→
        Polar,[angle=angle + argument.angle[],
            magnitude=magnitude*argument.magnitude[]][]
    equivalent[x]→
        x × z;Complex ×realPart[] = z.realPart[]
        ^ ×imaginaryPart[] = z.imaginaryPart[]
        else = False
```

Consequently,
- Polar,[theAngle = 0°, theMagnitude = 1].realPart[] is equivalent to 1
- (Polar,[theMagnitude = 1]).equivalent[Cartesian,[1, 0]] is equivalent to True
Lists, i.e., [ | ] using Spread, i.e., [ | ]

A list expression begins with “List” followed by the type of list element\(^{i}\) and expressions for list elements\(^{ii}\). Similarly “Lists” is used for a list of lists. The prefix operator ”\(|\) can be used to spread the elements of a list. For example

- \(\text{List}\langle\text{Integer}\rangle\{1, \text{\[2, 3, 4]\}}\) is equivalent to \(\text{List}\langle\text{Integer}\rangle\{1, 2, 3, 4\}\).
- \(\text{Lists}\langle\text{Integer}\rangle\{1, 2, \text{\[3, 4]\}}\) is equivalent to \(\text{Lists}\langle\text{Integer}\rangle\{1, 2, 3, 4\}\).
- If \(y\) is \(\text{List}\langle\text{Integer}\rangle\{5, 6\}\), then \(\text{Lists}\langle\text{Integer}\rangle\{1, 2, \text{\[y\]}, \text{\[y\]}\}\) is equivalent to \(\text{Lists}\langle\text{Integer}\rangle\{1, 2, 5, 6, 5, 6\}\).
- \(\text{List}\langle\text{Integer}\rangle\{1, 2\}\) is the list of integers of type \(\text{Integer}\) with just 1 and 2.
- \(\text{List}\langle\text{Integer}\rangle\{1, 2.0\}\) throws an exception because 2.0 is not of type \(\text{Integer}\).

The formal syntax of list expressions is in the following end note: \(^{57}\).

A list pattern begins with “List” followed by the type of list element\(^{iii}\) and patterns for list elements\(^{iv}\). Within a list, “|” is used to match the pattern that follows with the list zero or more elements. Similarly “Lists” is used for a list of lists. For example:

- \(\text{Lists}\langle\text{Integer}\rangle\{\text{\[x\]}, 2, \text{\[\text{\[y\]}\]}\}\) is a pattern that matches \(\{\{1, 2\}, 3, 4\}\) and binds \(x\) to 1 and \(y\) to \(\{3, 4\}\).
- \(\text{Lists}\langle\text{Integer}\rangle\{\{1, 2\}, \text{\[\text{\[y\]}\]}\}\) is a pattern that only matches \(\text{Lists}\langle\text{Integer}\rangle\{\{1, 2\}, 3, 4\}\) if \(y\) is \(\text{Lists}\langle\text{Integer}\rangle\{3, 4\}\).
- \(\text{List}\langle\text{Integer}\rangle\{\text{\[\text{\[x\]}\]}, \text{\[\text{\[y\]}\]}\}\) is an illegal pattern because it can match ambiguously.

The formal syntax of patterns is in the following end note: \(^{58}\).

\(^{i}\) delimited by <and >
\(^{ii}\) delimited by “[” and “]”
\(^{iii}\) delimited by <and >
\(^{iv}\) delimited by “[” and “]”
As an example of the use of spread, the following procedure returns every other element of a list beginning with the first:69

\[
\text{AlternateElements} \equiv \begin{cases} 
\text{List} & \text{if List[0] \neq []}, \\
\text{List} & \text{if List[0] = [\_]}, \\
\text{List} & \text{if List[0] = [firstElement, secondElement]}, \\
\text{else} & \\
\text{List} & \text{if List[0] = [firstElement, remainingElements]}, \\
\text{else} & \\
\text{List} & \text{if List[0] = [firstElement, secondElement, remainingElements]}. 
\end{cases}
\]

Consequently,
- \text{AlternateElements}([\text{List}\{1\}]) \equiv \text{List}\{1\}
- \text{AlternateElements}([\text{List}\{3\}]) \equiv \text{List}\{3\}
- \text{AlternateElements}([\text{List}\{3, 4\}]) \equiv \text{List}\{3\}
- \text{AlternateElements}([\text{List}\{3, 4, 5\}]) \equiv \text{List}\{3, 5\}

\textbf{Sets, i.e., \{} \text{ using spreading, i.e., \{} \text{ \}}}
A set is an unordered structure with duplicates removed.

The formal syntax of sets is in the following end note: 60.

\textbf{Multisets, i.e., \{} \text{ using spreading, i.e., \{} \text{ \}}}
A set is an unordered structure with duplicates allowed.

The formal syntax of multisets is in the following end note: 61.

\textbf{Maps, i.e., Map\{ \}}
A map is composed of pairs. For example Map\{[3, “a"], ["x", "b"]\}.

Pairs in maps are unordered, e.g., Map\{[3, “a"], ["x", "b"]\} \equiv \text{Map\{["x", "b"], [3, “a”]\}}.

However, the expression Map\{["y", "b"], ["y", “a"]\} throws an exception because a map is univalent. As another example, for the contact records of
1.1 billion people, the following can compute a list of pairs from age to average number of social contacts of US citizens sorted by increasing age:

\[ \text{Age} \equiv \text{Integer that is } \geq 0 \leq 130 \]

\[ \text{AgeToAverageOfNumberOfContactsPairsSortedByAge} \equiv 62 \]

\[ \text{records, filter}^\text{ii} \equiv \text{List<ContactRecord>} \]

\[ \text{filter}^\text{ii} \equiv \text{[aRecord: ContactRecord] determine } \rightarrow \]

\[ \text{aRecord[citizenship] } \equiv \text{"US" : True, else : False} \]

\[ \text{collect}^\text{iii} \equiv \text{[aRecord: ContactRecord] determine } \rightarrow \]

\[ \text{[aRecord[yearsOld], aRecord[numberOfContacts]]} \]

\[ \text{reduceRange}^\text{iv} \equiv \text{[aSetOfNumberOfContacts: Set<Integer>] determine } \rightarrow \]

\[ \text{aSetOfNumberOfContacts[average][]} \]

\[ \text{sort}^\text{vi} \equiv \text{[LessThanOrEqual]} \]

The formal syntax of maps is in the following end note: 63.

\[ ^1 \text{Structure ContactRecord: yearsOld } ] \equiv \text{Age, numberOfContacts } ] \equiv \text{Integer, citizenship } ] \equiv \text{String} \]

\[ ^\text{ii} \text{Set:<ContactRecord> has filter[[ContactRecord] } ] \equiv \text{Boolean} ] \rightarrow \text{Set:<ContactRecord> } ] \]

\[ ^\text{iii} \text{Set:<ContactRecord> has collect [[ContactRecord] } ] \equiv \text{[Age, Integer]] } ] \rightarrow \text{Map<Age, Set<Integer>>}[ ] \]

\[ ^\text{iv} \text{Map<Age, Set<Integer>> has reduceRange[<Set<Integer>> } ] \equiv \text{Float] } ] \rightarrow \text{Map<Age, Float> } ] \]

\[ ^\text{v} \text{Set:<Number> has [average[] } ] \equiv \text{Float} \]

\[ ^\text{vi} \text{Map<Age, Float> has sort[[Age, Age] } ] \equiv \text{Boolean} ] \rightarrow \text{List<[Age, Float]> } ] \]
Futures, i.e., Future and ↓
A future [Baker and Hewitt 1977] for an expression can be created in ActorScript by using “Future” preceding the expression. The operator “↓” can be used to "resolve" a future by returning an Actor computed by the future or throwing an exception. For example, the following expression is equivalent to \[\text{Factorial} \[9999\]\]

\[
\begin{align*}
\text{Let } a\text{Future} &\leftarrow \text{Future} \text{Factorial} \[9999\], \\
\downarrow a\text{Future} &\quad \text{// do not proceed until \text{Factorial} \[9999\] has resolved}
\end{align*}
\]

Futures allow execution of expressions to be adaptively executed indefinitely into the future.\(^6\) For example, the following returns a future

\[
\begin{align*}
\text{Let } a\text{Future} &\leftarrow \text{Future} \text{Factorial} \[9999\], \\
g &\leftarrow (\text{afuture:Future< Integer> } \rightarrow 5), \\
g \downarrow a\text{Future} &\quad \text{// g returns 5 regardless of its argument}
\end{align*}
\]

Note that the following are all equivalent:\(^6\):

- \(\downarrow \text{Future} (4+ \text{Factorial} \[9999\])\)
- \(4+\downarrow \text{Future} \text{Factorial} \[9999\]\)
- \(4+\text{\textcircled{}} \text{Factorial} \[9999\]\)
- \(\text{\textcircled{}} (4+ \text{Factorial} \[9999\])\)

Also \(\text{\textcircled{}} \text{Factorial} \[9999\]+\text{\textcircled{}} \text{Fibonacci} \[9000\]\) is equivalent to the following:

\[
\begin{align*}
\text{Let } \{n^* &\leftarrow \text{\textcircled{}} \text{Factorial} \[9999\], \\
m &\leftarrow \text{\textcircled{}} \text{Fibonacci} \[9000\] \\
n+m &\quad \text{// return Factorial} \[9999\]+\text{Fibonacci} \[9000]\}
\end{align*}
\]

\(^1\) f is of type \text{Future< Integer>}
\(^ii\) i.e. returned or threw an exception
\(^iii\) i.e. \text{Factorial} \[1000\] might not have returned or threw an exception when 5 is returned. The future f will be garbage collected.
\(^iv\) n is of type \text{Integer}
In the following example, `Factorial_{9999}` might never be executed if `readCharacter_{[ ]}` returns the character 'x':

\[
\text{Let } a\text{Future} \leftarrow \text{Future Factorial}_{9999}, \\
\text{readCharacter}_{[ ]} \quad \rightarrow \quad 'x' \uparrow 1, \quad \text{// readCharacter}_{[ ]} \text{ returned 'x'} \\
\text{else } \uparrow 1+ \text{aFuture} \quad \text{// readCharacter}_{[ ]} \text{ returned something other than 'x'}
\]

In the above, program resolution of `aFuture` is highlighted in yellow.

Futures can be chained, as in the following example:

\[
\text{Size}_{[ } \text{aFutureList: Future}_{\text{List}<\text{String}>}[ ] \text{]: Future}_{\text{Integer}} \equiv \text{aFutureList } \Rightarrow \\
\text{Future}_{\text{List}<\text{String}>}[ ] \quad \Rightarrow \\
\text{Future 0}, \\
\text{Future}_{\text{List}<\text{String}>}[ \text{aFirst: String}, \text{aRest: Future}_{\text{List}<\text{String}>}[ ]] \quad \Rightarrow \\
\text{Future aFirst, length[ ] + Size}_{[ \text{aRest} ]} \quad \Rightarrow 
\]

The above procedure can compute the size of a list concurrently with creating the list. It does so by making use of a partially resolved future highlighted in yellow above.

Below is the definition of a procedure that computes a future of a list that is the “fringe” of the leaves of tree.¹

\[
\text{Fringe}_{[ } \text{aTree: Tree}_{\text{aType}}[ ] \text{]: Future}_{\text{List}<\text{aType}>}[ ] \equiv \text{aTree } \Rightarrow \\
\text{Leaf}_{\text{aType}}[ \text{x} ] \quad \Rightarrow \text{Future}_{[ \text{x} ]}, \\
\text{Fork}_{\text{aType}}[ \text{tree1, tree2} ] \Rightarrow \text{Future} \\
\text{[ } \forall \text{Fringe},_{[ \text{tree1} ]}, \forall \text{Postpone}_{[66]} \text{Fringe},_{[ \text{tree2} ]} \text{]} \quad \Rightarrow 
\]

¹ See definition of Tree above in this article.
The above procedure can be used to define SameFringe that determines if two lists have the same fringe [Hewitt 1972]:

\[
\text{SameFringe} \langle \text{aType} \rangle \\
\text{[aTree} : \text{Tree} \langle \text{aType} \rangle \rangle, \text{anotherTree} : \text{Tree} \langle \text{aType} \rangle \rangle : \text{Boolean} \equiv \\
// \text{ test if two trees have the same fringe}
\]

\[
\text{Fringe} \langle \text{aTree} \rangle \equiv \\
\text{Future List} \langle \text{aType} \rangle \langle[\text{aTree} \rangle \rangle \equiv \\
\text{True, else} \equiv \text{False} \equiv \\
\text{Future List} \langle \text{aType} \rangle \langle[\text{first}, \forall \text{rest}] \rangle \equiv \\
\text{Fringe} \langle \text{anotherTree} \rangle \equiv \\
\text{Future List} \langle \text{aType} \rangle \langle[\text{anotherFirst, \forall \text{anotherRest}] \rangle \equiv \\
\text{first} = \text{anotherFirst} \equiv \\
\text{True} \equiv \text{SameFringe} \langle \text{aType} \rangle \langle[\text{aRest, anotherRest}, \rangle, \rangle \equiv \text{False} \equiv \text{False}
\]

The procedure below given a list of futures returns a future list with the same elements:

\[
\text{Futurize} \langle \text{aType} \rangle \\
\langle[\text{aListOfFutures} : \text{List} \langle \text{Future} \langle \text{aType} \rangle \rangle : \text{Future} \langle \text{List} \langle \text{aType} \rangle \rangle \rangle \equiv \text{aListOfFutures} \equiv \\
\text{Future List} \langle \text{aType} \rangle \langle[], \rangle \\
\text{List} \langle \text{Future} \langle \text{aType} \rangle \rangle \langle[\text{aFirst} : \text{Future} \langle \text{aType} \rangle , \rangle, \rangle \equiv \text{aRest} : \text{List} \langle \text{Future} \langle \text{aType} \rangle \rangle \rangle \rangle \equiv \\
\text{Future List} \langle \text{aType} \rangle \langle[\text{LaFirst, \forall \text{Futurize} \langle \text{aType} \rangle \langle[\text{aRest}] \rangle \rangle \rangle \equiv
\]

The formal syntax of futures is in the following end note: 67.
In-line Recursion (e.g., looping), i.e., $[\leftarrow, \leftarrow] ⇑$

In-line recursion (often called looping) is accomplished using an initial invocation with identifiers initialized using “$←$” followed by “$≜$” and the body.\(^1\)

Below is an illustration of a loop Factorial with two loop identifiers $n$ and accumulation. The loop starts with $n$ equals 9 and value equal 1. The loop is iterated by a call to Factorial with the loop identifiers as arguments.

```plaintext
Factorial[n ← 9, accumulation ← 1] ≜
   n $\diamondsuit$ 1 $\vdash$ accumulation,
   else $\vdash$ Factorial, [n ← 9, n* accumulation] $\sqsubset i$
```

The above compiles as a loop because the call to Factorial in the body is a “tail call” [Hewitt 1970, 1976; Steele 1977].

The following returns a list of ten times successively calling the procedure $P$ (of type $[\rightarrow Integer]$) in order with no arguments:

```plaintext
FirstTenSequentially[n ← 10]:List<Integer> ≜
   n $\diamondsuit$ 1 $\vdash$ [P[],]
   else $\vdash$ Let $x ← P,[],$ [$x, \forall \text{FirstTenSequentially}, [n ← 10]]$ $\sqsubset i$
```

The following returns one of the results of concurrently calling the procedure $P$ (of type $[\rightarrow Integer]$) ten times with no arguments:

```plaintext
OneOfTen[n ← 10]:List<Integer> ≜
   n $\diamondsuit$ 1 $\vdash$ P[],
   else $\vdash \mathbb{C}P,[],$ either $\mathbb{C}\text{OneOfTen}, [n ← 10]]$ $\sqsubset i$
```

The formal syntax of looping is in the following end note: 68.

**Type Discrimination, i.e., Discrimination and $\Delta$**

A discrimination is a type of alternatives differentiated by type using “Discrimination” followed by a type name, “{” a list of types separated using

\(^1\)This construct takes the place of **while**, **for**, **etc.** loops used in other programming languages.

\(^i\)equivalent to the following:

```
Factorial, [n:Integer ← 9, accumulation:Integer ← 1]:Integer ≜
   n $\diamondsuit$ 1 $\vdash$ accumulation,
   else $\vdash$ Factorial, [n ← n-1, n* accumulation] $\sqsubset i$
```

\(^ii\)The procedure $P$ may be indeterminate, i.e., return different results on successive calls.

\(^iv\)The procedure $P$ may be indeterminate, i.e., return different results on different calls.
“,” and terminated by “}". A discriminate can be selected by using a discrimination followed by “∆” and the type to be selected.

For example, consider the following definition:

Discrimination IntegerOrFloat {Integer, Float}

Consequently,

- $(\text{IntegerOrFloat<Integer>[3]})\Delta\text{Integer}$ is equivalent to 3.
- $(\text{IntegerOrFloat<Float>[3.0]})\Delta\text{Integer}$ throws an exception because Integer is not the same as the discriminant Float.
- The pattern x:Float matches IntegerOrFloat<Float>[3.0] and binds x to 3.0.
- The expression $(\text{IntegerOrFloat<Float>[3.0]})\colon\text{x:Float} \Rightarrow x \mapsto x+1$ is equivalent to 4.0.

A nullable is a discrimination:

Discrimination Nullable<@Type> {@Type, Null}@Type}

There is exactly one Actor that is of type Null<@Type>, namely Null.@Type

A nullable can be created as follows:

Nullable x:@Type ≡ Nullable<@Type>[x]

Basic (whose is understood by the pattern matcher) can be defined as follows:

Discrimination Basic

{Integer, Float, Character, Boolean, String,
 Nullable<Basic>, List<Basic>, Set<Basic>,
 Multiset<Basic>, Map<Basic, Basic>}

The formal syntax of type discrimination is in the following end note: 69.

Strings

Strings are Actors that can be expressed using “String”, “[”], string arguments, and “]”. For example,

- String["1", "2", "3", "4"] is equivalent to "1234".
- String["1", "2", "3", "4", "5"] is equivalent to "123456".
- String[String["1", "2", "3"] is equivalent to "1234".
- String[[]] is equivalent to "".

String patterns are delimited by “String”, “[” and “]”. Within a string pattern, “?” is used to match the pattern that follows with the list zero or more characters.
For example:

- \texttt{String[x, '2', \_y]} is a pattern that matches “1234” and binds \texttt{x} to ‘1’ and \texttt{y} to “34”.
- \texttt{String[1, '2', \$\$y]} is a pattern that only matches “1234” if \texttt{y} is “34”.
- \texttt{String[\_x, \_y]} is an illegal pattern because it can match ambiguously.

As an example of the use of spread, the following procedure reverses a string:

\begin{verbatim}
Reverse([aString : String] : String) ≡ 
   aString \[\]
   String[] \[\]
   String[first, \_rest] \[\[\]
   String[\_rest, first]
\end{verbatim}

The formal syntax of string expressions is in the following end note: 71.

**General Messaging, \textsl{i.e.,} \texttt{\_} and \texttt{\_}**

The syntax for general messaging is to use an expression for the recipient followed by \texttt{\_} and an expression for the message.

For example, if \texttt{anExpression} is of type \texttt{Expression<\texttt{Integer}>} then,

\begin{verbatim}
anExpression.eval[anEnvironment]1
\end{verbatim}

is equivalent to the following:

\begin{verbatim}
Let aMessage1 ≡ eval[Expression<\texttt{Integer}>][anEnvironment],
anExpression.aMessage1
\end{verbatim}

The formal syntax of general messaging is in the following end note: 72.

---

\textsuperscript{1} \texttt{aMessage: Message<Expression<\texttt{Integer}>>}

---
Language extension, i.e., ( )

The following is an illustration of language extension that illustrates postponed execution:

\[\text{"Postpone\} anExpression:Expression} < \text{aType}\> : \text{Postpone} < \text{aType}\> \equiv \text{Actor implements Expression} < \text{Future} < \text{aType}\> \text{ using} \]
\[\text{eval[anEnvironment]} \rightarrow \]
\[\text{Future Actor implements aType using} \]
\[\text{aMessage} \rightarrow \quad \text{// aMessage received} \]
\[\text{Let postponed: aType} \leftarrow \quad \text{anExpression, eval[anEnvironment].} \]
\[\text{postponed, aMessage} \]
\[\text{// return result of sending aMessage to postponed} \]
\[\text{become postponed} \quad \text{// become the Actor postponed for} \]
\[\text{// the next message received} \]

The formal syntax of language extension is in the following end note: 73.

---

1. A Postpone expression does not begin execution of Expression until a request is received. Illustration:

\[\text{IntegersBeginningWith} \langle n: Integer\rangle : \langle \text{Future} < \text{List} < \text{Integer}\rangle \rangle \equiv \]
\[\langle n, \text{Postpone} \text{IntegersBeginningWith} < [n+1]\rangle \rangle \]

2. Note: A Postpone expression can limit performance by preventing concurrency

3. aMessage: Message < aType>

4. this is allowed because postponed is of type aType
Atomic Operations, *i.e.* Atomic compare update then else
For example, the following example implements a lockable that spins to
lock: 74

\[
\text{Actor } \text{SpinLock[ ]} \text{ unserialized}
\begin{align*}
\text{locked } & \equiv \text{False}. & \quad \text{// initially unlocked} \\
\text{implements Lockable} & \quad \text{using} \\
& \text{lock[ ]} \rightarrow \text{Attempt[ ]} \triangleq \\
& \quad \text{// perform the loop Attempt as follows} \\
& \quad \text{Atomic locked compare False update True} \\
& \quad \text{// attempt to atomically update locked from False to True} \\
& \quad \text{then Precondition locked=} \text{True,} \\
& \quad \text{// locked must have contents True} \\
& \quad \text{Void,} \quad \text{// if updated return Void} \\
& \quad \text{else Attempt[ ]} \triangledown \quad \text{// if not updated perform Attempt} \\
& \quad \text{unLock[ ]} \rightarrow \\
& \quad \text{Precondition locked } = \text{True,} \quad \text{// locked must have contents True} \\
& \quad \text{Void afterward locked } \equiv \text{False} \quad \text{// reset locked to False}
\end{align*}
\]

The formal syntax of atomic operations is in the following end note: 75.

Enumerations, *i.e.*, Enumeration \{ \} using Qualifiers, *i.e.*, 75
An enumeration provides symbolic names for alternatives. For example,

\[
\text{Enumeration DayName} \{ \text{Monday, Tuesday, Wednesday, Thursday, Friday, Saturday, Sunday} \}
\]

From the above definition, an enumerated day is available using a qualifier, *e.g.*, \text{Monday} \equiv \text{DayName}. Qualifiers provide structure for namespaces.

The formal syntax of qualifiers is in the following end note: 76.

---

\[1 \text{ Interface Lockable } \{ \text{lock[ ]} \rightarrow \text{Void,} \\
\quad \text{unLock[ ]} \rightarrow \text{Void} \]
The procedure below computes the name of following day of the week given the name of any day of the week:

UsingNamespace | DayName |
--- | --- |
FollowingDay | [aDay: `DayName`]: `DayName` ≡ `aDay` \ Monday \ Tuesday, `Tuesday`: `Wednesday`, `Wednesday`: `Thursday`, `Thursday`: `Friday`, `Friday`: `Saturday`, `Saturday`: `Sunday`, `Sunday`: `Monday` |

The formal syntax of enumerations is in the following end note: 77.

**Native types, e.g., JavaScript, JSON, Java, and XML**

`Object` can be used to create JavaScript Objects. Also, `Function` can be used to bind the reserved identifier `This`. For example, consider the following ActorScript for creating a JavaScript object `aRectangle` (with length 3 and width 4) and then computing its area 12:

```actor
Let {aRectangle ← Object{"length": 3, "width": 4}}, aFunction ← Function[[] → This["length"] * This["width"]], Do aRectangle["area"] ≔ aFunction( aRectangle["area"] ),[]
```

The `setTimeout` JavaScript object can be invoked with a callback as follows that logs the string "later" after a time out of 1000:

```javascript
setTimeout( Function [[] → console.log("later")], 1000, [] )
```

**JSON** is a restricted version of `Object` that allows only Booleans, numbers, strings in objects and arrays.

Native types can also be used from Java. For example

```java
(s: `String`).substring[3, 5] \ is the substring of \ s from the 3\textsuperscript{rd} to the 5\textsuperscript{th} characters inclusive.
```

---

\(a\)Rectangle is of type `Object`: `JavaScript`

\(i.e.,\) the following JavaScript types are not included in JSON: `Date`, `Error`, `Regular Expression`, and `Function`.

\(\text{substring}\) is a method of the `String` class in Java.
Java types can be imported using `import`, e.g.:

```
Namespace mynamespace;
Import java.math.BigInteger;
Import java.lang.Number;
```

After the above, `BigInteger.new("123").instanceof[Number]` is equivalent to `true`:

```
BigIn
teger
new
"123"
instanceof
Number

```

The following notation is used for XML:

```
XML <"PersonName"> <"First">"Ole-Johan" <="First">
<="Last"> "Dahl" </="Last"> <="PersonName">
```

and could print as:

```
<PersonName> <First> Ole-Johan </First>
<Last> Dahl </Last> </PersonName>
```

XML Attributes are allowed so that the expression

```
XML <"Country"  "capital"="Paris"> "France" </="Country">
```

and could print as:

```
<Country capital="Paris"> France </Country>
```

XML construction can be performed in the following ways using the append operator:

```
• XML <"doc">1, 2, [3] </="doc"> ] is equivalent to XML <"doc">1, 2, 3 </="doc"> ]

• XML <"doc">1, 2, [3], [4] </="doc"> ] is equivalent to XML <"doc">1, 2, 3, 4 </="doc"> ]
```
One-way messaging, e.g., ⊞, ↹, and ↠

One-way messaging is often used in hardware implementations.

Each one-way named-message send consists of an expression followed by “¤”, a message name, and arguments delimited by “[“ and “]”.

The following is a interface for a customer that is used in request/response message passing for return type aType:\n
\begin{verbatim}
Interface Customer<aType> {
    return[aType] ↠ ⊞,
    throw[anException] ↠ ⊞}
\end{verbatim}

For example, if aCustomer is of type Customer<Integer>, then 3 can be returned to aCustomer ↹ return[3].

The formal syntactic definition of one-way named-message sending is in the end note: 80

Each one-way message handler implementation consists of a named-message declaration pattern followed by “↠” and a body for the response which must ultimately be “⊞” which denotes no response.

The formal syntactic definition of one-way named-message implementation is in the following end note: 81
The following is an implementation of an arithmetic logic unit that implements \texttt{jumpGreater} and \texttt{addJumpPositive} one-way messages:

```plaintext
Actor ArithmeticLogicUnit\langle aType\rangle []
implements ALU\langle aType\rangle using
\texttt{jumpGreater}[x:aType, y:aType, firstGreaterAddress:Address, elseAddress:Address] ↞
InstructionUnit ← \texttt{Execute}(x>y) {\textbf{True}} 
    firstGreaterAddress,
else \textbf{False} elseAddress }]

\texttt{addJumpPositive}[x:aType, y:aType, sumLocation:Location\langle aType\rangle, 
positiveAddress:Address, elseAddress:Address] ↞
Let z ← (x+y),
sumLocation
    aVariableLocation:VariableLocation\langle aType\rangle {\textbf{II}} 
    Do aVariableLocation,store[z] ⊝ 
    // continue after acknowledgement of \texttt{store}
    (z >0) {\textbf{True}} 
    InstructionUnit ← \texttt{execute}[positiveAddress],
    False \texttt{InstructionUnit ← execute}[elseAddress] ⊝,
    aTemporaryLocation:TemporaryLocation\langle aType\rangle {\textbf{III}} 
    Do aTemporaryLocation ← \texttt{write}[z],
    // continue concurrently with processing \texttt{write}
    (z >0) {\textbf{True}} 
    InstructionUnit ← \texttt{execute}[positiveAddress]
    False \texttt{InstructionUnit ← execute}[elseAddress] ⊝ ⊝ ⊝
```

Arrays

Arrays are lists of locations that can be updated using \texttt{swap} messages.

They are included to provide backward compatibility and to support certain kinds of low level optimizations. An array element can be referenced using the array followed by array indices enclosed by “[" and "]”.

\begin{itemize}
\item \texttt{Interface ALU\langle aType\rangle} \{ \texttt{jumpGreater [aType, ]} \mapsto ∅, \texttt{addJumpPositive [anException]} \mapsto ∅ \}
\item \texttt{VariableLocation\langle aType\rangle} \texttt{has store[aType]} \mapsto \texttt{Void}
\item \texttt{TemporaryLocation\langle aType\rangle} \texttt{has write[aType]} \mapsto ∅
\end{itemize}
In the in-place implementation of QuickSort\(^2\) (below), left is the index of the leftmost element of the subarray, right is the index of the rightmost element of the subarray (inclusive), and the number of elements in the subarray is right-(left+1).

\[
\text{QuickSort} \left[ \text{anArray}: \text{Array<Number>}, \text{left: Integer, right: Integer}: \text{Void} \equiv \\
\text{Precondition} \text{anArray}_\text{lower} \leq \text{left} \leq \text{right} \leq \text{anArray}_\text{upper} \right].
\]

\[
\text{(left<right)} \rightarrow \text{True} : \text{Void} \equiv \\
\text{Let pivIndex} \leftarrow \left. \text{Partition} \left[ \text{anArray}, \text{left, right, left}+(	ext{right-left})/2 \right] \right. \\
\text{Precondition} \text{left} \leq \text{pivIndex} \leq \text{right}, \\
\text{Do } \left( \text{QuickSort} \left[ \text{anArray}_\text{left, pivIndex-1} \right] \right) \left( \text{QuickSort} \left[ \text{anArray}_\text{pivIndex+1, right} \right] \right) \\
\text{False} \rightarrow \text{Void} \equiv
\]

\[
\text{Partition} \left[ \text{anArray}: \text{Array<Number>}, \text{left: Integer, right: Integer, pivIndex: Integer}: \text{Integer} \equiv \\
\text{Precondition} \text{anArray}_\text{lower} \leq \text{left} \leq \text{pivIndex} \leq \text{right} \leq \text{anArray}_\text{upper} \right].
\]

\[
\text{Let piv} \leftarrow \text{anArray}_{\text{pivIndex}} \left. \right. \\
\text{Do anArray}_\text{swap}[\text{pivIndex, right}] \equiv
\]

\[
\text{Let finalStoreIndex} \leftarrow \left. \text{Move} \left[ \text{iterationIndex: Integer} \leftarrow \text{left,} \\
\text{storeIndex: Integer} \leftarrow \text{left} \right] \rightarrow \text{Integer} \equiv \\
\text{Precondition} \text{left} \leq \text{storeIndex} \leq \text{iterationIndex} \leq \text{right} \equiv \\
\text{True} : \text{Void} \equiv \\
\text{anArray}_{\text{iterationIndex}} \leq \text{pivotValue} \equiv \\
\text{True} : \\
\text{Do anArray}_\text{swap}[\text{iterationIndex, storeIndex}] \left. \right. \\
\text{Move}_{\text{iterationIndex+1, storeIndex+1}}, \\
\text{False} \rightarrow \text{Void} \equiv \\
\text{storeIndex} \equiv
\]

\[
\text{Do anArray}_\text{swap}[\text{finalStoreIndex, right}] \rightarrow \text{Void} \equiv
\]

\[
\text{finalStoreIndex} \leftarrow \left. \text{Move Actor stored at right to its final place} \right. \\
\text{Final Example, consider the following example:}
\]

\[
\text{Let anArray} \leftarrow \text{Array}[3, 2, 1].
\]

\[
\text{Do QuickSort} \left[ \text{anArray, 0, 1} \right] \equiv
\]

\[
\text{anArray} \equiv
\]
The above returns \texttt{Array[1, 2, 3]}.

**Extending Implementations, i.e., extends**

Consider the following implementation of \texttt{Account}:

\begin{verbatim}
Actor SimpleAccount::<aCurrency<<Currency>:[aBalance:aCurrency]
myBalance := aBalance,
implements Account::<aCurrency>> using
  getBalance[aCurrency -> myBalance]
  deposit[anAmount] →
    Void afterward myBalance := myBalance+anAmount]
  withdraw[anAmount] →
    (anAmount > myBalance) ▽
      True ¶ Throw OverdrawnException[],
      False ¶
        Void afterward myBalance := myBalance–anAmount
\end{verbatim}

A \texttt{facet} is an address of an Actor whose type is of a subsidiary interface of the Actor which is expressed using "≡" followed by the name of the interface.

An implementation can be extended using "extends" followed by a constructor. For example, the implementation \texttt{Account} above can be extended as follows:

\begin{verbatim}
Actor FeeAccount::<aCurrency<<Currency>:[initialBalance:aCurrency,
  fee:aCurrency] extends SimpleAccount::<aCurrency>>[initialBalance]
  partially reimplements Account::<aCurrency>> using
  withdraw[anAmount:aCurrency]:Void override →
  Do ▽ Account::withdraw[anAmount] ¶
    // Use Account for delegated withdraw of
    // anAmount from this account.
    // Note that myBalance changes.
  ▽ Account::withdraw[fee] ¶
    // return delegated withdraw of fee from this account
\end{verbatim}

Please note the following:

- \texttt{FeeAccount::<Euro>>, [€3]: Account} is equivalent to \texttt{False} because a \texttt{FeeAccount} is not of exact type \texttt{Account}
- \texttt{FeeAccount::<Euro>>, [€3]: Account} is equivalent to \texttt{True} because a \texttt{FeeAccount} is of extended type of \texttt{Account}
Also, the implementation \texttt{Account} can be extended as follows to provide the ability to revoke abilities to change an account. For example, \texttt{SimpleAccountMonitor} below implements both the \texttt{Account} and \texttt{AccountRevoker} interfaces as an extension of the implementation \texttt{SimpleAccount}:

\begin{verbatim}
Actor SimpleMonitor≪aCurrency≪Currency≫ [initialBalance:aCurrency] extends SimpleAccount≪aCurrency≪Currency≫ [initialBalance]
    withdrawingIsRevoked = False,
    depositingIsRevoked = False,
    implements AccountMonitor≪aCurrency≫ using
        getAccount[ ] -> Account≪aCurrency≫
        withdrawingFee[anAmount ] ->
            Void afterward myBalance = myBalance - anAmount // withdraw fee even if balance goes negative
    also partially implements Account≪aCurrency≫ using
        withdrawing[anAmount:aCurrency ] ->
            withdrawingIsRevoked ✐
            True ≔ Throw Revoked[ ],
            False ≔ Account≪aCurrency≫ * withdrawing[anAmount] // withdraw[anAmount]
        depositing[anAmount:aCurrency ] ->
            depositingIsRevoked ✐
            True ≔ Throw Revoked[ ],
            False ≔ Account≪aCurrency≫ * depositing[anAmount] // deposit[anAmount]
    also implements AccountRevoker using
        revokeDepositing[ ] ->
            Void afterward depositingIsRevoked = True #
        revokeWithdrawing[ ] ->
            Void afterward withdrawingIsRevoked = True$.
\end{verbatim}

For example, the following expression returns €5:

\begin{verbatim}
Let aMonitor ← SimpleAccountMonitor≪Euro≫.[€3].
Let {anAccount ← aMonitor.getAccount[ ],
    aRevoker ← aMonitor.getRevoker[ ]},
Do {anAccount.deposit(€2) // the balance in anAccount is €5
    aRevoker.revokeDepositing[ ] // depositingIsRevoked in aMonitor is True
    Try anAccount.deposit(€5) // try another deposit
    catch _ ✐ Void[ ] # // ignore the thrown exception
    anAccount.getBalance[ ] // the balance in anAccount remains €5
\end{verbatim}
Appendix 2: Meta-circular definition of ActorScript

It might seem that a meta-circular definition is a strange way to define a programming language. However, as shown in the references, concurrent programming languages are not reducible to logic. Consequently, an augmented meta-circular definition may be one of the best alternatives available.

The message eval

John McCarthy is justly famous for Lisp. One of the more remarkable aspects of Lisp was the definition of its interpreter (called Eval) in Lisp itself. The exact meaning of Eval defined in terms of itself has been somewhat mysterious since, on the face of it, the definition is circular.88

The basic idea is to send an expression an eval message with an environment to instead of the Lisp approach of send the procedure Eval the expression and environment as arguments.

Each eval message has an environment with the bindings of program identifiers:

\[
\begin{align*}
\text{Interface } & \text{Expression aType} \\
\text{extends } & \text{Construct}\ aType \\
\text{eval[Environment]} & \rightarrow \text{aType!}
\end{align*}
\]

The tokens ( and ) are used to delimit program syntax.

\[
\{\text{anIdentifier: Identifier aType}\};\text{Expression aType} \equiv \\
\text{eval[anEnvironment]} \rightarrow \text{anEnvironment lookup[anIdentifier]!}
\]

Querying an Actor using isOfExactly Query and isOfAnExtension Query

There is a special distinguished message named isOfExactly Query that can be used to query whether an Actor implements a type by sending it a hash for the type.

\[
\{\text{anExpression: Expression aType} \text{"." aTypeExpression: Type}\} \\
\text{eval[anEnvironment]} \rightarrow \\
\text{anExpression.eval[anEnvironment]} \\
\text{.isOfExactly Query[aTypeExpression]} \\
\text{.eval[anEnvironment]!} \\
// \text{anExpression implements aTypeExpression}
\]
In addition, there is a special distinguished message named isOfAnExtension that can be used to query whether an Actor inherits from a type by sending it a hash for the type.

The interface Type implements isExtension

The interface Type has message isExtension:

```plaintext
Interface Type {isExtension[aType:Type]→ Boolean}
```

```plaintext
(anExpression:Expression "::" aTypeExpression:Type) :Expression<Boolean> ≡
eval[anEnvironment]→
anExpression.eval[anEnvironment]

.isOfAnExtension Query
[isExtension[aTypeExpression.eval[anEnvironment]]]
// anExpression implements aTypeExpression
```

```plaintext
(anotherType:Type "=>" aType:Type) :Expression<Boolean> ≡
eval[anEnvironment]→
(anotherType.eval[anEnvironment])

.isExtension[aType.eval[anEnvironment]]
```
Future, ↓, and ⦷

The interface `Future` is used for futures:

```
Interface Future<aType> { resolve[ ] → aType }
```

The message `match`

Patterns are analogous to expressions, except that they take receive match messages:

```
Interface Pattern<aType>

{ match[aType, Environment] → Nullable<Environment>,
  mustMatch[aType, Environment] → Environment }
```
\{anIdentifier: Identifier \textless\textless aType\textgreater\textgreater\}: Pattern \textless\textless aType\textgreater\textgreater \equiv
\begin{align*}
\text{match}[\text{anActor}: aType, \text{anEnvironment}] \rightarrow \\
\text{anEnvironment}, \text{bind}[\text{anIdentifier}, \text{to } \square \text{anActor}]\end{align*}

\{(\_\_\_): UniversalPattern \textless\textless aType\textgreater\textgreater \equiv
\begin{align*}
\text{match}[\text{anActor}: aType, \text{anEnvironment}] \rightarrow \text{anEnvironment}\end{align*}

\{(aPattern: Pattern \textless\textless aType\textgreater\textgreater \texttt{"."} aTypeExpression: Type) \texttt{.: TypedPattern \textless\textless aType\textgreater\textgreater} \equiv
\begin{align*}
\text{match}[\text{anActor}, \text{anEnvironment}] \rightarrow \\
\text{anActor}, [\text{aTypeExpression}, \text{eval}[\text{anEnvironment}]]
\end{align*}
\begin{align*}
\text{transitive} \equiv \text{False} \& \& \\
\text{True} \equiv \text{anActor directly implements aTypeExpression} \\
\text{False} \equiv \text{Null Environment \& &}
\end{align*}

\{(\$\$\$ anExpression: Expression \textless\textless expressionType\textgreater\textgreater) \texttt{.: ValuePattern \textless\textless aType\textgreater\textgreater} \equiv
\begin{align*}
\text{match}[\text{anActor}: aType, \text{anEnvironment}] \rightarrow \\
\text{anExpression = anExpression, eval[anEnvironment]} \equiv
\begin{align*}
\text{True} \equiv \text{anEnvironment,} \\
\text{False} \equiv \text{Null Environment \& &}
\end{align*}
\end{align*}
Message sending, e.g.,

\[
\text{procedure:Expression} \begin{array}{c}
\text{argumentsType} \\
\text{returnType}
\end{array} \\
\begin{array}{c}
\text{arguments:Arguments} \\
\text{returnType}
\end{array} \\
\begin{array}{c}
\text{procedureSend:ArgumentsType, returnType} \\
\text{eval[anEnvironment]} \\
\text{[expressions:eval[anEnvironment]]}
\end{array} \equiv
\]

\[
\text{recipient:Expression} \begin{array}{c}
\text{recipientType}
\end{array} \\
\begin{array}{c}
\text{name:MessageName} \\
\text{arguments:Arguments} \\
\text{returnType}
\end{array} \\
\begin{array}{c}
\text{NamedMessageSend:expressionType} \\
\text{Let aRecipient \leftarrow recipient,eval[anEnvironment],} \\
aRecipient \\
\text{Message[QualifiedName[name recipientType],} \\
\text{[arguments:eval[anEnvironment]]]}\end{array} \equiv
\]

\[
\text{recipient:Expression} \begin{array}{c}
\text{recipientType}
\end{array} \\
\begin{array}{c}
\text{aMessage:Message} \\
\text{recipientType}
\end{array} \\
\begin{array}{c}
\text{UnnamedMessageSend:expressionType} \\
\text{eval[anEnvironment]} \\
\text{(recipient,eval[anEnvironment],} \\
aMessage,\text{eval[anEnvironment])}\end{array} \equiv
\]
List Expressions and Patterns

{"[" firstExpression:Expression<type1> 
","" secondExpression:Expression <type2> ""]") 
:ListExpression <expressionType> ≡ 
 eval[anEnvironment]→ 
 Let {first ← firstExpression,eval[anEnvironment], 
 second ← secondExpression.eval[anEnvironment]} 
 [first, second]§

{"[" firstExpression:Expression<type1> 
 
","" restExpression:Expression <type2> ""]") 
:ListExpression <expressionType> ≡ 
 eval[anEnvironment]→ 
 Let {first ← firstExpression,eval[anEnvironment], 
 rest ← restExpression.eval[anEnvironment]} 
 [first, ∀rest]§

{"[" firstPattern:Pattern<type1> 
","" restPattern:Pattern<type1> ""]") 
:ListPattern <aType> ≡ 
 match[anActor:aType, anEnvironment]→ 
 anActor ⇒ [first:type1, ∀rest:tye2] § 
 firstPattern.match[first, anEnvironment] ◦ 
 Null Environment § Null Environment. 
 aNewEnvironment:Environment § 
 restPattern.match[restValue, aNewEnvironment] §§, 
 else § Null Environment §§
Exceptions

`("Try" anExpression:Expression <aType>)
   "catch<>" exceptions:ExpressionCases <aType> ""]
:TryExpression <aType> ≡

eval[anEnvironment]→
   Try anExpression eval[anEnvironment] catch
   anException:Exception ⧅ CasesEval[anException, exceptions, anEnvironment] ⧅§↓

Continuations using perform

A continuations is a generalization of expression for executing in cheese, which receives perform messages:

Interface Continuation <aType> extends Construct <aType>
perform [Environment, CheeseQ]→ aType

Execute,[aConstruct:Construct <aType>],
anEnvironment:Environment,
aCheeseQ:CheeseQ] ≡
aConstruct <> aContinuation:Continuation <aType> ⧅
aContinuation,perform[anEnvironment, aCheeseQ],
else anExpression:Expression <aType> ⧅
anExpression,eval[anEnvironment] ⧅§↓
Atomic compare and update

\[
\text{perform}[\text{anEnvironment}, \text{aCheeseQ}] \mapsto \\
(\text{location}, \text{eval}[\text{anEnvironment}]) \\
, \text{compareAndConditionallyUpdate}[\text{comparison}, \text{eval}[\text{anEnvironment}], \\
\text{update}, \text{eval}[\text{anEnvironment}]] \\
\text{True} \mapsto \text{compareIdentical}. \text{perform}[\text{anEnvironment}, \text{aCheeseQ}], \\
\text{False} \mapsto \text{compareNotIdentical}. \text{perform}[\text{anEnvironment}, \text{aCheeseQ}]
\]

\text{Actor Simple.Location}<\text{anotherType}> \text{[initialContents]} \\
\text{contents} \equiv \text{initialContents}, \\
\text{implements Location}<\text{anotherType}> \text{ using} \\
\text{compareAndConditionallyUpdate}[\text{comparison}, \text{update}] \mapsto \\
(\text{contents} = \text{comparison}) \\
\text{True} \mapsto \text{True} \text{ afterward contents} \equiv \text{update}, \\
\text{False} \mapsto \text{False} \\
\text{¶}
Cases

{anExpression : Expression <anotherType> "\""
  cases : expressionCases <aType> "\"]"
} ; CasesExpression <aType> ⊑

eval [anEnvironment] →
  CasesEval [anExpression , eval [anEnvironment] ,
  cases ,
  anEnvironment] ⊑

CasesEval [anActor : anotherType ,
  cases : List <ExpressionCase <aType>> ,
  anEnvironment : Environment] ⊑

cases ⊑
  [ ] ⊑ Throw NoApplicableCase [],

  [first , rest] ⊑

  first ⊑
    {aPattern : Pattern <anotherType> "\""
     anExpression : Expression <aType> }
    : ExpressionCase <aType> ⊑

  aPattern , match [anActor , anEnvironment] ⊑

  Null Environment ⊑

  CasesEval [anActor , rest , anEnvironment] ,
  newEnvironment : Environment ⊑
  anExpression , eval [newEnvironment] ⊑,

  ("else" elsePattern : Pattern <anotherType> "\""
   elseExpression : Expression <aType> )
  : ExpressionElseCase <aType> ⊑

  elsePattern , match [anActor , anEnvironment] ⊑

  Null Environment ⊑

  Throw ElsePatternMustMatch [],

  newEnvironment : Environment ⊑
  elseExpression , eval [newEnvironment] ⊑,

  ("else" "\""
   elseExpression : Expression <aType> )
  : ExpressionElseCase <aType> ⊑

  elseExpression , eval [anEnvironment] ,
  else : Throw NoApplicableCase [] ⊑
anExpression:Expression <anotherType> "" cases:ContinuationCases <aType> ""
  :CasesContinuation <aType> ⇐
  perform[anEnvironment, aCheeseQ] →
  CasesPerform,[anExpression, eval[anEnvironment], cases, anEnvironment, aCheeseQ]§
CasesPerform,[anActor:anotherType,
  cases:List<ContinuationCase<aType>>,
  anEnvironment:Environment,
  aCheeseQ:CheeseQ] ⇐
cases ""
[ ] § Throw NoApplicableCase[].
[first, □rest] §
  first "" (aPattern:Pattern <anotherType> ""
    aContinuation:Continuation <aType>)
    :ContinuationCase <aType> ""
    aPattern.match[anActor, anEnvironment] ""
    Null Environment §
    CasesPerform,[anActor,
      rest,
      anEnvironment,
      aCheeseQ].
    newEnvironment:Environment §
    aContinuation.perform[newEnvironment,
      aCheeseQ] \,
(""else"
  elsePattern:Pattern <anotherType> ""
    elseContinuation:Continuation <aType>)
    :ContinuationElseCase <aType> ""
    elsePattern.match[anActor, anEnvironment] ""
    Null Environment §
    Throw ElsePatternMustMatch[],
    newEnvironment:Environment §
    elseContinuation.eval[newEnvironment] \,
(""else"" ""
  elseContinuation:Continuation <aType>)
  :ContinuationElseCase <aType> ""
  elseContinuation.perform[anEnvironment, aCheeseQ],
else § Throw NoApplicableCase[] \] [\] [\]
Holes in the cheese

\[
\begin{align*}
\text{perform} & : \text{Environment}, \text{Cheese} \rightarrow \\
\text{let} & : \text{Expression} \rightarrow \text{eval} \rightarrow \text{someAssignments} \rightarrow \text{carryOut} \rightarrow \\
\text{let} & : \text{Expression} \rightarrow \text{eval} \rightarrow \text{someAssignments} \rightarrow \text{carryOut} \rightarrow \\
\text{let} & : \text{Expression} \rightarrow \text{eval} \rightarrow \text{someAssignments} \rightarrow \text{carryOut} \rightarrow \\
\end{align*}
\]
"Hole" anExpression: Expression < anotherType >
"afterward" anAfterward: AfterwardContinuation < aType > "[?]

perform [ anEnvironment, aCheese Q ] →
  Let frozenEnvironment ← anEnvironment . freeze [ ] ●
  Do aCheeseQ . leave [ ] ●
  Try Let anActor ← anExpression . eval [ frozenEnvironment ] ●
    Do [ aCheeseQ . enter [ ] ●
      anAfterward . perform [ anEnvironment, aCheeseQ ] ] ●
    anActor afterward aCheeseQ . leave [ ]
catch anException: ApplicationException $
  Do [ aCheeseQ . enter [ ] ●
    anAfterward . perform [ anEnvironment, aCheeseQ ] ] ●
  throw anException afterward aCheeseQ . leave [ ] $

"Hole" anExpression: Expression < anotherType >
"returned" returnedCases: ContinuationCases < aType > "[?]
"threw" threwCases: ContinuationCases < aType > "[?]

perform [ anEnvironment, aCheese Q ] →
  Let frozenEnvironment ← anEnvironment . freeze [ ] ●
  Do aCheeseQ . leave [ ] ●
  Try Let anActor ← anExpression . eval [ frozenEnvironment ] ●
    Do aCheeseQ . enter [ ] ●
      CasesPerform . [ anActor, returnedCases, anEnvironment, aCheeseQ ]
catch anException: ApplicationException $
  Do aCheeseQ . enter [ ] ●
    CasesPerform . [ anException, threwCases, anEnvironment, aCheeseQ ]$
A Simple Implementation of Actor
The implementation below does not implement queues, holes, and relaying.

There are special distinguished messages named **isOfExactly** and **isOfAnExtension** that can be used to query an Actor whether it exactly implements a type or implements and an extension of a type.
Initialized | anInterface: aType,
            handlers: List<Handler<aType>>,
            anEnvironment: Environment,
            cheeseQ: CheeseQ | ≡

**Actor implements** anInterface **using**

receivedMessage: Message<aType> →

// receivedMessage received for anInterface

receivedMessage ⋆

**isOfExactly** Query[aType] ⋆

aType = anInterface,

// test if this Actor implements anotherType

**isOfAnExtension** Query[aType] ⋆

aType = anInterface ⋆

True ⋆ True,

False ⋆ aType, **isExtension** [anInterface] ⋆ ⋆,

else ⋆

Do aCheeseQ.enter[] ⋆

Let aReturned ← Try Select,[receivedMessage, handlers, anEnvironment, aCheeseQ]

**cleanup** aCheeseQ.leave[] ⋆

// leave cheese and rethrow exception

Do aCheeseQ.leave[] ⋆
aReturned ⋆
Select\textsubscript{\$}[\text{receivedMessage} : \textit{Message} \langle \textit{aType} \rangle, \\
\text{handlers} : \textit{List}<\text{Handler} \langle \textit{aType} \rangle >, \\
\text{anEnvironment} : \textit{Environment}, \\
\textit{aCheeseQ} : \textit{CheeseQ}] \triangleq \textit{aType} \\
\text{handlers} \ \bullet \\
[\ ] \triangleq \textit{Throw NotApplicable} [ ], \\
[[\text{aMessageDeclaration} : \textit{MessageDeclaration} \langle \textit{aType} \rangle ``\rightarrow`` \\
\text{body} : \textit{Continuation} \langle \textit{aType} \rangle ) \\
: \textit{ContinuationHandler} \langle \textit{aType} \rangle , \\
\text{restHandlers}] \odot \\
\text{aMessageDeclaration}.\textbf{match}[\text{receivedMessage}, \\
\text{anEnvironment}] \odot \\
\textbf{Null Environment} \odot \text{Select\textsubscript{\$}}[\text{receivedMessage}, \\
\text{restHandlers}, \\
\text{anEnvironment}, \\
\textit{aCheeseQ}], \\
\text{ // process next handler} \\
\text{newEnvironment} : \textit{Environment} \odot \\
\text{Execute\textsubscript{*}}[\text{body}, \text{newEnvironment}, \textit{aCheeseQ}] \odot \textbf{\textit{\|\|}} \\
\text{ // execute \textit{body} with extension of \textit{anEnvironment} }
An implementation of cheese that never holds a lock

The following is an implementation of cheese that does not hold a lock:

**Actor** SimpleCheeseQ\[\]

- **Invariant** \( a\text{Tail} = \text{Null Activity} \Leftrightarrow a\text{previousToTail} = \text{Null Activity} \)
  - \( a\text{HeadHint} = \text{Null Activity}, \quad \text{aHeadHint}:\text{Nullable<Activity>} \)
  - \( a\text{Tail} = \text{Null Activity}, \quad \text{aTail}:\text{Nullable<Activity>} \)

- **implements** CheeseQ\[\]

  - **enter\[\] in** myActivity \( \rightarrow \)
    - **Preconditions** \( \langle \text{myActivity}[\text{previous}] = \text{Null Activity}, \text{myActivity}[\text{nextHint}] = \text{Null Activity} \rangle \)
    - attempt\[\] \( \rightarrow \)
      - Do \( \text{myActivity}[\text{previous}] = \text{aTail} \) \( \bullet \) \( \text{// set provisional tail of queue} \)
      - **Atomic** \( \text{aTail compare aTail update myActivity} \)
        - **then** \( \text{// inserted myActivity in the cheese queue with previous} \)
          - Do \( \text{myActivity}[\text{previous}] = \text{Null Activity} \) \( \diamond \)
            - True \( \Rightarrow \) Void,
            - False \( \Rightarrow \) Suspend \( \bullet \) \( \text{// current activity is suspended} \)
        - **else** attempt\[\] \( \rightarrow \)
      - **leave\[\] in** myActivity \( \rightarrow \)
        - **// leave** message received running myActivity

- **Precondition** \( a\text{Tail} \neq \text{Null Activity} \)
  - Let \( \text{ahead} \leftarrow \text{SubCheeseQ}\[\] \)
  - **Precondition** \( \text{ahead} = \text{myActivity} \)
    - **Atomic** \( \text{aTail compare ahead update Null Activity} \)
      - **then** \( \text{// last activity has left this cheese queue} \)
        - Do \( \text{aHeadHint} \leftarrow \text{Null Activity} \) \( \bullet \)
          - Void,
        - **else** \( \text{// another activity is in this cheese queue} \)
          - Do \( \text{aHeadHint} = \text{ahead}[\text{nextHint}] \) \( \bullet \)
            - MakeRunnable \( \text{aHeadHint}:\text{Activity} \), \( \$ \)
    - **also implements** SubCheeseQ\[\] \( \rightarrow \)
      - **Precondition** \( a\text{Tail} \neq \text{Null Activity} \)
        - findHead\[\] \( \rightarrow \)
          - **Precondition** \( a\text{HeadHint} \neq \text{Null Activity} \)
            - **atomic** \( \text{aHeadHint\_compare\_prev\_next\_hint\_update\_null\_activity} \)
              - **then** \( \text{// backIterator is at the head of the cheese queue} \)
                - Do \( \text{aHeadHint} \leftarrow \text{Null activity} \) \( \bullet \)
                  - backIterator:
                    - previousBackIterator:
                      - **// backIterator is not the head of this CheeseQ**
                      - Do \( \text{previousBackIterator}[\text{nextHint}] = \text{Null activity} \) \( \bullet \)
                        - **// set nextHint of previous to backIterator**
            - **else** \( \text{// backIterator is at the head of the cheese queue} \)
                - Do \( \text{aHeadHint} = \text{Null activity} \) \( \bullet \)
                  - backIterator:
                    - previousBackIterator:
                      - **// backIterator is not the head of this CheeseQ**
                      - Do \( \text{previousBackIterator}[\text{nextHint}] = \text{Null activity} \) \( \bullet \)
                        - **// set nextHint of previous to backIterator**
  - **findHead\[\] [\] backIterator\[\] Activity \( \leftarrow \)
    - **null Activity \( \neq \text{aTail}\_\text{Activity} \),**
    - **else \( \Rightarrow \text{aHeadHint}\_\text{Activity} [\] Activity \( \leftarrow \)
    - **backIterator [\] previous\[\] Activity \( \leftarrow \)
      - **null Activity \( \neq \text{aTail}\_\text{Activity} \),**
      - **else \( \Rightarrow \text{aHeadHint}\_\text{Activity} [\] Activity \( \leftarrow \)

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The algorithm used in the implementation of CheeseQ above is due to Blaine Garst [private communication] cf. [Ladan-Mozes and Shavit 2004].

There is a state diagram for the implementation below:
Actor SimpleInternalQ[aCheeseQ:CheeseQ] unserialized
aHead := Null Activity, // aHead: Nullable<Activity>
aTail := Null Activity,
implements InternalQ using
enqueueAndLeave[ ] in myActivity →
  // enqueueAndLeave message received in myActivity
  Do [subInternalQ*remove[myActivity]] ||
  aCheeseQ.leave[ ] || // myActivity is the head of aCheeseQ
  Suspend // myActivity is suspended and when resumed returns Void
enqueueAndDequeue[anInternalQ] in myActivity →
  Precondition → anInternalQ.isEmpty[ ].
  Do [subInternalQ*add[myActivity]] ||
  deque[ ] ||
  Suspend
  // myActivity is the head of aCheeseQ
  MakeRunnable [subInternalQ*remove[ ]]
  // make runnable the removed activity
isEmpty[ ] → aTail = Null Activity
also implements subInternalQ using
add[anActivity] →
  Precondition anActivity[rest] = Null Activity;
  // anActivity must not be in another internal cheese queue
  aTail ◁
  Null Activity ▷
  Void afterward {aHead = Nullable anActivity,
  aTail = Nullable anActivity },
  theTail: Activity ▷ Void afterward theTail[rest] = anActivity ▷
  remove[ ]: Activity → Precondition → ■ isEmpty[ ];
  Let theFirst ← aHead ▷
  aTail = aHead ◁
  True ◁ theFirst afterward {aHead = Null Activity,
  aTail = Null Activity },
  False ◁ theFirst afterward aHead = (aHead ▷ Activity)[rest] ▷
Appendix 3. Inconsistency Robust Logic Programs

Logic Programs\(^8\) can logically infer computational steps.

**Forward Chaining**

Forward chaining is performed using \(\vdash\)

\[
(\text{"}\vdash\text{Theory PropositionExpression}\text{"
} \\
\text{Assert PropositionExpression for Theory.}
\]

Illustration of forward chaining:

\(\vdash\) Human[Socrates]\(\uparrow\)

When \(\vdash\) Human\([x]\) \(\rightarrow\) \(\vdash\) Mortal\([x]\)\(\uparrow\)

will result in asserting Mortal[Socrates] for theory \(t\)

**Backward Chaining**

Backward chaining is performed using \(\models\)

\[
(\text{"}\models\text{Theory aGoal:Pattern} \rightarrow \text{Expression}\text{"
} \\
\text{Set aGoal for Theory and when established evaluate Expression.}
\]

\[
(\text{"}\models\text{Theory aGoal:Pattern}\text{:Expression}\text{"}
\text{Set aGoal for Theory and return a list of assertions that satisfy the goal.}
\]

\[
(\text{"}\text{When } \models\text{Theory aGoal:Pattern}\rightarrow \text{Expression}\text{"}
\text{When there is a goal that matches aGoal for Theory, evaluate Expression.}
\]
Illustration of backward chaining:

\[
\vdash_1 \text{Human}[\text{Socrates}] \\
\text{When } \vdash_1 \text{Mortal}[x] \rightarrow (\vdash_1 \text{Human}[\$x] \rightarrow \vdash_1 \text{Mortal}[x]) \\
\vdash_1 \text{Mortal}[\text{Socrates}] 
\]

will result in asserting Mortal[Socrates] for theory t.

**SubArguments**

This section explains how subarguments\(^1\) can be implemented in natural deduction.

\[
\text{When } \vdash_2 (\psi \vdash_1 \phi) \\
\text{Let } t' \leftarrow \text{extension}[t], \\
\text{Do } \vdash_1 \psi, \\
\vdash_1 \phi \rightarrow \vdash_1 (\psi \vdash_1 \phi)
\]

Note that the following hold for t' because it is an extension of t:

- when \( \vdash_1 \theta \rightarrow \vdash_1 \theta \)
- when \( \vdash_1 \theta \rightarrow \vdash_1 \theta \)

---

\(^1\) See appendix on Inconsistency Robust Natural Deduction.
Aggregation using Grounded-Complete Predicates

Logic Programs in ActorScript are a further development of Planner. For example, suppose there is a grounded-complete predicate \texttt{Street[aName, anAddress, anotherAddress, aDistance]} that is true exactly when the street with \texttt{aName}, \texttt{anAddress} and \texttt{anotherAddress} has \texttt{aDistance}.

\textbf{When} \texttt{\impl Street[aName, anAddress, anAddress, aDistance]}\texttt{\impl aDistance=0} \\
\texttt{// when a goal is set for a distance between \texttt{anAddress} and itself} \\
\texttt{// assert that the distance from an address to itself is 0}

The following goal-directed Logic Program works forward from \texttt{start} to find the distance to \texttt{finish}:

\textbf{When} \texttt{\impl Distance[start, finish, aDistance]}\texttt{\impl \hspace{1em} aDistance=Minimum} \\
\hspace{2em} \texttt{| Street[aName, start, next, nextDistance],} \\
\hspace{3em} \texttt{Distance[next, finish, remainingDistance]}\}^{100} \\
\hspace{1em} \texttt{// the distance from \texttt{start} to \texttt{finish} is the minimum of the set of the sums of the} \\
\hspace{1em} \texttt{// distance for the next address after \texttt{start} and} \\
\hspace{1em} \texttt{// the distance from that address to \texttt{finish}}

The following goal-directed Logic Program works backward from \texttt{finish} to find the distance from \texttt{start}:

\textbf{When} \texttt{\impl Distance[start, finish, aDistance]}\texttt{\impl \hspace{1em} aDistance=} \\
\hspace{2em} \texttt{Minimum} \\
\hspace{3em} \texttt{| Street[aName, previous, finish, previousDistance],} \\
\hspace{4em} \texttt{Distance[start, previous, remainingDistance]}\}^{101} \\
\hspace{1em} \texttt{// the distance from \texttt{start} to \texttt{finish} is the minimum of the set of the sums of the} \\
\hspace{1em} \texttt{// distance for the previous address before \texttt{finish} and} \\
\hspace{1em} \texttt{// the distance from \texttt{start} to that address}

Note that all of the above Logic Programs work together concurrently.

The following procedure computes the shortest path from one location to another:

\texttt{ShortestPath, [start, finish] \equiv} \\
\hspace{1em} \texttt{start \;\hspace{1em} \texttt{finish \; [start], \;}} \\
\hspace{2em} \texttt{// the shortest path from \texttt{start} to itself is \texttt{[start]}\} \\
\hspace{1em} \texttt{else \;\hspace{1em} \texttt{[start, \;\;\texttt{\impl Distance[start,}} \\
\hspace{2em} \hspace{2em} \hspace{2em} \hspace{2em} \texttt{next,} \\
\hspace{2em} \hspace{2em} \hspace{2em} \hspace{2em} \hspace{2em} \texttt{Minimum} \\
\hspace{3em} \hspace{3em} \hspace{3em} \hspace{3em} \texttt{| Street[, start, between \neq start, _]} \\
\hspace{4em} \hspace{4em} \hspace{4em} \hspace{4em} \texttt{Distance[between,} \\
\hspace{5em} \hspace{5em} \hspace{5em} \hspace{5em} \texttt{finish,}} \\
\hspace{6em} \hspace{6em} \hspace{6em} \hspace{6em} \texttt{aDistance]}\} \\
\hspace{2em} \hspace{2em} \hspace{2em} \hspace{2em} \texttt{\impl ShortestPath[[next, finish]]} \\
\hspace{2em} \hspace{2em} \hspace{2em} \hspace{2em} \texttt{[next, \;\;\texttt{\impl ShortestPath[}} \\
\hspace{3em} \hspace{3em} \hspace{3em} \hspace{3em} \hspace{3em} \hspace{3em} \texttt{]]}
### Appendix 4. ActorScript Symbols with Readings. IDE ASCII, and Unicode code points

| Symbol | IDE ASCII | Read as | Category | Matching Delimiters | Unicode (hex) |
|--------|-----------|---------|----------|---------------------|---------------|
| `;`    | ; ;       | end     | top level terminator |                      | 32DA          |
| `:`    | ;         | of exact type | infix |                      |               |
| `::`   | ; ;       | of extended type | infix |                      |               |
| `[ ]`  | [ ; ]    | cast this actor to | prefix |                      | 2360          |
| `\_`   | \_/      | discriminate | infix |                      | 2206          |
| `\`    | \       | resolve | prefix |                      | 2139          |
| `[ ]`   | [ . ]    | qualified by | infix |                      | 22A1          |
| `.`    | .        | is sent | infix |                      |               |
| `..`   | . .      | delegate to this Actor | prefix |                      |               |
| `??`   | ( [ ] )  | concurrently | prefix |                      | 29B7          |
| `\`    | \       | message type | infix |                      | 21A6          |
| `\`    | \       | message received | infix |                      | 2192          |
| `<<`   | < ==     | be | infix |                      | 2190          |
| `?>`   | ? >     | has cases | separator |        | FFFD          |
| `?`    | [ ? ]   | end cases | terminator |                      | 2370          |
| `\`    | \       | another case | separator for handlers |                | 00B6          |
| `\`    | \       | end handlers | terminator | implements | 00A7          |
| `;`    | ;        | case | separator for case |                      | 2982          |
| `;`    | ;        | before | separator | Let bindings, | 00C4          |
| `;`    | ;        | to be | infix |                      | 2261          |
| `;`    | ;        | is assigned | infix |                      | 225C          |
| `;`    | ;        | matches value | prefix |                      | 2254          |
| `;`    | ;        | same as? | infix |                      | 2338          |

1 These are only examples. They can be redefined using keyboard macros according to personal preference.
| Symbol | Description | Category | Unicode Hex |
|--------|-------------|----------|-------------|
| < | assignable field | infix | |
| < | begin type parameters | left delimiter | (Unicode hex: 0077) |
| \ | spread | prefix | 2A5B |
| { | begin set | left delimiter | |
| [ | begin list | left delimiter | |
| } | begin multi-set | left delimiter | 2983 |
| ] | begin multi-set | left delimiter | (Unicode hex: 27E7) |
| ( | begin grouping | left delimiter | |
| { | begin set | left delimiter | |
| | begin multi-set | left delimiter | 2985 |
| ) | begin grouping | left delimiter | |
| ⟨ ⟩ | nothing | expression | 229D |
| ← | one-way send | infix | 219E |
| → | one-way receive | infix | 21A0 |
| ⟨ ⟩ | join | infix | 2294 |
| ⟷ | constrained by | infix | 2291 |
| ⟸ | extends | infix | 2292 |
| ⊆ | logical implication | infix | 21E8 |
| γ | logical equivalence | infix | 21D4 |
| ∧ | logical conjunction | infix | 00D9 |
| ∨ | logical disjunction | infix | 00DA |
| ¬ | logical negation | prefix | 00D8 |
| ⊢ | assert | prefix and infix | 22A2 |
| ⊢ | goal | prefix and infix | 22A9 |
| /* | begin comment | prefix | */ |
Appendix 5. Grammar Precedence

In the diagram below, if there is no precedence relationship, then parentheses must be used.

For example, parentheses must be used in the following examples:

- `(t[p]).m[x]`
- `(x p1 $ y1 $) p2 $ y2 $`
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End Notes

1 Quotation by the author from late 1960s.

2 To use a reserved word as an identifier it could prefixed, e.g., _actor

3 The delimiters ( and ) are used to delimit program syntax with the character " and the character " to delimit tokens. For example, (_3 "+" 4) is an expression that can be evaluated to 7. A special font is used for syntactic categories. For example Numerical is the syntactic category of numerical expressions. The character □ can be used to make categorizations.

For example, (_x: Numerical "+" y: Numerical): Numerical □ with x and y that are both of category Numerical.

Also,

\[
\begin{align*}
\text{Numerical} & \equiv \text{Expression} \\
\text{Expression} & \equiv \text{Type} \\
\text{Type} & \equiv \text{Expression}
\end{align*}
\]

4 See explanation of syntactic categories above. A word must begin with an alphabetic character and may be followed by one or more numbers and alphabetic characters.

Identifier □ Word □ Expression □

// an Identifier is a Word, which is a subcategory of Expression

\[
\begin{align*}
\text{Expression} & \equiv \text{Definition} \cup \text{Judgment} \\
\text{Definition} & \equiv \text{Identifier} \cup \text{Expression} \cup \text{Definition}
\end{align*}
\]

5 Type □ Expression □

\[
\begin{align*}
\text{aType:Type} & \rightarrow \text{anotherType:Type} \\
\text{"[" Types"]} & \equiv \text{Type} \\
\text{MoreTypes} & \equiv \text{Types} \\
\text{Type} & \equiv \text{Type} \cup \text{MoreTypes} \\
\text{Identifier} \equiv \text{aType} \cup \text{Definition} \cup \text{Identifier}
\end{align*}
\]
An overloaded procedure is one that takes different actions depending on the types of its arguments.

Note the Symbols box provided by an Integrated Development Environment (IDE) above to make it easier to construct a program by selecting symbols from a context sensitive picker. Also an IDE can automatically provide syntax completion alternatives Analogous to `ctrl+space` in Eclipse, etc..

```plaintext
("[" ArgumentTypes ""]")
  "↦" returnType:TypeExpression
ProcedureSignature ⊑ Expression
    // signature for a procedure with ArgumentTypes and returnType
    ( U MoreArgumentTypes):ArgumentTypes
    {TypeExpression
      U {TypeExpression "," MoreArgumentTypes})
    :MoreArgumentTypes

("(" Interface Identifier<Type>
  "[" MoreProcedureSignatures "])":ProcedureInterface
{ProcedureSignature
  ( U MoreProcedureSignatures)):MoreProcedureSignatures

("[" ArgumentDeclarations "]" ( U "{:" Type<#Type> }}
  ( U "{sponsor" Identifier<Sponsor> })
  "↦" Expression<#Type>:Procedure
Procedure ⊑ Expression
  // Procedure with ArgumentDeclarations that returns
  // Expression of type returnType.
  ( U MoreDeclarations):ArgumentDeclarations
  {SimpleDeclaration( U {"," MoreKeywordDeclarations})
   U {SimpleDeclaration "," MoreDeclarations}}
  :MoreDeclarations

  // Comma is used to separate declarations.
  {[Identifier
    U {Identifier "," Expression<#Type> }}
  ( U "default" Expression)):SimpleDeclaration
KeywordArgumentDeclaration
    U {KeywordDeclaration "," MoreKeywordDeclarations})
  :MoreKeywordDeclarations
(Keyword "{" SimpleDeclaration}):KeywordDeclaration
Keyword ⊑ Word

The symbol ∎ is fancy typography for an ordinary period when it is used to denote message sending.

{Recipient:Expression "," "{[" Arguments ""]":ProcedureSend
ProcedureSend ⊑ Expression
  // Recipient is sent a message with Arguments
  ( U MoreArguments):Arguments

Expression

\[\text{MoreKeywordArguments} \cup \text{MoreArguments} \rightarrow \text{MoreArguments} \]

\text{Expression}

\[\text{MoreArguments} \cup \text{MoreKeywordArguments} \rightarrow \text{MoreArguments} \]

\text{Expression}

\[\text{MoreArguments} \cup \text{MoreKeywordArguments} \rightarrow \text{MoreArguments} \]

\text{Expression}

\[\text{MoreArguments} \cup \text{MoreKeywordArguments} \rightarrow \text{MoreArguments} \]

\text{Expression}

\[\text{MoreArguments} \cup \text{MoreKeywordArguments} \rightarrow \text{MoreArguments} \]

\text{Expression}

\[\text{MoreArguments} \cup \text{MoreKeywordArguments} \rightarrow \text{MoreArguments} \]

\text{Expression}

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\text{Expression}

\[\text{MoreArguments} \cup \text{MoreKeywordArguments} \rightarrow \text{MoreArguments} \]

\text{Expression}

\[\text{MoreArguments} \cup \text{MoreKeywordArguments} \rightarrow \text{MoreArguments} \]
\( \sqcup \{ \text{LetBinding} \ ("\sqcup \ "\bullet") \ \text{MoreDependentLetBindings} \} \)  
\( \sqcup \ \text{MoreDependentLetBindings} \)

// Each binding before a "\bullet" is completed before its successors
(Pattern \( \leftarrow \) Expression):letBinding

Dijkstra [1968] famously blamed the use of the goto as a cause and symptom of poorly structure programs. However, assignments are the source of much more serious problems.

17 The example could be written as follows using fewer symbols:

\( \text{Actor Account [startingBalance:Currency]} \)

\[ \text{myBalance := startingBalance} \]

\[ \text{getBalance[\rightarrow myBalance} \]

\[ \text{deploy[\rightarrow myBalance} + \text{anAmount} \]

\[ \text{withdraw[\rightarrow (amount > myBalance) ? Throw OverdrawnException[] : Void} \]

\[ \text{myBalance := myBalance – anAmount} \]

18 ("Actor" Constructor ActorBody):Expression:\n
// The above expression creates an Actor with
// declarations for variables and message handlers

(\sqcup \{ "extends" Constructor \})

(\sqcup "management" Expression \( \larrow \) Manager\( \rightarrow \))

NamedDeclaration
MessageHandlers
InterfaceImplementations\( \rightarrow \)ActorBody

(\sqcup \{ MoreNameDeclarations \}):NamesDeclarations

(\sqcup \{ NameDeclaration \})

Identifier
(\sqcup \{ "\text{Type <aType>}" \})

"\text{←}" Expression\( \larrow \)IdentifierDeclaration

IdentifierDeclaration\( \sqcup \)NameDeclaration

(Variable \( \sqcup \{ "\text{Type <aType>}" \})

"\text{="}" Expression\( \larrow \)InstanceVariableAQualifications\( \sqcup \)VariableDeclaration

VariableDeclaration\( \sqcup \)NameDeclaration

Word

InstanceIVariableQualifications\( \sqcup \)InstanceQualifications

(\sqcup \)InstanceVariableQualification
Continuations in ActorScript are related to continuations introduced in [Reynolds 1972] in that they represent a continuation of a computation. The difference is that a continuation of Reynolds is a procedure that takes as an argument the result of the preceding computation. Consequently, a continuation of Reynolds is closer to a customer in the Actor Model of computation.
"→" Continuation <aType>::UniversalMethod <aType>↓
   (⊔ MoreMethods);Methods ↓
   (Method ⊔ (Method "|" MoreMethods));MoreMethods ↓
   // The method separator is "|
   (MessageName "[" ArgumentDeclarations "]")
      (⊔ "", returnType: Type <aType>)
      (⊔ ("sponsor" Identifier <Sponsor>))
      "→" Continuation <aType>::Method ↓
   // For a message with MessageName with arguments,
   // the response is Continuation
   (Expression <aType>
     "afterward" "{" Afterward "}");Continuation <aType>↓
   // Return Expression and afterward perform
   // MoreVariableAssignments
   (VariableAssignment
      (⊔ VariableAssignment "," MoreVariableAssignments))
   :MoreVariableAssignments ↓
   // Variable assignments are separated using ","
   (Variable "=" Expression <aType>);VariableAssignment <aType>↓
22 ("elier" anExpression: Expression <aType>
      (⊔ ("sponsor" Expression <Sponsor>));Expression <aType>↓
   // Execute anExpression concurrently and respond with the outcome.
   // In every case, anExpression must complete before execution leaves
   // the lexical scope in which it appears.
23 ("Do" "{" MoreConcurrentAntecedents "}" "{" " ""})
      Continuation <aType>↓
   ("Do" "{" MoreSequentialAntecedents "}" (⊔ " ""
      Continuation <aType>↓)
   ("Do" Antecedent (" ""))
      Continuation <aType>↓
   ("Let" "{" MoreConcurrentLetBindings "}" "{" " ""
      result:Continuation <aType>↓)
   ("Let" "{" MoreDependentLetBindings "}" "{" " ""
      result:Continuation <aType>↓
   (Antecedent ⊔ (Antecedent " " MoreConcurrentAntecedents))
      :MoreConcurrentAntecedents ↓
   (Antecedent ⊔ (Antecedent " " MoreSequentialAntecedents))
      :MoreSequentialAntecedents ↓
Expression <Antecedent ↓
StructureAssignment <Antecedent ↓
ArrayAssignment <Antecedent ↓
Swiss cheese was called “serializers” in the literature. Sussman and Steele 1975 introduced the name “continuation passing style” for explicit use of continuations [Reynolds 1972] in programs. However, in the "string bean style" used here, continuations are not made explicit while programs are required to be linear between holes in the cheese.

without leaving the cheese provided that \texttt{aQueue} is nonempty

without leaving the cheese provided that \texttt{aQueue} is nonempty

\texttt{⦅Enqueue passThruQ:Expression ⦆⦆}

\texttt{⦅⦅⦅⦆}

\texttt{⦆⦆⦆⦆}

\texttt{⦆}

\texttt{⦆}

\texttt{⦆}

\texttt{⦆}

1. Perform Preparation
2. Enqueue activity in \texttt{QueueExpression}
3. Leave the cheese
4. When the cheese is re-entered perform \texttt{Continuation}.

\texttt{⦅⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇⦇镱
MoreContinuationElseCases <aType>
{ContinuationElseCase <aType>
  
  | (ContinuationElseCase <aType>
  
  "", MoreContinuationElseCases <aType>)
  
  :MoreContinuationElseCases <aType> 1

}

MoreContinuationElseCases <aType> 1

} <|ContinuationElseCase <aType>|

LI ("else" "i" Continuation <aType>)

LI ("else" Pattern "i"

Continuation <aType>)) :ContinuationElseCase <aType>

Popularized in [Dijkstra 1965]. Note that secondBarber only shaves if a
customer comes in when firstBarber is shaving.

**Interface BarberShop visit**[Client] -> Void

because it is an internal error condition that should never occur
after shaving permit next customer
leave cheese while shaving after recording that first barber is shaving
after shaving permit next customer
ReadersWriterConstraintMonitor defined below monitors a resource and
throws an exception if it detects that ReadersWriter constraint is violated,
*e.g.*, for a resource r using the above scheduler,
ReadingPriority[ReadersWriterConstraintMonitor[r]].

**Actor** ReadersWriterConstraintMonitor [theResource:ReadersWriter]  
writing := False,  
numberReading: (Integer thatIs ≥ 0) := 0,  
implements ReadersWriter using  
read[query] →  

Precondition ¬writing:  
  Hole theResource.read[query]  
  after numberReading++
  afterward numberReading--[]  
write[update] →  

Preconditions numberReading = 0, ¬writing:
  Hole theResource.write[update]  
  after writing:=True
  afterward writing := False § 1
A downside of this policy is that readers may not get the most recent
information.
A downside of this policy is that writing and reading may be delayed
because of lack of concurrency among readers.
Precondition that is present for inconsistency robustness.
++ is postfix increment
-- is postfix decrement
Precondition that is present for inconsistency robustness.
The following are allowed in the cheese for a response to message
affecting the next message:
(\textit{Expression <aType>}
  ( (\textit{\textit{permit}} aQueue:Expression))
  ( (\textit{\textit{afterward}} "{\textit{\textit{Afterward}}}"))));Continuation <aType>
  1. If there are activities in aQueue, then the one of them gets the
  cheese next and also perform \textit{Afterward}; then leave the cheese
  and return the value of \textit{Expression}.

The following can be used temporarily leave the cheese:
(\textit{\textit{\textit{Hole}}} Expression <aType>);Continuation <aType>
  1. Leave the cheese
  2. The response is the result of evaluating \textit{Expression}

(\textit{\textit{\textit{Hole}}} Expression <anotherType>
  ( (\textit{\textit{\textit{after}}} Preparation)));Continuation <aType>
  1. Carry out \textit{Preparation}
  2. Leave the cheese
  3. The result is the result of evaluating \textit{Expression}

(\textit{\textit{\textit{Hole}}} Expression <aType>
  ( (\textit{\textit{\textit{after}}} Preparation))
  ( (\textit{\textit{\textit{afterward}}} \textit{Afterward});Continuation <aType>
  1. Carry out \textit{Preparation}
  2. Leave the cheese
  3. Evaluate \textit{Expression}
  4. When a response is received, reacquire the cheese, carry
out \textit{Afterward} and the result is the result of evaluating
\textit{Expression}

If \textit{Expression} throws an exception, continue using the exception
\textit{ContinuationCases}.
(\textit{\textit{\textit{Hole}}} Expression <anotherType>
  ( (\textit{\textit{\textit{after}}} Preparation))
  ( (\textit{\textit{\textit{returned}}} \textit{ContinuationCases <aType}}>"\textit{\textit{[}}}\textit{\textit{\textit{]}}}"));Continuation <aType>
  ( (\textit{\textit{\textit{threw}}} \textit{ContinuationCases <aType'}}>"\textit{\textit{[}}}\textit{\textit{\textit{]}}}"));Continuation <aType>
  1. Carry out \textit{Preparation}
  2. Leave the cheese
  3. Evaluate \textit{Expression}
  4. When a response is received, reacquire the cheese, carry
out \textit{Afterward} and the result is the result of evaluating
\textit{Expression}

If \textit{Expression} throws an exception, continue using the exception
\textit{ContinuationCases}.
1. Carry out Preparation
2. Leave the cheese
3. Evaluate Expression
4. When a response is received, reacquire the cheese
   - If Expression returns, continue using the returned Actor with ContinuationCases
   - If Expression throws an exception, continue using the exception ContinuationCases.

{Identifier<Type>
   "<" ParametersDeclarations">"  
   "≡" Expression):ParameterizedDefinition |
   ParameterizedDefinition≡Definition |
   (U MoreParameterDeclarations):ParametersDeclarations |
   ParameterDeclaration |
   (U (ParameterDeclaration 
       ""," MoreParameterDeclarations))) |
   :MoreParameterDeclarations |
   (Identifier<Type> (U Qualifier)):ParameterDeclaration |
   (U ("extends" Identifier<Type>)):TypeQualifier |
   (Identifier<Type> "<" Parameters">":TypeExpression |
   (Identifier<Type> |
     (U (Identifier<Type> "," Parameters)):Parameters |
     {Identifier<#Type> "([ Arguments ])";Expression <#Type> |
     (Identifier<#Type> "([ Patterns ])";Pattern <#Type> |
     {"Structure" Identifier<Type> "([ FieldDeclarations ]"]
     StructureImplementation):Definition |
     // Structure definition with StructureImplementation |
   (U MoreFieldDeclarations):FieldDeclarations |
   (\SimpleFieldDeclaration |
     (U ("," MoreNamedFieldDeclarations))) |
   (SimpleFieldDeclaration |
     ""," MoreFieldDeclarations));MoreFieldDeclarations |
   // Comma is used to separate declarations. |
   (\Identifier |
     (Identifier ":" TypeExpression)) |
   (U "default" Expression)):SimpleFieldDeclaration |
   (NamedFieldDeclaration |
     (NamedFieldDeclaration |
       "," MoreNamedFieldDeclarations)) |
   :MoreNamedFieldDeclarations |
   {FieldName |
     ("≡" U "≡") SimpleFieldDeclaration))}
NamedFieldDeclaration:

FieldName ⊑ QualifiedName

// "." is used for assignable fields.
(\( [ Identifier ] \) \) : StructureImplementation
( Expression “[" FieldName"]” ) : FieldSelector
  // FieldName of Expression which must be a structure
FieldSelector ⊑ Expression

(\( \bigcup \) MoreFieldExpressions) : FieldExpressions

([SimpleFieldExpression\( \bigcup [",\] MoreNamedFieldExpressions\)\)]
  \( \bigcup \) (SimpleFieldExpression "", MoreFieldExpressions) : MoreFieldExpressions

(NAMEdFieldExpression
  \( \bigcup \) (NamedFieldExpression "", MoreNamedFieldExpressions)
) : MoreNamedFieldExpressions

(FieldName
  \( \bigcup [",\] SimpleFieldExpression\)\)
) : NamedFieldExpression

(\( \bigcup \) MoreFieldPatterns) : FieldPatterns

([SimpleFieldPattern\( \bigcup [",\] MoreNamedFieldPatterns\)\)]
  \( \bigcup \) (SimpleFieldPattern "", MoreFieldPatterns)
) : MoreFieldPatterns

(NAMEdFieldPattern
  \( \bigcup \) (NamedFieldPattern "", MoreNamedFieldPatterns)
) : MoreNamedFieldPatterns

(FieldName \( \bigcup [",\] SimpleFieldExpression\)\)
) : NamedFieldPattern

53 ("Try" anExpression : Expression \(<aType>\)
  "catch" ExpressionCases \(<aType>\["\]") : Expression \(<aType>\)

- If anExpression throws an exception that matches the pattern of a case, then the value of TryExpression is the value computed by ExpressionCases
- If anExpression doesn't throw an exception, then then the value of TryExpression is the value computed by anExpression.

("Try" anExpression : Expression \(<aType>
  "catch" ContinuationCases \(<aType>\["\]")
) : Continuation \(<aType>\)
• If anExpression throws an exception that matches the pattern of a case, then the response of TryContinuation is the response computed by the expression of the case.
• If aContinuation doesn't throw an exception, then then the response of TryExpression is the response computed by anExpression.

```plaintext
("Try" anExpression:Expression<#aType> "cleanup" cleanup:Expression<aType>;Expression<aType>]

• If anExpression throws an exception, then the value of TryExpression is the value computed by cleanup.
• If anExpression doesn't throw an exception, then then the value of TryExpression is the value computed by anExpression.
```

54 ("Precondition" Expressions:;" Expression):Expression I
// Each of Expressions must evaluate to True or an exception is thrown
("Precondition" Expressions:;" Continuation):Continuation I
// Each of Expressions must evaluate to True or an exception is thrown
{value:Expression<aType>
"postcondition" pre:Expression<[#aType]→Boolean>)}
:Expression<aType> I

// The expression pre must evaluate to True when sent value
// or an exception is thrown

55 * is a reserved postfix operator for degrees of angle
i.e., i*1=-1 where i is the imaginary number Cartesian[0, 1]

56 ("[" ComponentExpressions "]") :Expression<#List>
// An ordered list with elements Expressions
{ ( U MoreComponentExpressions):ComponentExpressions I
( ( ( U "\" ") Expression
""," MoreComponentExpressions))
:MoreComponentExpressions I

("[" TypeExpressions "]") :TypeExpression I
{ ( U MoreTypeExpressions):TypeExpressions I
{ TypeExpression U (TypeExpression
""," MoreTypeExpressions))
:MoreTypeExpressions I

58 ("_ "):UnderscorePattern I
UnderscorePattern Pattern I
Identifier Pattern I
{Pattern<#aType>:" Type<#aType>}:Pattern<#aType> I
{Pattern "suchThat" Expression}:SuchThat I
SuchThat Pattern I
{Pattern "thatIs" Expression}:ThatIs I
ThatIs Pattern I
(" $$" Expression<#Type>:Pattern<#Type> I

91
ComponentPatterns

Pattern

// A pattern that matches a list whose elements match ComponentPatterns

(⊔ MoreComponentPatterns):ComponentPatterns ⊔

Pattern

⊔ ( "Pattern" )
⊔ (Pattern," MoreComponentPatterns")

: MoreComponentPatterns ⊔

59 Equivalent to the following:
AlternateElements.[[aList: List<<aType>>]:List<<aType>>] ≡

aList €
List<<aType>>] ⊔ List<<aType>>[ ],
List<<aType>>[anElement] ⊔ List<<aType>>[anElement],
List<<aType>>[firstElement, secondElement] ⊔
List<<aType>>[firstElement],
else
List<<aType>>[firstElement, secondElement,]
∀remainingElements] ⊔
List<<aType>>[firstElement,]
∀AlternateElements,[remainingElements]]

60 (""
ComponentExpressions"") Expression<Set>

A set of Actors without duplicates

("
ComponentPatterns"") Pattern<Set>

61 (""
ComponentExpressions"") Expression<Multiset>

A multiset of the Actors with possible duplicates

("
ComponentPatterns"") Pattern<Multiset>

62 Optimization of this program is facilitated because:
- The records are determinate because their type is Set<<ContactRecord>>
- All of the operators return determinate results
• The operators are annotated as `determinate`

---

It is possible to define a procedure that will produce a "bottomless" future.

For example, `f[]:Future<aType> ≡ Future f[[]]`

the examples using `⊑` can be slightly more efficient as written

```plaintext
(Postpone Expression<<aType>>):Expression<<Future<<aType>>>
```

postpone execution of an expression until the value is needed.

```plaintext
("Future" aValue:Expression<<aType>>

{"U" "sponsor" Expression<<Sponsor>>})

:Expression<<Future<<aType>>>
```

A future for `aValue`.

```plaintext
{"U" "Expression" Future<<aType>>>>:Expression<<aType>>>
```

Resolve a future

```plaintext
(LoopName : Identifier "." "[" Initializers "]

{" U (" ReturnType:aType ")

"≜" Expression<<aType>>):Expression<<aType>>>
```

```plaintext
{" U MoreInitializers};Initializers]
```

```plaintext
(Initializer U (Initializer "," MoreInitializers))

:MoreInitializers
```

```plaintext
(Identifier ({" U (".:" TypeExpression)}) "≜" Expression):Initializer
```

```plaintext
("Discrimination" Identifier<<Type>>

{"["MoreTypeDiscriminations"]":Expression<<Type>>
```

```plaintext
(Identifier<<Type>>

{" U (Identifier">Type"

","MoreTypeDiscriminations")})

:MoreTypeDiscriminations
```

```plaintext
(Expression<<aDiscriminationType>> "≜" Type<<aType>>;
```

```plaintext
:Expression<<aType>>
```

// Discriminate to have the type `Type<<aType>>` if possible.

// Otherwise, an exception is thrown.

The implementation below requires careful optimization.

```plaintext
{"["String"[" ComponentExpressions "]":Expression<<String>>
```

```plaintext
{"["String"[" ComponentPatterns "]":Pattern<<String>>
```

```plaintext
{recipient:Expression<<recipientType>>

"." message:MessageExpression<<recipientType>>):Expression
```

Send recipient the message

```plaintext
{"["MoreGrammers "]":Grammar
```

```plaintext
{"["Grammar":"Grammar"]":Grammar
```

```plaintext
(ReservedWord (" U StartsWithIdentifier\));StartsWithReserved
```

```plaintext
StartsWithReserved ≡ MoreGrammers
```

```plaintext
(Identifier (" U StartsWithReserved\));StartsWithIdentifier
```

```plaintext
StartsWithIdentifier ≡ MoreGrammers
```
The use of \ escapes the next character in a string so that \ has just one character that is ".

The implementation below can be highly inefficient.

Atomically compare the contents of location with the value of comparison. If identical, update the contents of aLocation with the value of update and execute compareIdentical.

Declarations provide version number, encoding, schemas, etc.

If a customer is sent more than one response (i.e., return or throw message) then it will throw an exception to the sender of the response.

Atomically compare the contents of location with the value of comparison. If identical, update the contents of aLocation with the value of update and execute compareIdentical.

One-way method implementation

Hoare[1962]. The implementation below is adapted from Wikipedia.
Move Actor at pivotIndex to end

Interface Account<@Currency>=Currency>

{getBalance[ ] -> aCurrency,
  deposit[aCurrency] -> Void,
  withdraw[aCurrency] -> Void}!

cf. [Crahen 2002, Amborn 2004, Miller, et. al. 2011]

Interface AccountMonitor<@Currency>

{getRevoker[ ] -> AccountRevoker,
  getAccount[ ] -> Account
  withdrawFee[aCurrency] -> Void}!

Interface AccountRevoker<@Currency>

{revokeDeposit[ ] -> Void,
  revokeWithdraw[ ] -> Void}!

Consider a dialect of Lisp which has a simple conditional expression of
the following form:

⦅"if" test:Expression then:Expression else:Expression."⦆

which returns the value of then if test evaluates to True and otherwise
returns the value of else.

The definition of Eval in terms of itself might include something like the
following [McCarthy, Abrahams, Edwards, Hart, and Levin 1962]:

(Eval expression environment) ≡
  (if (Numberp expression) // if expression is a number then
    expression // return expression else
    (if ((Equal (First expression) (Quote if)) // if First of expression is "if" then
      (if (Eval (First (Rest expression) environment) // if Eval of First of Rest of expression is True then
        (Eval (First (Rest (Rest expression)) environment)) // return Eval of First of Rest of Rest of expression else
        (Eval (First (Rest (Rest (Rest expression)) environment)) // return Eval of First of Rest of Rest of Rest of expression
        ...
      ))
    )

The above definition of Eval is notable in that the definition makes use of
the conditional expressions using if expressions in defining how to Eval an
If expression!

The implementation CheeseQ uses activities to implement its queue where
for type Activity the following holds:

Structure Activity[previous : Nullable<Activity>,
   nextHint : Nullable<Activity>]!

if non-null points to head with current holder of cheese
if non-null, pointer to backwards list ending with head that holds cheese

Interface CheeseQ {enter[ ] ⊸ Void,
leave[ ] ⊸ Void} □

enter message received running myActivity
this cheese queue is not empty because myActivity is at the head of the queue

Interface SubCheeseQ head[ ] ⊸ Activity □

Interface InternalQ {enqueueAndLeave[ ] ⊸ Void,
enqueueAndDequeue[InternalQ] ⊸ Activity,
dequeue[ ] ⊸ Activity,
isEmpty[ ] ⊸ Boolean} □

Interface subInternalQ {add[Activity] ⊸ Void,
remove[ ] ⊸ Activity} □

[Church 1932; McCarthy 1963; Hewitt 1969, 1971, 2010; Milner 1972,
Hayes 1973; Kowalski 1973]. Note that this definition of Logic Programs
does not follow the proposal in [Kowalski 1973, 2011] that Logic Programs
be restricted only to clause-syntax programs.
A grounded-complete predicate is one for which all instances in which the
predicate holds are explicitly manifest, i.e. instances can be generated using
patterns. See [Ross and Sagiv 1992, Eisner and Filardo 2011].
Execution can proceed differently depending on whether this set fits in
memory.
Execution can proceed differently depending on whether this set fits in
memory.
following expression is executed concurrently
Used in type specifications for interfaces.
Used in methods.
Used to bind identifiers in Let.
Three equal signs because two equal signs have a meaning in Java
Used in patterns.
Used in structures.
Used in one-way message passing.
