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

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

One computer is no computer in IoT

Carl Hewitt

This article is dedicated to Alonzo Church, John McCarthy, Ole-Johan Dahl and Kristen Nygaard.

ActorScript™ is a general purpose programming language for efficiently implementing robust applicationsⁱⁱ using iAdaptive™ concurrency that manages resources and demand with the following goal:

All physically possible digital computation can be directly implemented using ActorScript.

ActorScript is differentiated from previous programming 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.

ⁱ C# is a registered trademark of Microsoft, Inc.

Java and JavaScript are registered trademarks of Oracle, Inc.

Objective C is a registered trademark of Apple, Inc.

ⁱⁱ with no single point of failure

- 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.
- Performanceⁱ
 - 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 the 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.

Message passing using types is the foundation of system communication:

- Messages are the unit of communication
- Typesⁱⁱ enable secure communication with Actors

Computer software should not only work; it should also appear to work.¹

ⁱ 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" [Jon Bentley and Doug McIlroy]
- "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.

ⁱⁱ Each type is an Actor. However, it may be the case that a type will work some places and not others. For example, to be used in message passing, the type of an address may require access to particular hardware.

Introduction

ActorScript is based on the Actor mathematical model of computation that treats "*Actors*" as the universal conceptual primitive of digital computation [Hewitt, Bishop, and Steiger 1973; Hewitt 1977; Hewitt 2010a]. 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.*¹

- type identifiers
 - blue for types in general (e.g., **Account**)
 - green for the special case of implementation types (e.g., **SimpleAccount**)
- program variables (e.g., **aBalance**)
- message names (e.g., **withdraw**)
- reserved words² for language constructs (e.g., **Actor**)
- 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.³

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 conceptual primitive 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

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.*

physical laws. The advent of massive concurrency through client-cloud computing and many-core computer architectures has galvanized interest in the Actor model.

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
- 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 coordinating all kinds of digital information for individuals, groups, and organizations so their information usefully links together. Information coordination 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.*

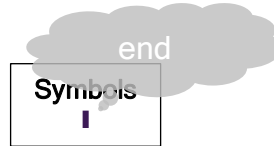
The Actor Model is designed to provide a foundation for inconsistency robust information coordination.

Notation

To ease interoperability, ActorScript uses an intersection of the orthographic conventions of Java, JavaScript, and C++ for wordsⁱ 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:ⁱⁱ



Expressions evaluate to Actors. For example, $1+3$ █ⁱⁱⁱ 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. Type names are shown as follows:

- blue for types in general (e.g., **Account**)
- green for the special case of implementation types (e.g., **SimpleAccount**)

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

ⁱ sometimes called "names"

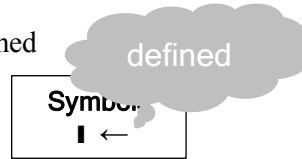
ⁱⁱ Furthermore, all special symbols have ASCII equivalents for input with a keyboard. An IDE can convert ASCII for a symbol equivalent into the symbol. See table in an appendix to this article.

ⁱⁱⁱ An IDE can provide a box with symbols for easy input in program development. The grey callout bubble is a hover tip that appears when the cursor hovers above a symbol to explain its use.

^{iv} in the sense of having the same value and the same effects

Identifier Definitions, *i.e.*, ←

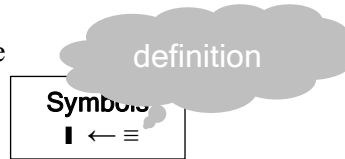
An identifier definition has an identifier to be defined followed by "←" followed by the definition. For example, `x←3` defines the identifier `x` to be the Actor `3`.



The formal syntax of an identifier definition is in the end note: **6**.

Procedure Definitions, *i.e.*, →

A procedure is an Actor that can receive a list of Actors in a message and return an Actor as its value, which can be defined using "Define", followed by a procedure name, a list of formal arguments, return type, "→" and body of the procedure.⁷ For example the procedure can be defined as follows:¹



Define `Double`.`[v:Integer]:Integer` ≡ `v+v`

The formal syntax of a procedure definition is in the end note: **8**.

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 arguments delimited by "[" and "]". For example, `Double.[2+1]` means send `Double` the message `[3]`. Thus `Double.[2+1]` is equivalent to `6`.

The formal syntactic definition of procedural message sending is in the end note: **10**.

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 anythingⁱⁱ
- `∅x` is a pattern that matches the value of `x`.
- `∅(x+2)` is a pattern that matches the value of the expression `x+2`.

ⁱ Anonymous procedures are also allowed as in the following:

`λ [v:Integer]:Integer → v+v`

ⁱⁱ e.g., `_` matches `7`

Identifiersⁱ can be bound using patterns as in the following examples:

- x is a pattern that matches "abc" and binds x to "abc"

Cases, *i.e.*, `⊖ : , : ?`

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 "`⊖`"ⁱⁱⁱ and then followed by a number of cases separated by "," terminated by "`?`".¹¹ A case consists of

- a pattern followed by ":" 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, ":", and an expression to compute the value for the case. An **else** case applies *only* if none of the patterns in the preceding casesⁱⁱⁱ match the value on which to perform case analysis.

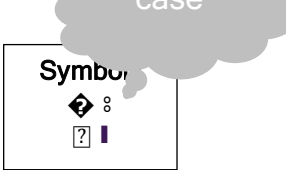
As an arbitrary example purely to illustrate the above, suppose that the procedure `Random`, which has no argument and returns **Integer**, in the following example:

`Random.[] ⊖`

```

0 : // Random.[ ] returned 0iv
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.[ ]

```



The formal syntax of cases is in the following end note: **12**.

ⁱ An identifier is a name that is used in a program to designate an Actor

ⁱⁱ "`⊖`" is fancy typography for "?"

ⁱⁱⁱ *including* patterns in previous else cases

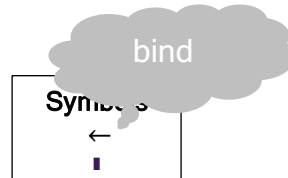
^{iv} As is standard, ActorScript uses the token "://" to begin a one-line comment.

^v Reserved words are shown in bold black.

Binding identifiers, *i.e.*, ←

Identifiers can be bound using an identifier, followed by "←" and an expression. For example, `aProcedure["G", "F", "F"]` is equivalent to the following:

```
(x ← "F", // x is "F"  
aProcedure["G", x, x])
```



Dependent bindings (in which each can depend on previous ones) can be accomplished as follows:

```
(x ← "F", // x is "F"  
y ← aProcedure["G", x, x], // y is aProcedure["G", "F", "F"]  
anotherProcedure[x, y])
```

The above is equivalent to

```
anotherProcedure["F", aProcedure["G", "F", "F"]]
```

The formal syntax of bindings is in the following end note: **13**.

The formal syntactic definition of named-message sending is in the following end note: **14**

Lists, *i.e.*, [] using Spread, *i.e.*, [v]

The prefix operator "v" can be used to spread the elements of a list. For example

- `[1, v[2, 3], 4]`¹⁵ is equivalent to `[1, 2, 3, 4]`.
- `[[1, 2], v[3, 4]]` is equivalent to `[[1, 2], 3, 4]`
- If `y` is `[5, 6]`, then `[1, 2, y, vy]` is equivalent to `[1, 2, [5, 6], 5, 6]`
- `[v[2, 3.0]::[Integer, Float]]` is equivalent to `[2, 3.0]::[Integer, Float]`ⁱ

The formal syntax of list expressions is in the following end note: **16**.

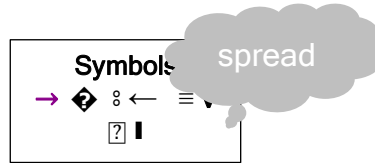
ⁱ `::[Integer, Float]` is the type of a two element list, the first of which is of type `Integer` and the second of type `Float`

Within a list, "V" is used to match the pattern that follows with the list zero or more elements. For example:

- $[[x, 2], \forall y]$ is a pattern that matches $[[1, 2], 3, 4]$ and binds x to 1 and y to $[3, 4]$
- if y is $[3, 4]$ then $[[1, 2], \forall \rho y]$ matches $[[1, 2], 3, 4]$
- $[\forall x, \forall y]$ is an illegal pattern because it can match ambiguously

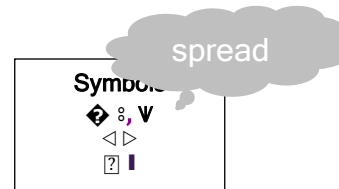
Below is the definition of a procedure that computes the reverse of a list.

Define Reverse<aType>. [aList:[aType[⊙]]]:[aType[⊙]] ≡
 aList ◊
 [] ⊃ [],
 [first, Vrest] ⊃ [Vrest, first] ? |¹⁷



The formal syntax of patterns is in the following end note: 18.

The following procedure returns every other element of a list beginning with the first:



Define AlternateElements<aType>. [aList:[aType^{⊙*}]]:[aType^{⊙*}] ≡
 aList ◊
 [] ⊃ [],
 [anElement] ⊃ [anElement],
 [firstElement, secondElement] ⊃ [firstElement],
 else ⊃
 [firstElement, secondElement, VremainingElements] ⊃
 [firstElement, VAlternateElements.[remainingElements]] ? |

Consequently,

- AlternateElements<Integer>.[[]] is equivalent to []:Integer
- AlternateElements<Integer>.[[3]] is equivalent to [3]:Integer
- AlternateElements<Integer>.[[3, 4]] is equivalent to [3]:Integer
- AlternateElements<Integer>.[[3, 4, 5]] is equivalent to [3, 6]:Integer

General Message-passing interfaces

An interface can be defined using "Interface" followed by an interface name, "with", and a list of message handler signatures, where message handler signature consists of a message name followed by argument types delimited by "[" and "]", "→", and a return type. For example, the interface type can be defined as follows:

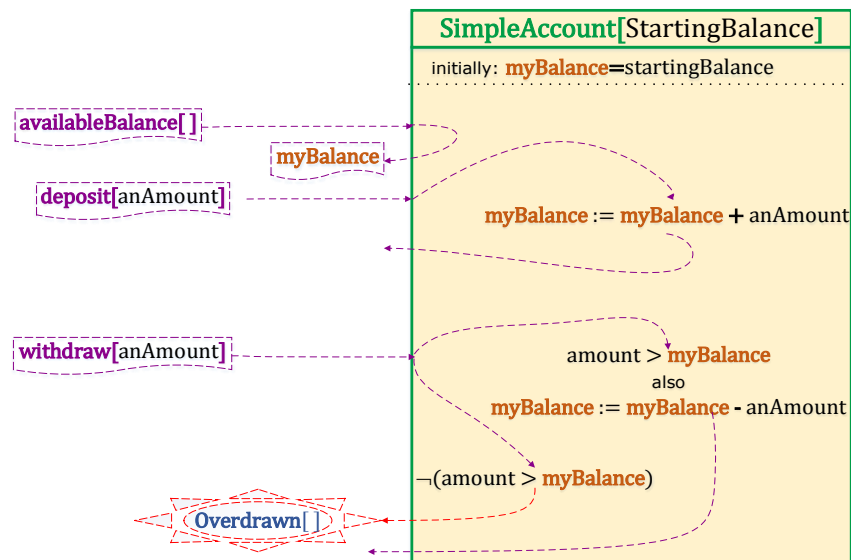
```
Interface Account with availableBalance[ ]→Euro,
                        deposit[Euro]→Void,
                        withdraw[Euro]→Void;
```

Actors that change, i.e., Actor using :=

Using the expressions introduced so far, actors do not change. However, some Actors change behaviors over time.

Message handlers in an Actor execute mutually exclusively while in a region of mutual exclusion which is called "cheese." 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.¹⁹

Below is a diagram for the implementation SimpleAccount of Account:



Variable races are impossible in ActorScript

An Actor can be created using "Actor" optionally followed by the following:

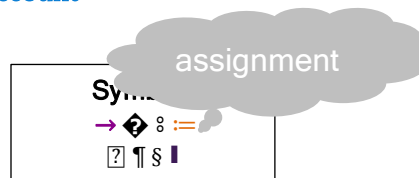
- constructor name with formal arguments delimited using brackets
- declarations of variablesⁱ terminated by "|"
- implementations of interface(s).

ActorScript is referentially transparent in the sense that a variable never changes while in a continuous part of the cheese.²⁰ For example, in the **deposit** message handler change is accomplished using the following:

```
Void; myBalance := myBalance+anAmount
```

which returns **Void** and updates **myBalance** for the *next* message received.

An implementation that of the **Account** interface can be expressed as follows:



Actor SimpleAccount[startingBalance:Euro]

```
locals myBalance := startingBalance |
```

```
// myBalance is an assignable variable initialized with startingBalance
```

```
implements Account using
```

```
availableBalance[:Euro] → myBalance¶
```

```
deposit[anAmount:Euro]:Void →
```

```
Void ∪ myBalance := myBalance+anAmount¶
```

```
// return Void; afterward the next message is
```

```
// processed with myBalance reflecting the deposit
```

```
withdraw[anAmount:Euro]:Void →
```

```
(amount > myBalance) ◆
```

```
True ∶ Throw Overdrawn[ ],
```

```
False ∶ Void ∪ myBalance := myBalance-anAmount ¶$¶
```

```
// return Void; afterward the next message is processed with
```

```
// updated myBalance
```

As a result of the above definition,

Implementation SimpleAccount extends Account!

The formal syntax of **Actor** expressions is in the following end note: **21**.

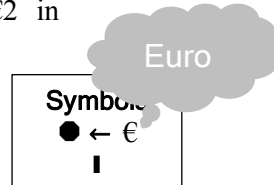
ⁱ variable declarations separated by commas

Antecedents, Preparations, and Necessary Concurrency, *i.e.*, \textcircled{P}

Concurrency can be controlled using preparation that is expressed in a continuation using preparatory expressions, " \bullet " and an expression that proceeds only *after* the preparations have been completed.

The following expression creates an account `anAccount` with initial balance €6 and then concurrently withdraws €1 and €2 in preparation for reading the balance:

```
(anAccount ← SimpleAccount[€6],  
  // € is a reserved prefix operator  
  anAccount.withdraw[€1] |||  
  anAccount.withdraw[€2] ● // proceed only after both of the  
  // withdrawals have been acknowledged  
  anAccount.availableBalance[ ])■
```



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 while at the same time facilitating implementations that run exponentially faster than those in the parallel lambda calculus.¹

The formal syntax of compound expressions is in the following end note: **22**

An expression can be annotated for concurrent execution by preceding it with " \textcircled{P} " indicating that the following expression *must* be considered for parallel execution if resources are available. For example \textcircled{P} Factorial.[1000]+ \textcircled{P} Fibonacci.[2000]■ is annotated for concurrent execution of Factorial.[1000] and Fibonacci.[2000] both of which *must* complete execution. This does not require that the executions of Factorial.[1000] and Fibonacci.[2000] actually overlap in time.²³

The formal syntax of explicit concurrency is in the following end note: **24**.

¹ For example, implementations using Actors of Direct Logic can be exponentially faster than implementations in the parallel lambda calculus.

Implementing multiple interfaces , *i.e.*, also implements

The above implementation of **Account** can be extended as follows to provide the ability to revoke²⁵ some abilities to change an account.²⁶ For example, the **AccountSupervisor** implementation below implements both the **Account** and **AccountRevoker** interfaces as an extension of the implementation **SimpleAccount** where:

```
Interface AccountRevoker with revokeDepositable[ ] → Void,  
                                revokeWithdrawable[ ] → Void
```

```
Actor AccountSupervisor[initialBalance: Euro]  
  uses SimpleAccount[initialBalance] |  
                                // uses SimpleAccount implementation27  
  locals withdrawableIsRevoked := False,  
         depositableIsRevoked := False |  
  [[revoker]]: AccountRevoker → [:AccountRevoker] |  
                                // this Actor as AccountRevoker  
  [[account]]: Account → [:Account] | // this Actor as Account  
  withdrawFee[anAmount: Euro]: Void →  
    Void ∪ myBalance := myBalance - anAmount$  
    // withdraw fee even if balance goes negative28  
    // myBalance is myBalance ◦ SimpleAccount  
  partially reimplements Account using  
  // (availableBalance[ ] → Euro) from SimpleAccount  
  withdraw[anAmount: Euro]: Void →  
    withdrawableIsRevoked ⚡  
    True ∶ Throw Revoked[ ],  
    False ∶ [:SimpleAccount].withdraw[anAmount] [?] |  
    // use withdraw of SimpleAccount  
  deposit[anAmount: Euro]: Void →  
    depositableIsRevoked ⚡  
    True ∶ Throw Revoked[ ],  
    False ∶ [:SimpleAccount].deposit[anAmount] [?] $  
  also implements AccountRevoker using  
  revokeDepositable[ ]: Void →  
    Void ∪ depositableIsRevoked := True |  
  revokeWithdrawable[ ]: Void →  
    Void ∪ withdrawableIsRevoked := True
```

As a result of the above definition:

```
Implementation AccountSupervisor has  
  [[revoker]] ↦ AccountRevoker,  
  [[account]] ↦ Account,  
  withdrawFee[Euro] ↦ Void
```

For example, the following expression returns *negative* €3:

```
(anAccountSupervisor ← AccountSupervisor.[€3],  
 anAccount ← anAccountSupervisor.[account],  
 aRevoker ← anAccountSupervisor.[revoker],  
 anAccount.withdraw[€2] ● // the balance is €1  
 aRevoker.revokeWithdrawable[] ●  
 // withdrawableIsRevoked is True  
 Try anAccount.withdraw[€5] // try another withdraw  
   catch _ : Void ● // ignore the thrown exception29  
 // myBalance remains €1  
 anAccountSupervisor.withdrawFee[€4] ●  
 // €4 is withdrawn even though withdrawableIsRevoked  
 // myBalance is negative €3  
 anAccount.availableBalance[] )
```

The formal syntax of the programs below is in the following end note: 30

Type Extension

Subtyping of an implementation is not allowed so that an implementation can be securely branded.ⁱ

The following interface expresses that each **Tree** has an integer identifier:

```
Interface Tree with [[hash]] ↦ Integer
```

An implementation of **Leaf** can be defined as an extension of **Tree** as follows:

```
Structure Leaf[aString:String]  
  implements Tree using  
  [[hash]]:Integer → Hash.[aString]
```

As a result of the above definition:

```
Implementation structure Leaf[String] extends Tree
```

ⁱ As shown elsewhere in this article, multiple implementations can be used in another implementation. Of course, interface types can be extended

For example,

- "The" is equivalent to the following:
 $(\text{Leaf}[\text{aString}] \leftarrow \text{Leaf}["\text{The}"], \text{aString})$
- $\text{Leaf}["\text{The}"].\text{hash}$ is equivalent to $\text{Hash}["\text{The}"]$.

For example,

$((\text{Leaf}["\text{The}"]):\text{Tree}).\text{hash}$ is equivalent to $\text{Hash}["\text{The}"]$.

Fork can be defined as an extension of **Tree** using:

```
Structure Fork[left:Tree, right:Tree]
  extends Tree using
    hash:Integer → Hash.[left.hash, right.hash]
```

As a result of the above definition:

Implementation structure Fork[Tree, Tree] extends Tree

For example, $\text{Hash}[\text{Hash}["\text{The}"], \text{Hash}["\text{boy}"]]$ is equivalent to the following:

$(\text{Fork}[\text{Leaf}["\text{The}"], \text{Leaf}["\text{boy}"]]).\text{hash}$

Testing for convertibility from of a type to an extension of the type is done using an expression of the extension can followed by "↓?" and the type. For example,

- $((\text{Leaf}["\text{The}"]):\text{Tree})\downarrow?\text{Fork}$ is equivalent to **False**.
- $((\text{Leaf}["\text{The}"]):\text{Tree})\downarrow?\text{Leaf}$ is equivalent to **True**.

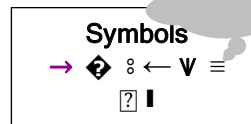
Conversion from of a type to an extension of the type is done using an expression of the extension can followed by "↓" and the type. For example,

- $((\text{Leaf}["\text{The}"]):\text{Tree})\downarrow\text{Leaf}$ is equivalent to $\text{Leaf}["\text{The}"]$.
- $((\text{Leaf}["\text{The}"]):\text{Tree})\downarrow\text{Fork}$ throws an exception.

"◇◇↓" followed by a pattern can be used to match the pattern with something which has been extended from the type of that pattern. For example,³¹

Define $\text{Fringe}[\text{aTree}:\text{Tree}]:[\text{String}^\ominus] \equiv$

```
aTree ◇
◇◇↓ Leaf[aString] :
  [aString],
◇◇↓ Fork[left, right] :
  [vFringe.[left],
  vFringe.[right]] ?
```



For example, ["The", "boy"]:String is equivalent to the following:

```
Fringe.[Fork[Leaf["The"], Leaf["boy"]]]32
```

The procedure Fringe can be used to define SameFringe? that determines if two trees have the same fringe [Hewitt 1972]:

```
Define SameFringe?.[aTree:Tree, anotherTree:Tree]:Boolean ≡  
  // test if two trees have the same fringe  
  Fringe.[aTree] = Fringe.[anotherTree]
```

Casting is as allowed only as follows:

1. Casting self to an interface implemented by this Actor
2. Upcasting
 - a. an Actor of an implementation type to the interface type of the implementation
 - b. an Actor of an interface type to the interface type that was extended
 - c. an Actor to a restricted interface of the Actor
3. Conditional downcasting of an Actor of an interface type to an extension of the interface type.ⁱ Downcasting of an interface type I is allowed only to an extension of I. For example, if x is of interface type I, then either
 - i. E is an extension of I and there is some y of type E such that x=y:I and therefore x↓E=y
 - ii. x↓E throws an exception because E is not an extension of I or there is no y of type E such that x=y:I

Swiss cheese

Swiss cheese [Hewitt and Atkinson 1977, 1979; Atkinson 1980]³³ 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.

ⁱ An implementation type *cannot* be downcast because there is nothing to which to downcast. Note that this means that an implementation type *cannot* be subtyped although an implementation can use other implementations for modularity. Of course, for interface types there is *no* semantic guarantee of what an implementation of the interface might do as long as it obeys the signatures.

By contrast with the nondeterministic lambda calculus, there is an always-halting Actor Unbounded that when sent a `[]` message can compute an integer of unbounded size. This is accomplished by creating a **Counter** with the following variables:

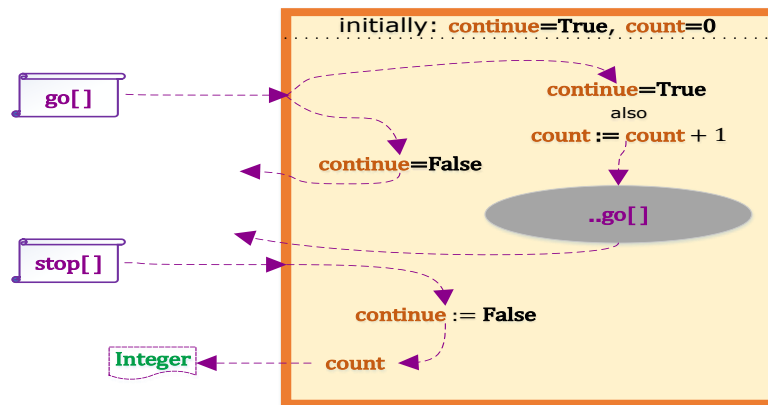
- **count** initially **0**
- **continue** initially **True**

and concurrently sending it both a `stop[]` message and a `go[]` message such that:

- When a `go[]` message is received:
 1. if **continue** is **True**, increment **count** by 1 and return the result of sending this counter a `go[]` message.
 2. if **continue** is **False**, return **Void**
- When a `stop[]` message is received, return **count** and set **continue** to **False** for the next message received.

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

A diagram is shown below for an implementation of **Counter**. In the diagram, a hole in the cheese is highlighted in grey and variables are shown in orange. The color has no semantic significance.

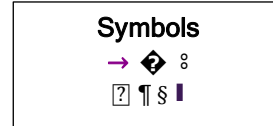


```

Define CreateUnbounded.[ ]:Integer ≡
  (aCounter ← Counter.[ ], // let aCounter be a new Counter
  ⊕aCounter.go[ ] ||| // send aCounter a go message and concurrently
  ⊕aCounter.stop[ ]) | // return the result of sending aCounter stop[ ]

```

As a notational convenience, when an Actor receives message then it can send an arbitrary message to itself by prefixing it with **".."** as in the following example for the Actor implementation **Counter**:



```

Actor Counter[ ]
  locals count := 0, // the variable count is initially 0
         continue := True |
  stop[ ]:Integer → count ∪ continue := False †
    // return count; afterward continue is updated to
    // False for the next message received
  go[ ]:Void →
    continue ◆
    True : ( count := count+1 ●, // increment count
             hole ..go[ ] ), // send go[ ] to this counter
    False : Void ?$ | // if continue is False, return Void

```

As a result of the above definition
Implementation Counter has **go**[] → Void,
stop[] → Integer |

The above example illustrates how nondeterministic branching (in Turing Machines) is not a good model for message reception in IoT.

The formal syntax of the programs above is in the following end note: 34

Coordinating Activities

Coordinating activities of 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.

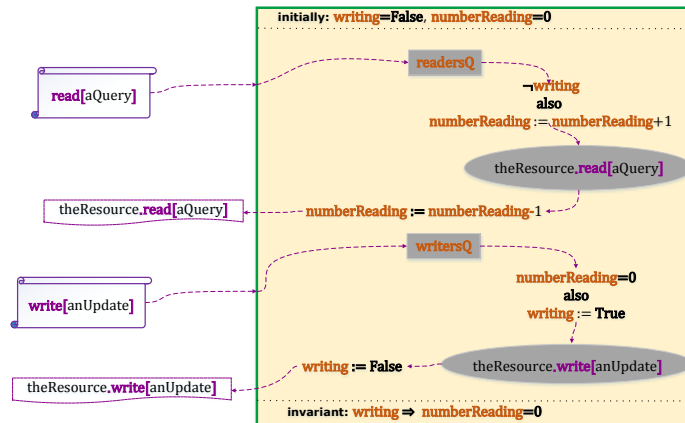
Below are two implementations of readers/writer guardians for a shared resource that implement different policies:³⁵

1. *ReadingPriority*: The policy is to permit maximum concurrency among readers without starving writers.³⁶
 - 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.³⁷
 - 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 with `read[Query]→ QueryAnswer,`
`write[Update]→ Void`

Cheese diagram for **ReadersWriter** implementations:



Note:

1. At most one activity is allowed to execute in the cheese.
2. The value of a variableⁱ changes only when leaving the cheese.ⁱⁱ

When an exception is thrown exogenously by an activity that is in a queue (e.g., **readersQ**, **writersQ**), a **backout** handler can be used to clean up cheese variables before rethrowing the exception.

The formal syntax of the programs below is in the following end note: **38**

ⁱ A variable is orange in the diagram

ⁱⁱ Of course, other external Actors can change.

In the implementations below, preconditions present are commentary for error checking. An exception is thrown if a precondition is not met at runtime. A precondition has no operational effect.

Actor **ReadingPriority**[theResource:ReadersWriter]

invariants $\text{numberReading} \geq 0, \text{writing} \Leftrightarrow \text{numberReading} = 0$

queues **readersQ**, **writersQ** | // **readersQ** and **writersQ** are initially empty

locals **writing** := False,

numberReading := 0

implements **ReadersWriter** using

read[aQuery:Query]:QueryAnswer →

((**writing** ∨ ¬IsEmpty **writersQ**) ◊

True : **Enqueue readersQ** // release cheese while in **readersQ**

backout (¬**writing** ∧ **numberReading** = 0 ∧ IsEmpty **readersQ**) ◊

True : Void **permit writersQ**,

False : Void ?

Void,

False : Void ? ●

¬**writing** // commentary for error checking

(**numberReading** ++ ● // increment **numberReading**

permit readersQ

hole theResource.**read**[aQuery] // release cheese for reading

⊔ (IsEmpty **writersQ**) ◊ // after releasing if **writersQ** is empty

True : **Permit readersQ**,³⁹

False : **numberReading** = 1 ◊

True : **Permit writersQ** also **numberReading** --,

False : **numberReading** -- ? ?) ↑

write[anUpdate:Update]:Void →

((**numberReading** > 0 ∨ ¬IsEmpty **readersQ** ∨ **writing** ∨ ¬IsEmpty **writersQ**) ◊

True : **Enqueue writersQ** // release cheese while in **writersQ**

backout (IsEmpty **writersQ** ∧ ¬**writing**) ◊

True : Void **permit readersQ**,

False : Void ?

Void,

False : Void ? ●

numberReading = 0 ∧ ¬**writing** precondition

// commentary for error checking

(**writing** := True ● // record that writing is happening

hole theResource.**write**[anUpdate] // release cheese for writing

⊔ (IsEmpty **readersQ**) ◊ // after writing if **readersQ** is empty

True : **Permit writersQ** also **writing** := False,

False : **Permit readersQ** also **writing** := False ?) § |

Symbols

→ ◊ § ∧ ∨ ¬

? ↑ § |

Illustration of writing-priority:

Actor **WritingPriority**[theResource:**ReadersWriter**]

invariants **numberReading** ≥ 0 , **writing** \Rightarrow **numberReading** = 0 |

queues **readersQ**, **writersQ** |

locals **writing** := False,

numberReading := 0 |

implements **ReadersWriter** using

read[aQuery:**Query**]:**QueryAnswer** \rightarrow

((**writing** \vee \neg **IsEmpty** **writersQ**) \diamond

True : **Enqueue** **readersQ** // release cheese while in **readersQ**

backout \neg **writing** \wedge **numberReading** = 0 \wedge **IsEmpty** **readersQ** \diamond

True : Void **permit** **writersQ**,

False : Void ?

Void,

False : Void ? \bullet

\neg **writing** precondition // commentary for error checking

(**numberReading**++) \bullet

permit **IsEmpty** **writersQ** \diamond True : **readersQ**, False : Void ?

hole theResource.**read**[aQuery] // release cheese for reading

\cup (**IsEmpty** **writersQ**) \diamond // after reading if **writersQ** is empty

True : **Permit** **readersQ**,

False : **numberReading** = 1 \diamond

True : **Permit** **writersQ** also **numberReading** --,

False : **numberReading** -- ? ?) \uparrow

write[anUpdate:**Update**]:Void \rightarrow

((**numberReading** > 0 \vee \neg **IsEmpty** **readersQ** \vee **writing** \vee \neg **IsEmpty** **writersQ**) \diamond

True : **Enqueue** **writersQ** // release cheese while in **writersQ**

backout (**IsEmpty** **writersQ** \wedge \neg **writing**) \diamond

True : Void **permit** **readersQ**,

False : Void ?

Void,

False : Void ? \bullet

numberReading = 0 \wedge \neg **writing** precondition

// commentary for error checking

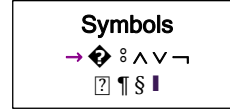
(**writing** := True) \bullet

hole theResource.**write**[anUpdate] // release cheese for writing

\cup (**IsEmpty** **readersQ**) \diamond // after writing if **readersQ** is empty

True : **Permit** **writersQ** also **writing** := False,

False : **Permit** **readersQ** also **writing** := False ?) \S \uparrow



Conclusion

By the time the Software Engineering of a language gets in good shape, the language has become obsolete in “needed expressiveness”!
Alan Kay⁴⁰

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.

ActorScript has been designed for use with a TIDE (Team Integrated Development Environment). Implementation is the next task before us!

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ActorScript is intended to provide a foundation for information coordination in client-cloud computing that protects citizens sensitive information [Hewitt 2009b].

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ⁱ In the sense that the implementation holds a hardware lock.

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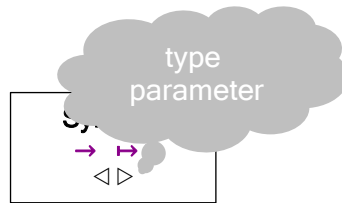
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Appendix 1. Extreme ActorScript

Parameterized Types, *i.e.*, \triangleleft , \triangleright

Parameterized Types are specialized using other types delimited by " \triangleleft " and " \triangleright ":

```
Actor Double<aType $\exists$ Arithmetic>  
  [x:aType]:aType  $\rightarrow$  aType[x+x]§  
  // addition for aType that is Arithmetic
```



Parameterized Types have become increasingly important. For example, the following is adapted from [Greenman, Muehlboeck, and Tate 2014]:

```
Interface Graph<Graph, Edge, Vertex>  
  with [[vertices]]  $\mapsto$  [Vertex $\otimes$ ]  
  §
```

```
Interface Edge<Graph, Edge, Vertex>  
  with [[graph]]  $\mapsto$  Graph,  
       [[source]]  $\mapsto$  Vertex,  
       [[target]]  $\mapsto$  Vertex  
  §
```

```
Interface Vertex<Graph, Edge, Vertex>  
  with [[graph]]  $\mapsto$  Graph,  
       [[incoming]]  $\mapsto$  [Edge $\otimes$ ],  
       [[outgoing]]  $\mapsto$  [Edge $\otimes$ ]  
  §
```

```
Actor GeoMap[]  
  implements Graph<GeoMap, Road, Intersection> using ...  
  §
```

```
Actor Road[] implements Edge<GeoMap, Road, Intersection> using ...  
  §
```

```
Actor Intersection[] implements  
  Vertex<GeoMap, Road, Intersection> using ...  
  §
```

The formal syntax of parameterized types is in the following end note: 41 .

Type Discrimination, *i.e.*, Discrimination ↑ and ↓

A discrimination definition is a type of alternatives differentiated by type using "Discrimination" followed by a type name, "between", types separated using "," terminated by "┆".

A discrimination can be constructed using an expression followed by "↑" and the discrimination type. A discrimination can be tested if it holds a discrimination of a certain type with an expression for the discrimination followed by "↓?" and the type to be tested. An expression for a discrimination followed by "↓" and a type is the discriminate of that type.

For example, consider the following definition:

Discrimination IntegerOrString between Integer, String┆

Consequently,

- $(3↑IntegerOrString)↓Integer┆$ is equivalent to $3┆$.
- $("a"↑IntegerOrString)↓Integer┆$ throws an exception because **String** is not the same as the discriminant **Integer**.
- $(3↑IntegerOrString)↓?Integer┆$ is equivalent to **True┆**.
- $(3↑IntegerOrString)↓?String┆$ is equivalent to **False┆**.
- $[3↑IntegerOrString, "a"↑IntegerOrString]:IntegerOrString$ is of type $[IntegerOrString^⊛]$

A pattern followed by "◇↓" and the type to be projected matches an Actor if the pattern matches the projection.

- The pattern $x◇↓String$ matches $"a"↑IntegerOrString$ and binds x to $"a"$.
- The pattern $x◇↓String$ does not match $3↑IntegerOrString$
- The expression below is equivalent to $2┆$:
 $3↑IntegerOrString ◇ y↓Integer ∋ y-1,$
 $x↓String ∋ x [?]┆$

Discriminations can also be used in crypto as in the following definition:

**Discrimination EmployeeNumberOrEncrypted between
EmployeeNumber,
Encrypted┆**

with the result that having an address x of type **EmployeeNumberOrEncrypted** does not by itself provide access to an encrypted employee number from x without also having the type **EmployeeNumber** using `Decrypt<EmployeeNumber>.[x↓Encrypted]`

The formal syntax of type discrimination is in following end note: 42.

Structures

A structure is an Actor used in pattern matching that can be defined using an identifier by "[", parts separated by "," and "]".

Discrimination can be used with structures. For example, a `Trie<aType>` is a discrimination of `Terminal<aType>` and `TrieFork<aType>`:

```
Discrimination Trie<aType> between
Terminal<aType>,
TrieFork<aType>■
```

where the structure `Terminal` can be defined as follows:

```
Structure Terminal<aType>[anActor:aType]■
```

For example,

- The expression $(x \leftarrow 3, \text{Terminal}\langle\text{Integer}\rangle[x]) \blacksquare$ is equivalent to `Terminal<Integer>[3]■`
- The pattern `Terminal<Integer>[x]` matches `Terminal<Integer>[3]` and binds `x` to 3.

The structure `TrieFork` can be defined as follows:

```
Structure TrieFork<aType>[left:Trie<aType>, right:Trie<aType>]
flip[ ]:TrieFork<aType> → // flip the branches
TrieFork<aType>[right, left]■
```

For example,

- The expression $(x \leftarrow 3, \text{TrieFork}[\text{Terminal}[x], \text{Terminal}[x+1]]) \blacksquare$ ⁴³ is equivalent to the following:
`TrieFork[Trie[Terminal[5], Trie[Terminal[6]]]■`
- The pattern `TrieFork<Integer>[x, y]` matches `TrieFork[Trie[Terminal[5], Trie[Terminal[6]]]■` and binds `x` to `Terminal[5]` and `y` to `Terminal[6]`.

" $\diamond\downarrow$ " followed by a structure pattern an Actor if the pattern matches the projection.

ⁱ x is of type `Integer`

Below is the definition of a procedure that computes a list that is the "fringe" of the terminals of a Trie.ⁱ

```

Define TrieFringe<aType>.[aTrie:Trie<aType>]:[aType⊙] ≡
  aTrie ◆
  ◆◆↓Terminal<aType>[x] ⑆
    [x].
  ◆◆↓TrieFork<aType>[left, right] ⑆
    [▼TrieFringe.[left], ▼TrieFringe<aType>.[right]] ?■

```

The above procedure can be used to define TrieSameFringe? that determines if two lists have the same fringe [Hewitt 1972]:

```

Define TrieSameFringe?<aType>.[left:Trie<aType>,
  right:Trie<aType>]:Boolean ≡
  // test if two Tries have the same fringe
  TrieFringe<aType>.[left] = TrieFringe<aType>.[right]■

```

The formal syntax of structures is in the following end note: 44

Nullable

Distinguishing a special case to indicate the absence of an Actor is a long-time issue [Hoare 2009].

In an expression,

- "⊙" followed by an expression of type **Nullable<aType>** is the Actor (of type **aType**) in the nullable or throws an exception if there is no Actor.
- "**Nullable**" followed by an expression of type **aType** is the nullable (of type **Nullable<aType>**) containing the value of the expression.
- "**Null**" followed by a type is the null for that type.

For example,

- **Nullable** 3 is of type **Nullable<Integer>**
- **⊙Nullable** 3■ is equivalent to 3■
- **⊙Null Integer**■ throws an exception

ⁱ See definition of **Trie** above in this article.

In a pattern,

- " $\diamond\odot$ " followed by a pattern matches a nullable if and only if it is non-null and the pattern matches the Actor in the nullable.
- **TheNull** only matches the null.

For example,

- The pattern $\diamond\odot x$ matches **Nullable** 3, binding x to 3
- The pattern $\diamond\odot x$ does not match **Null Integer**
- The pattern **TheNull** matches **Null Integer**

The formal syntax of nullables is in following end note: 45.

Processing Exceptions, *i.e.*, **Try catch** $\diamond\circledast$, \circledast \odot and **Try cleanup**

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

```
Try Throw Exception["This is a test."] catch  $\diamond\circledast$   
  Exception[aString]  $\circledast$  aString  $\odot$   $\mathbf{\!}$ 
```

The following illustration performs **Reset**. \odot $\mathbf{\!}$ and then rethrows **Exception**["This is another test.":

```
Try Throw Exception["This is another test."] cleanup Reset. $\odot$   $\mathbf{\!}$ 
```

The formal syntax of processing exceptions is in the following end note: 46.

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:

```
(x  $\leftarrow$  -1,  
 x  $\geq$  0 precondition SquareRoot. $\odot$ [x] )  $\mathbf{\!}$ 
```

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

```
SquareRoot. $\odot$ [2] postcondition  $\lambda$  [y:Float]:Boolean  $\rightarrow$  y < 1  $\mathbf{\!}$ 
```

The formal syntax requirements is in the following end note: 47.

Multiple implementations of a type

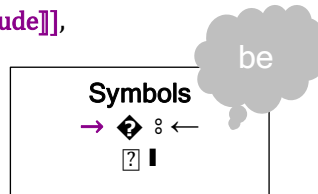
The interface type **Complex** is defined as follows:

```
Interface Complex with [[real]] |..> Float,
                       [[imaginary]] |..> Float,
                       [[magnitude]] |..> Float,
                       [[angle]] |..> Degrees!
```

Cartesian Actors that implement **Complex** can be defined as follows:

Structure Cartesian[myReal:**Float** default 0, myImaginary:**Float** default 0]
implements **Complex** using

```
[[real]]:Float → myReal¶
[[imaginary]]:Float → myImaginary¶
[[magnitude]]:Float →
  SquareRoot,[[myReal*myReal + myImaginary*myImaginary]]¶
[[angle]]:Degrees →
  (theta ← Arcsine,[[myImaginary]/,[[magnitude]]],
  myReal>0 ◆
  True § theta,
  False §
    myImaginary >0 ◆
    True §180°-theta,48
    False §180°+theta ? ?)§!
```



Consequently,

- **Cartesian**[1, 2].**[[real]]**! is equivalent to 1!
- **Cartesian**[3, 4].**[[magnitude]]**! is equivalent to 5.0!

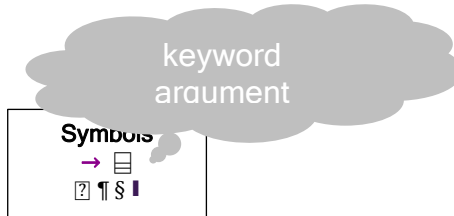
For example, cartesianans can be used in the following procedure definitions:⁴⁹

```
Define Times<Complex>,[[u:Complex, v:Complex]:Complex ≡
  Cartesian[u,[[real]]*v,[[real]] - u,[[imaginary]]*v,[[imaginary]],
  u,[[imaginary]]*v,[[real]] + u,[[real]]*v,[[imaginary]]]!50
```

```
Define Equivalent,[[u:Complex, v:Complex]:Boolean ≡
  u,[[real]]=v,[[real]] ∧ u,[[imaginary]]=v,[[imaginary]]!
```

Arguments with named fields, *i.e.*, `⊞` and `⊟`

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



```
Structure Polar[angle _:Degrees⊞ default 0°,
// angle of type Degrees is a named argument of Polar with
// default 0°
magnitude _:Length⊞ default 1.0]
implements Complex using
[[real]:Float → magnitude*Sine.[angle]⊞
[[imaginary]:Float → magnitude*Cosine.[angle]⊞
```

Consequently,

- `Polar[].[real]` is equivalent to `1`

For example, the procedure Times for polars can be defined as follows:

```
Define Times<Polar>.
[Polar[angle:Angle⊞, magnitude:Length⊞,
Polar[angle⊞ anotherAngle, magnitude⊞ anotherMagnitude]]
:Complex ≡
Polar[angle⊞ angle +anotherAngle,
magnitude⊞ magnitude *anotherMagnitude]⊞51
```

The formal syntax of named arguments is in the following end note: 52.

Sets, i.e., { } using spreading, i.e., { V }

A set is unordered with duplicates removed.

The formal syntax of sets is in the following end note: **53.**

Multisets, i.e., { } using spreading, i.e., { V }

A set is unordered with duplicates allowed.

The formal syntax of multisets is in the following end note: **54.**

Maps,

A map is composed of pairs. For example, the following is a map:

```
Map<Integer, String>[[3]→"a", [4]→"b"]
```

Pairs in maps are unordered, e.g.,

```
Map<Integer, String>[[3]→"a", [4]→"b"]
```

 is equivalent to

```
Map<Integer, String>[[4]→"a", [3]→"b"]
```

However, the expression `Map<Integer, String>[[4]→"a", [4]→"b"]` throws an exception because a map is univalent.

The formal syntax of multisets is in the following end note: **55.**

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 making use of the following:

```
Structure ContactRecord[yearsOld:Age,
                        numberOfContacts:Integer,
                        citizenship:String]
```

`[ContactRecord]` has

```
filter[[ContactRecord] |> Boolean]
  |> {ContactRecord},
collect [[ContactRecord] |> [Age, Integer]]
  |> Map<Age, {Integer}>
```

`Map<Age, {Integer}>` has

```
reduceRange[[{Integer}] |> Float]
  |> Map<Age, Float>
```

```
{Number⊕} has average[ ] |..> Float|
```

```
Map<Age, Float> has  
  sort[[Age, Age] |..> Boolean]  
  |..> [Age, Float]|
```

The program is as follows:⁵⁶

```
Define AgeWithAverageOfNumberOfContactsSortedByAge.  
  [records:{ContactRecord⊕}] : Sorted<Age> ≡  
  records.filter [[aRecord:ContactRecord]  
    ..> aRecord.[citizenship] ◆  
      "US" : True,  
      else : False ?]  
  .collect [[aRecord:ContactRecord]  
    ..> [aRecord.[yearsOld],  
      aRecord.[numberOfContacts]]  
  .reduceRange  
    [[aSetOfNumberOfContacts:{Integer⊕}]  
    ..> aSetOfNumberOfContacts.average[ ]]  
  .sort[LessThanOrEqual<Age>]|
```

Encryption

Actor addresses can be type-encrypted using **Encrypt**. Using the above definition, the following is a contact record with fields **yearsOld**, **numberOfContacts**, and **citizenship** type encrypted:

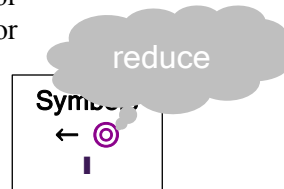
```
Encrypt ContactRecord[yearsOld ≡ 5,  
  numberOfContacts ≡ 7,  
  citizenship ≡ "UK"]57|
```

The above encrypted contact record can be decrypted only by using the type **ContactRecord**. For example, the encrypted record above matches the following pattern:

```
Decrypted<ContactRecord> aRecord  
with aRecord bound to the decrypted record.
```

Futures, *i.e.*, **Future** and \odot

A future [Baker and Hewitt 1977] for an expression can be created in ActorScript by using "**Future**" preceding the expression. The operator " \odot " can be used to "reduce" a future by returning an Actor computed by the future or throwing an exception. For example, the following expression is equivalent to `Factorial.[9999]`!



```
(aFuturei ← Future Factorial.[9999],
 $\odot$ aFuture) ! // do not proceed until Factorial.[9999] has
// been reducedii
```

Futures allow execution of expressions to be adaptively executed indefinitely into the future.⁵⁸ For example, the following returns a future

```
(aFuture ← Future Factorial.[9999],
g ← ( $\lambda$  [afuture:Future<Integer>]:Integer → 5),
// g returns 5 regardless of its argument
g.[aFuture]) !
// return 5 regardless of whether Factorial.[9999] has completediii
```

Note that the following are all equivalent:

- \odot **Future** (4+Factorial.[9999])!
- 4+ \odot **Future** Factorial.[9999]!
- 4+ \oplus Factorial.[9999]!
- \oplus (4+Factorial.[9999])!

Also \oplus Factorial.[9999]+ \oplus Fibonacci.[9000]! is equivalent to the following:

```
(n ←  $\oplus$ Factorial.[9999],
m ←  $\oplus$ Fibonacci.[9000],
n+m) ! // return Factorial.[9999]+Fibonacci.[9000]
```

ⁱ f is of type **Future**<Integer>

ⁱⁱ *i.e.* returned or threw an exception

ⁱⁱⁱ *i.e.* Factorial.[1000] might not have returned or thrown an exception when 5 is returned. The future f will be garbage collected.

In the following example, `Factorial.[9999]` might never be executed if `readCharacter.[]` returns the character 'x':

```
(aFuture ← Future Factorial.[9999],
 readCharacter.[ ] ⚡
  'x' ⋮ 1, // readCharacter.[ ] returned 'x'
  else ⋮ 1+ ⓄaFuture [?])!
```

// readCharacter.[] returned something other than 'x'

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

The above procedure can be used to define `SameFringe?` that determines if two lists have the same fringe [Hewitt 1972]:

```
Define SameFringe?<aType>.
  [aTrie:Trie<aType>, anotherTrie:Trie<aType>]:Boolean ≡
    // test if two Tries have the same fringe
  TrieFringe<aType>.[aTrie] = TrieFringe<aType>.[anotherTrie]!
  // = reduces futures in the fringes
```

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

```
Define ListOfReducedElements<aType>.
  [aListOfFutures:[Future<aType>⊙]]:[aType⊙] ≡
  aListOfFutures ⚡
  [] ⋮ [],
  [aFirst, VaRest] ⋮
  [ⓄaFirst,
   VListOfReducedElements<aType>.[aRest]] [?]!
```

The formal syntax of futures is in the following end note: 59.

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

The following is an illustration of language extension that illustrates postponed execution:⁶⁰

```
Actor ("Postpone" anExpression:Expression<aType>))
                                     :Postpone<aType>
implements Expression<Future<aType>> using
  eval[e:Environment]:Future<aType> →
    Future Actor implements aType using
      aMessage → // aMessage received
      (postponed ← anExpression.eval[e],
       postponed.aMessage||
        // return result of sending aMessage to postponed
       become postponed)§
      // become the Actor postponed for
      // the next message receivedi
```

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

ⁱ this is allowed because postponed is of type **aType**

In-line Recursion (e.g., looping), i.e. Loop `[← , ←] is`

Inline recursion (often called looping) is accomplished using "Loop", an initial invocation with identifiers initialized using "←" followed by "is" and the body.ⁱ

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.

```
Loop Factorial.[n ← 9, accumulation ← 1] is
  n=1 ◆ True ∶ accumulation,
  False ∶ Factorial.[n-1, n*accumulation] ?ii
```

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 expression returns a list of ten times successively calling the parameterless procedure Pⁱⁱⁱ (of type `[] → Integer`):

```
Loop FirstTenSequentially.[n ← 10] is
  n=1 ◆ True ∶ [P.[ ]],
  False ∶ (x ← P.[ ]) ●
  [x, ∀FirstTenSequentially.[n-1]] ?iv
```

The following returns one of the results of concurrently calling the procedure P^{iv} (which has no arguments and returns `Integer`) ten times with no arguments:

```
Loop OneOfTen.[n ← 10] is
  n=1 ◆ True ∶ P.[ ],
  False ∶ ⊕P.[ ] either ⊕OneOfTen.[n-1] ?62
```

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

ⁱ This construct is used instead of **while**, **for**, *etc.* loops used in other programming languages.

ⁱⁱ equivalent to the following:

```
Loop Factorial.[n:Integer ← 9, accumulation:Integer ← 1]:Integer is
  n=1 ◆ True ∶ accumulation,
  False ∶ Factorial.[n-1, n*accumulation] ?
```

ⁱⁱⁱ 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.

Strings

Strings are Actors that can be expressed using `"`, string arguments, and `'''`. For example,

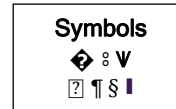
- `"1", "23", "4"` is equivalent to `"1234"`.
- `"1", "2", "34", "56"` is equivalent to `"123456"`.
- `""1", "2""", "34""` is equivalent to `"1234"`.
- `""` is equivalent to `"`.

String patterns are delimited by `"` and `'''`. Within a string pattern, `V` is used to match the pattern that follows with the list zero or more characters. For example:

- `"x, "2", Vy"` is a pattern that matches `"1234"` and binds `x` to `"1"` and `y` to `"34"`.
- `""1", "2", V0y"` is a pattern that only matches `"1234"` if `y` is `"34"`.
- `"Vx, Vy"` is an illegal pattern because it can match ambiguously.

As an example of the use of spread, the following procedure reverses a string:⁶⁴

```
Define Reverse.[aString:String]:String ≡
  aString ◊
  " " ◊ " " ,
  "first, Vrest" ◊ "Vrest, first" ?!
```



The formal syntax of string expressions is in the following end note: **65**.

General Messaging, *i.e.*, `.` and `⊙`

The syntax for general messaging is to use an expression for the recipient followed by `.` and an expression for the message.

For example, if `anExpression` is of type `Expression<Integer>` then, `anExpression.eval[anEnvironment]` is equivalent to the following:

```
(aMessage ← eval⊙Expression<Integer>[anEnvironment],
  anExpression.aMessage)!
```

The formal syntax of general messaging is in the following end note: **66**.

Atomic Operations, *i.e.* Atomic compare update updated notUpdated

For example, the following example implements a lockable that spins to lock:⁶⁷

```

Actor SpinLock[]
  locals locked := False | // initially unlocked
  implements Lockablei using
  lock[]:Void →
    Loop Attempt.[ ] is // perform the loop Attempt as follows
      Atomic locked compare False update True ⇨
        // attempt to atomically update locked from False to True
        updated : locked=True precondition
          // commentary for error checking:
          // locked must have contents True
          Void, // if updated return Void
        notUpdated : Attempt.[ ] ?↑ // if not updated, try again
  unLock[]:Void →
    locked =True precondition // commentary for error checking:
      // locked must have contents True
    Void ⇨ locked := False §! // reset locked to False
  
```

Symbols

→ ⇨ §

? ↑ § !

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

ⁱ Interface Lockable with lock[] → Void,
unLock[] → Void!

Enumerations, i.e., Enumeration of using **Qualifiers, i.e.,** `

An enumeration definition provides symbolic names for alternatives using "**Enumeration**" followed by the name of the enumeration, "**of**", a list of distinct identifiers terminated by "**!**".

For example,

Enumeration DayName of Monday, Tuesday, Wednesday, Thursday,
Friday, Saturday, Sunday**!**

From the above definition, an enumerated day is available using a qualifier, e.g., Monday_{DayName}. Qualifiers provide for namespaces.

The formal syntax of qualifiers is in the following end note: **69**.

The procedure below computes the name of following day of the week given the name of any day of the week:

UsingNamespace DayName!

Define 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: **70**.

Native types, e.g., JavaScript, JSON, Java, HTML (HTTP), and XML

Because Actor addresses are typed, almost any kind of addressed can be accommodated.

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:

```
(aRectanglei ← Object {"length": 3, "width": 4}),  
aFunction ← Function [ ] → This["length"] * This["width"],  
Rectangle["area"] := aFunction ●  
aRectangle["area"].[ ]!
```

ⁱ aRectangle is of type **Object** JavaScript

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

```
setTimeout@JavaScript.[1000,  
    Function []→  
    console@JavaScript.[log].[later]]
```

HTML strings can be used to create Actor addresses. For example, the Wikipedia English homepage can be retrieved as follows:⁷¹

```
(HTTPS[en.wikipedia.org]).get[ ]
```

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

Native types can also be used from Java. For example, if `s:String@Java`, then `s.substring[3, 5]`ⁱⁱ is the substring of `s` from the 3rd to the 5th characters inclusive.

Java types can be referenced using **Refer**ⁱⁱⁱ, e.g.:

Refer java.math.BigInteger

Refer java.lang.Number

The following notation is used for XML:⁷²

```
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>
```

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

ⁱⁱ **substring** is a method of the **String** type in Java

ⁱⁱⁱ **Refer** is called **Import** in Java

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

- **XML** <"doc"> 1, 2, **V**[3] </"doc">] is equivalent to **XML** <"doc">1, 2, 3</"doc">]
- **XML** <"doc">1, 2, **V**[3], **V**[4] </"doc">] is equivalent to **XML** <"doc"> 1, 2, 3, 4 </"doc">]

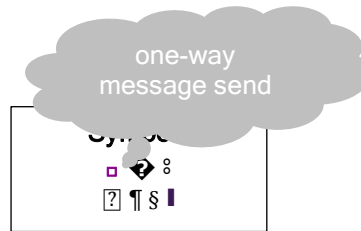
One-way messaging, e.g., Θ , and \square

One-way messaging is often used in hardware implementations.

Each one-way named-message send consists of an expression followed by " \square ", a message name, and arguments delimited by "[" and "]".

Each one-way message handler implementation consists of a named-message declaration pattern, ":", " Θ ", " \rightarrow " and a body for the response which must ultimately be " Θ " which denotes no response.

The following is an implementation of an arithmetic logic unit that implements **jumpGreater** and **addJumpPositive** one-way messages:



```

Actor ArithmeticLogicUnit<aType> []
  implements ALU<aType> using
    jumpGreater[x:aType, y:aType,
      firstGreaterAddress:Address, elseAddress:Address]:Θ →
      InstructionUnit◻Execute[(x>y) ◆
        True ◻ firstGreaterAddress,
        False ◻ elseAddress ?] †
    addJumpPositive[x:aType, y:aType, sumLocation:Location<aType>,
      positiveAddress:Address, elseAddress:Address]:Θ →
      (z ← (x+y),
      sumLocation ◆
      aVariableLocation:VariableLocation<aType>i ◻
      (VariableLocation.store[z] ●
        // continue after acknowledgement of store
      (z > 0) ◆ True ◻ InstructionUnit◻execute[positiveAddress],
        False ◻ InstructionUnit◻execute[elseAddress] ?),
      aTemporaryLocation:TemporaryLocation<aType>ii ◻
      (aTemporaryLocation◻write[z] † † †
        // continue concurrently with processing write
      (z > 0) ◆ True ◻ InstructionUnit◻execute[positiveAddress],
        False ◻ InstructionUnit◻execute[elseAddress] ?) ?$ †

```

The formal syntactic definition of one-way named-message and receiving is in the following end note: 73

ⁱ VariableLocation<aType> has store[aType] → Void †
ⁱⁱ TemporaryLocation<aType> has write[aType] → Θ †

Using multiple other implementations , i.e., ☐

This section presents an example of using multiple other implementations such as the ones below:

```
Actor Male[aLength:Meter]
  [[length]:Meter → aLength$!]
```

```
Actor Human[aMagnitude:Year]
  [[magnitude]:Year → aMagnitude$!]
```

Boy below makes use of both the Male and Human implementations:

```
Actor Boy[aMagnitude:Meter, aLength:Year]
  uses Male[aMagnitude], Human[aLength] |
  // uses implementations Male and Human74
  [[magnitude]:Meter → ([☐]Male).[[length]]!
  // using this Actor with Male interface
  [[length]:Year → ([☐]Human).[[magnitude]]$!
  // using this Actor with Human interface
```

For example,

- Boy[Meter[3], Year[4]].[[magnitude]]! is equivalent to Meter[3]!
- Boy[Meter[3], Year[4]].[[length]]! is equivalent to Year[4]!

Meta

Meta provides ability to provide extraordinary access to an Actor. For example, history of an Actor can be queried.

```
Interface Meta<aType> has
  [[history]] ↪ [Request<aType>⊕],
  reset[anActor:aType] ↪ Void!
```

```
Interface Request<aType> has
  [[message]] ↪ Message<aType> ,
  [[customer]] ↪ Customer<aType>,
  [[response]] ↪ Future<Response<anotherType>>>!
```

```
Discrimination Response<aType> between
  Returned<anotherType>,
  Threw!
```

Inconsistency Robust Logic Programs

Logic Programs⁷⁵ can logically infer computational steps.

Forward Chaining

Forward chaining is performed using \vdash

(\vdash *Theory* *PropositionExpression*)
Assert *PropositionExpression* for *Theory*.

(**When** \vdash *Theory* *aProposition:Pattern* \rightarrow *Expression*)
When *aProposition* holds for *Theory*, evaluate *Expression*.

Illustration of forward chaining:

\vdash_t Human[Socrates]■

When \vdash_t Human[x] \rightarrow \vdash_t Mortal[x]■

will result in asserting Mortal[Socrates] for theory t

Backward Chaining

Backward chaining is performed using \Vdash

(\Vdash *Theory* *aGoal:Pattern* \rightarrow *Expression*)
Set *aGoal* for *Theory* and when established evaluate *Expression*.

(\Vdash *Theory* *aGoal:Pattern*):*Expression*
Set *aGoal* for *Theory* and return a list of assertions that satisfy the goal.

(**When** \Vdash *Theory* *aGoal:Pattern* \rightarrow *Expression*)
When there is a goal that matches *aGoal* for *Theory*, evaluate *Expression*.

Illustration of backward chaining:

$\vdash_t \text{Human}[\text{Socrates}] \mathbf{!}$

When $\Vdash_t \text{Mortal}[x] \rightarrow (\Vdash_t \text{Human}[Ox] \rightarrow \vdash_t \text{Mortal}[x]) \mathbf{!}$

$\Vdash_t \text{Mortal}[\text{Socrates}] \mathbf{!}$

will result in asserting $\text{Mortal}[\text{Socrates}]$ for theory t .

SubArguments

This section explains how subargumentsⁱ can be implemented in natural deduction.

When $\Vdash_s (\psi \vdash_t \phi) \rightarrow$

$(t' \leftarrow \text{Extension} \cdot [t],$

$\vdash_{t'} \psi \mathbf{!}$

$\Vdash_{t'} \phi \rightarrow \vdash_s (\psi \vdash_t \phi)) \mathbf{!}$

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

- **when** $\vdash_t \theta \rightarrow \vdash_{t'} \theta \mathbf{!}$
- **when** $\Vdash_{t'} \theta \rightarrow \Vdash_t \theta \mathbf{!}$

ⁱ See appendix on Inconsistency Robust Natural Deduction.

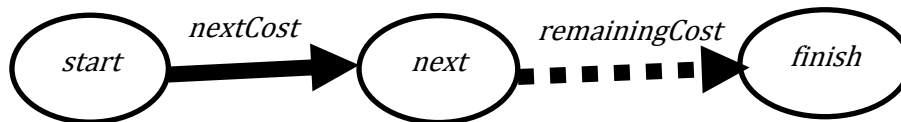
Aggregation using Ground-Complete Predicates

Logic Programs in ActorScript are a further development of Planner. For example, suppose there is a ground-complete predicate⁷⁶ `Link[aNode, anotherNode, aCost]` that is true exactly when there is a path from `aNode` to `anotherNode` with `aCost`.

```
When  $\vdash$  Path[aNode, aNode, aCost]  $\rightarrow$ 
    // when a goal is set for a cost between aNode and itself
     $\vdash$  aCost=0  $\mid$  // assert that the cost from a node to itself is 0
```

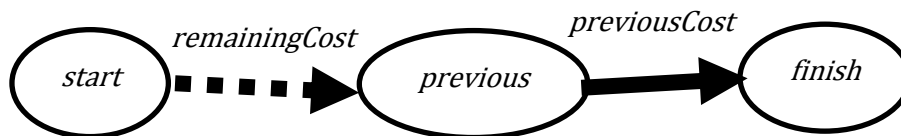
The following goal-driven Logic Program works forward from `start` to find the cost to `finish`:⁷⁷

```
When  $\vdash$  Path[start, finish, aCost]  $\rightarrow$ 
     $\vdash$  aCost=Minimum {nextCost + remainingCost
        |  $\vdash$  Link[start, next $\neq$ start, nextCost],
        Path[next, finish, remainingCost]}  $\mid$ 
    // a cost from start to finish is the minimum of the set of the sum of the
    // cost for the next node after start and
    // the cost from that node to finish
```



The following goal-driven Logic Program works backward from `finish` to find the cost from `start`:

```
When  $\vdash$  Path[start, finish, aCost]  $\rightarrow$ 
     $\vdash$  aCost= Minimum {remainingCost + previousCost
        |  $\vdash$  Link[previous $\neq$ finish, finish, previousCost],
        Path[start, previous, remainingCost]}  $\mid$ 
    // the cost from start to finish is the minimum of the set of the sum of the
    // cost for the previous node before finish and
    // the cost from start to that Node
```



Note that all of the above Logic Programs work together concurrently providing information to each other.

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.⁷⁸

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

`Construct`ⁱ is the fundamental type for ActorScript programming language constructs. `Expression<aType>` is an extension of `Construct` with an `eval` message that has an environment with the bindings of program identifiers and a message with an environment and cheese:

```
Interface Expression<aType> extends Construct with
    eval[Environment] -> aType,
    perform[Environment, CheeseQ] -> aType!
```

`BasicExpression<aType>` is an implementation that performs the functionality of leaving the cheese for expression being used as the continuation:

```
Actor BasicExpression<aType> [ ]
    perform[e:Environment, c:CheeseQ] ->
    Try (anActor ← [ ]Expression<aType>.eval[e] ●
        c.release[ ] |||
        anActor)
    cleanup c.release[ ] §!
```

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

```
Actor (anIdentifier: Identifier<aType>): Expression<aType:Type>
    uses BasicExpression<aType> [ ] |
    partially implements Expression<aType> using
        eval[e:Environment]:aType -> e.lookup[anIdentifier]!
```

ⁱ Interface `Construct`!

The interface Type

Interface `thisType`:: with

- `extension?[_]] |..> Boolean`,
- `has?[MethodSignature] |..> Boolean`,
- `sendOneWay[thisType, Message ↦ ⊖] ↦ ⊖`,
- `sendRequest[thisType, Message ↦ aReturnType] ↦ aReturnType`,
- `encrypt[_] ↦ Encrypted`,
- `encrypterType[Type] ↦ EncrypterTypei`,
- `decrypt[Encrypted] ↦ thisType`,
- `decrypterType[thisType, EncrypterType] ↦ DecrypterTypeii`,
- `decrypt?[Encrypted] ↦ Boolean`,
- `return[Customer<aReturnType>, aReturnType] ↦ Void`,
- `throw[Customer, Exception] ↦ Void`!

`CommunicationType` is a restriction that can be used only for communication:

Interface `thisType:CommunicationType` restricts `Type` with

- `sendOneWay[thisType, Message ↦ ⊖] ↦ ⊖`,
- `sendRequest[thisType, Message ↦ aReturnType] ↦ aReturnType`,
- `return[Customer<aReturnType>, aReturnType] ↦ Void`,
- `throw[Customer, Exception] ↦ Void`!

`SendingType` is a restriction of `CommunicationType` that can be used only for sending:

Interface `thisType:SendingType` restricts `CommunicationType` with

- `sendOneWay[thisType, Message ↦ ⊖] ↦ ⊖`,
- `sendRequest[thisType, Message ↦ aReturnType] ↦ aReturnType`!⁷⁹

ⁱ Implementation `EncrypterType` has `encrypt[thisType] ↦ Encrypted`!

ⁱⁱ Implementation `DecrypterType` has `decrypt[Encrypted] ↦ thisType`,
`decrypt?[Encrypted] ↦ Boolean`!

Suppose there is a type **Account** that needs have accounts that can be shared selectively among some IoT devices so thatⁱ

- some of the devices can operate using the address of an account
- some can only pass on an inoperable opaque address of the account
- some can convert an inoperable opaque address to an operable address of the account
- and some can convert an operable account address to an opaque inoperable address.

Construct type **et1** (that has the operations on accounts) using the constructor **EncrypterType** as follows:

```
et1 ← EncrypterType[Account]           // et1:EncrypterTypeii
```

Also, construct **dt1** (that has the operations on accounts) using the constructor **DecrypterType** as follows:

```
dt1 ← DecrypterType[Account, et1]    // dt1:DecrypterTypeiii
anAccount ← Account[$5]              // anAccount is a new Account with $5
anAccount.deposit[$1]                 // afterward anAccount has $6
x ← et1[anAccount]                  // x:et1
anAccount.deposit[$2]                 // afterward anAccount has $8
```

An IoT device⁸⁰ is given **x** (an address that can be used to perform operations on anAccount) and type **et1** (which can perform encryption) where:

```
u ← et1.encrypt[x]                 // u:Encrypted
```

An IoT device⁸¹ is given the encrypted address **u** and type **dt1** (which can perform decryption for addresses encrypted using **et1**) where:

```
y ← dt1.decrypt[u]                // y:dt1
y.deposit[$3]                        // afterward anAccount has $11 provided there
                                        // were no withdrawals or deposits after
                                        // the $2 deposit above
```

Then **x** and **y** are addresses for the same account and both can be used to operate on the account.

The same technique can be used for an individual account by creating encryption and decryption types for that account:

```
et2 ← EncrypterType[Account],
dt2 ← DecrypterType[Account, et2]
```

ⁱ Possession of **Account** enables both encryption and decryption of individual accounts

ⁱⁱ **Implementation** **EncrypterType** has **encrypt**[_:**EncrypterType**] ↦ **Encrypted** **!**

ⁱⁱⁱ **Implementation** **DecrypterType** has **decrypt**[**Encrypted**] ↦ _:**DecrypterType**,
decrypt?[**Encrypted**] ↦ **Boolean** **!**

Only an Actor that possesses `dt2` can decrypt an Actor address encrypted using `et2`.

```
Actor (anotherType:Type<anotherType>
      "∃?" aType:Type<aType>):Expression<Boolean>
uses BasicExpression<aType>[] |
partially implements Expression<Boolean> using
  eval[e:Environment]:Boolean →
    (anotherType.eval[e]).extension?[aType.eval[e]] |
```

Type Discrimination

Interface `DiscriminationType` extends `Type` with

- `up[Type] → Discrimination`,
- `down[Discrimination] → Type`,
- `down?[Discrimination] → Boolean` |

```
Actor (anExpression:Expression<aType:Type>
      "↑" castExpression:Type<aDiscriminationType:Discrimination>)
      :DiscriminationUp<aType, aDiscriminationType>

uses BasicExpression<aType>[] |
partially implements Expression<aType> using
  eval[e:Environment]:aType →
    castExpression.eval[e].up[anExpression.eval[e]] |
```

```

Actor
(aPattern: Pattern <aDiscriminationType>>
  "↑" castExpression: Type <aDiscriminationType>)
  : DiscriminationPatternUp <aType, aDiscriminationType>
uses BasicPattern <aDiscriminationType> [] |
partially implements Pattern <aDiscriminationType> using
  match[anActor: DiscriminationInstance <aType, aDiscriminationType>,
    e: Environment]: aType →
  aPattern.match[aDiscriminationType.up[anActor], e] |

```

```

Actor
(anExpression: Expression
  <DiscriminationInstance <aType, aDiscriminationType>>
  "↓" castExpression: Type <aType>)
  : DiscriminationDown <aType, aDiscriminationType>
uses BasicExpression <aType> [] |
partially implements Expression <aType> using
  eval[e: Environment]: aType →
  castExpression.eval[e].down[anExpression.eval[e]] |

```

```

Actor
(aPattern: Pattern <aType>
  "↓" castExpression: Type <aType>)
  : DiscriminationPatternDown <aType, aDiscriminationType>
uses BasicPattern <aType> [] |
partially implements Pattern <aType> using
  match[anActor: DiscriminationInstance <aType, aDiscriminationType>,
    e: Environment]: Nullable <Environment> →
  aPattern.match[aDiscriminationType.down[anActor], e] |

```

```

Actor
("⌚⌚↓" aStructurePattern:Pattern<aStructureType>)
  :DownPattern<aStructureType, aDiscriminationType>
uses BasicPattern<aStructureType>[] |
partially implements Pattern<aStructureType> using
  match[anActor:DiscriminationStructureInstance<aType,
    aDiscriminationType>,
    e:Environment]:Nullable<Environment> →
structurePattern._match[aDiscriminationStructureInstanceType
  _down?[anActor, aStructureType],
  e] ⚡
  True ⚡ structurePattern._match[aDiscriminationStructureInstanceType
    _down[anActor, aStructureType]
  e]
  False ⚡ Null Environment) |

```

```

Actor
(aDiscriminationStructureInstanceType
  "⌚↓" aStructurePattern:Pattern<aStructureType>)
  :TypeDownPattern<aStructureType, aDiscriminationType>
uses BasicPattern<aStructureType>[] |
partially implements Pattern<aStructureType> using
  match[anActor:DiscriminationStructureInstance<aType,
    aDiscriminationType>,
    e:Environment]:Nullable<Environment> →
structurePattern._match[aDiscriminationStructureInstanceType
  _down?[anActor, aStructureType],
  e] ⚡
  True ⚡ structurePattern._match[aDiscriminationStructureInstanceType
    _down[anActor, aStructureType],
  e]
  False ⚡ Null Environment) |

```

```

Actor
  (anExpression: Expression
    <DiscriminationInstance<aType,
      aDiscriminationType>>
    "↓?" castExpression: Type<aType>)
    : DiscriminationDownQuery<aType,
      aDiscriminationType>

  uses BasicExpression<Boolean>[] |
  partially implements Expression<Boolean> using
    eval[e: Environment]: Boolean →
      aDiscriminationType.down?[anExpression.eval[e]] |

```

```

Actor ("Discrimination" aDiscriminationType "between"
  typeExpressions: Types "I"): Definition
Actor implements Definition using
  eval[e: Environment]: Environment →
  (types ← typeExpressions.eval[e],
  e.bind[aDiscriminationType,
  type ≡ DiscriminationType,
  to ≡
  Actor partially implements DiscriminationType with
  up[anInstance: aType ∈ types]: aDiscriminationType →
  SimpleDiscriminationInstance
    <aType, aDiscriminationType>[anInstance] |
  down[anUpped
    : DiscriminationInstance
    <aType, aDiscriminationType>]: aType ∈ types →
  anUpped ◆
  ⌞ ⌞ ↓ SimpleDiscriminationInstance<aType>[anInstance] ⋮
    anInstance [?]
  else ⋮ Throw CastException[],
  down?[anUpped: DiscriminationInstance
    <aType, aDiscriminationType>]: Boolean →
  anUpped ◆
  ⌞ ⌞ ↓ SimpleDiscriminationInstance<aType>[_] ⋮
    True,
  else ⋮ False [?]) |

Structure SimpleDiscriminationInstance<aType, aDiscriminationType>
  [anInstance: aType]
  extends DiscriminationInstance<aType, aDiscriminationType> |

```

Type restriction

```
Interface RestrictionType<aType>  
  extends Type with up[aType] ↦ RestrictionType<aType> ◻
```

```
Actor (anExpression: Expression <aType>  
  "↑" castExpression: Type <RestrictionType<aType>>)  
  : RestrictionUp <aType>  
  
uses BasicExpression <aType> [ ] |  
partially implements Expression <RestrictionType<aType>> using  
eval[e: Environment]: RestrictionType<aType> →  
  castExpression, eval[e], up[anExpression, eval[e]] ◻
```

```
Actor ("Interface" aRestrictionType  
  "restricts" typeExpression: Type <aType>  
  "with" signatureExpressions: Signatures "◻"): Definition  
Actor implements Definition using  
eval[e: Environment]: Environment →  
  (signatures ← signatureExpressions, eval[e]  
  typeExpression, eval[e].has?[signatures] precondition  
  e.bind[aRestrictionType,  
    type ◻ RestrictionType<aType>,  
    to ◻  
  Actor implements RestrictionType<aType> using  
    up[anInstance: aType]: aRestrictionType →  
      RestrictionInstance[anInstance]) ◻  
  
Structure RestrictionInstance[anInstance: aType] uses BasicType [ ] |  
partially reimplements  
  RestrictionType<aType> having  
    (aMessage ↦ aReturnType) signatures) ◻ using  
sendRequest[aRecipient: aRestrictionType,  
  aMessage: aMessage]: aReturnType →  
  aRecipient ◻  
  ◻ ◻ ↓ RestrictionInstance[anInstance] ◻  
    sendRequest[anInstance, aMessage],  
  else ◻ Throw CastException [ ] ? ◻  
sendOneWay[aRecipient: aRestrictionType,  
  aMessage: aMessage]: ◻ →  
  aRecipient ◻  
  ◻ ◻ ↓ RestrictionInstance[anInstance] ◻  
    sendOneWay[anInstance, aMessage],  
  else ◻ Throw CastException [ ] ? ◻
```


Type extension

```
Interface Extension<aType>  
  extends Type with  
    up[ExtensionInstance<aType>] ↳ aType,  
    down[aType] ↳ Extension<aType>,  
    down?[aType] ↳ Boolean!
```

```
Actor (anExpression: Expression <anExtensionType>  
  "↑" castExpression: Type <aBaseType>)  
  :ExpressionUp <anExtensionType, aBaseType>  
  uses BasicExpression<aBaseType>[ ] |  
  partially implements Expression<aBaseType> using  
  eval[e: Environment]: aBaseType →  
  castExpression.eval[e].up[anExpression.eval[e]]!
```

```
Actor  
(aPattern: Pattern <anExtensionType>>  
  "↕↑" castExpression: Type <anExtensionType>)  
  :PatternUp <anExtensionType, aBaseType>  
  uses BasicPattern<anExtensionType>[ ] |  
  partially implements Pattern<anExtensionType> using  
  match[anActor: ExtensionInstance<anExtensionType, aBaseType>,  
  e: Environment]: aType →  
  aPattern.match[anExtensionType.up[anActor], e]!
```

```
Actor  
(anExpression: Expression <aBaseType>  
  "↓" castExpression: Type <anExtensionType>)  
  :ExtensionDown <anExtensionType, aBaseType>  
  uses BasicExpression<anExtensionType>[ ] |  
  partially implements Expression<anExtensionType> using  
  eval[e: Environment]: aType →  
  castExpression.eval[e].down[anExpression.eval[e]]!
```

```

Actor
(anPattern: Pattern <anExtensionType>
  "↯" castExpression: Type <anExtensionType>)
  : ExtensionPatternDown <aBaseType, anExtensionType>
uses BasicPattern <aBaseType> [ ] |
partially implements Pattern <aBaseType> using
  match[anActor: ExtensionInstance <aBaseType, anExtensionType>,
    e: Environment]: Nullable <Environment> →
    aPattern.match[castExpression.eval[e].down[anActor], e] |

```

```

Actor
(anExpression: Expression <aBaseType>
  "↯?" castExpression: Type <anExtensionType>)
  : ExpressionDownQuery <anExtensionType, aBaseType>
uses BasicExpression <Boolean> [ ] |
partially implements Expression <Boolean> using
  eval[e: Environment]: aType →
    castExpression.eval[e].down?[anExpression.eval[e]] |

```

```

Actor ("Actor" anExtensionType "extends" Type<aType> "I")
                                     :Definition
Actor implements Definition using
  eval[e:Environment]:Environment →
    e.bind[anExtensionType,
      type ⊆ RestrictionType<aType>,
      to ⊆ Actor uses BasicType[] |
        partially implements Extension<aType> using
          up[anInstance:anExtensionType]:aType →
            ExtensionInstance<aType>[anInstance]↑
          down[anUpped:aType]:anExtensionType →
            anUpped ◆
              ↻ ↻ ExtensionInstance<anExtensionType, aType>
                                     [anInstance] ⋮
            anInstance,
            else Throw CastException[]?↑
          down?[anUpped:aType]:Boolean →
            anUpped ◆
              ↻ ↻ ExtensionInstance<anExtensionType, aType>
                                     [] ⋮
            True,
            else False?§I

Structure ExtensionInstance<anExtension, aType>
                                     [anInstance:anExtension]
  extends aType>I

```

Nullable, e.g., ⊙

The type **Nullable** is used for nullables:

Implementation **Nullable**<aType> has
reduce?[] → **Boolean**,
reduce[] → **aType**!

```
Actor ("Nullable" anExpression: Expression <aType>))
                                     : Nullable <aType>
uses BasicExpression <Nullable <aType>> [ ] |
partially implements Expression <Nullable <aType>> using
eval[e: Environment]: Nullable <aType> →
(anActor ← anExpression.eval[e] ●
  Actor implements Nullable <aType> using
    reduce?[ ]: Boolean → True!
    reduce[ ]: aType → anActor$)!
```

```
Actor (Null aType: Type <aType>): NullExpression <aType>
uses BasicExpression <Nullable <aType>> [ ] |
partially implements Expression <Nullable <aType>> using
eval[e: Environment]: Nullable <aType> →
  Actor implements Nullable <aType> using
    reduce?[ ]: Boolean → False!
    reduce[ ]: aType → Throw IsNullException[ ] $!
```

```
Actor (TheNull): NullPattern <aType>
implements Pattern <Nullable <aType>> using
match[anActor: Nullable <aType>, e: Environment]
                                     : Nullable <Environment> →
  anActor ◆
    TheNull : Nullable e,
    else : Null Environment [?] $!
```

```
Actor ("⊙" anExpression: Expression <Nullable <aType>>))
                                     : Expression <aType>
uses BasicExpression <aType> [ ] |
partially implements Expression <aType> using
eval[e: Environment]: aType →
  (anExpression.eval[e].reduce[ ] $!
```

```

Actor ("ⓂⓄ" aPattern:Pattern<Nullable<aType>>))
                                     :Pattern<aType>
implements Pattern<Nullable<aType>> using
  match[anActor:Nullable<aType>, e:Environment]
                                     :Nullable<Environment> →
  anActor.reduce?[ ] ⚡
    True ⚡ aPattern.match[anActor.reduce[ ], e] ⚡
    TheNull ⚡ Nullable e,
    else ⚡ Null Environment [?],
    False ⚡ Null Environment [?]&#36;!

```

Future, e.g., Ⓞ, and Ⓟ

The type **Future** is used for futures:

Implementation **Future**<aType> has
 reduce[] → aType!

```

Actor ("Future" anExpression:Expression<aType>))
                                     :Future<aType>
uses BasicExpression<Future<aType>>[ ] |
partially implements Expression<Future<aType>> using
  eval[e:Environment]:Future<aType> →
  (aFuture ←
    Future Try anExpression.eval[e]
    catch ⚡
      anException ⚡
      Actor
        implements Future<aType> using
          reduce[ ]:aType →
            Throw anException[?]
  Actor implements Future<aType> using
    reduce[ ]:aType → ⓄaFuture §&#36;!

```

```

Actor ("Ⓞ" anExpression:Expression<Future<aType>>))
                                     :Reduction<aType>
uses BasicExpression<aType>[ ] |
partially implements Expression<aType> using
  eval[e:Environment]:aType →
  anExpression.eval[e].reduce[ ]&#36;!

```

```

Actor ("ⓂⓄ" aPattern:Pattern<Future<aType>>))
                                     :Pattern<aType>
implements Pattern<Future<aType>> using
  match[anActor:Future<aType>, e:Environment]
                                     :Nullable<Environment> →
  aPattern._match[anActor._reduce[ ], e] ⚡
  TheNull ⚡ Nullable e,
  else ⚡ Null Environment [?], $!

```

```

Actor ("Ⓟ" anExpression:Expression<aType>))
                                     :Mandatory<aType>
uses BasicExpression<aType>[ ] |
implements Expression<aType> using
  eval[e:Environment]:aType →
  ⓄFuture anExpression._eval[e] $!

```

The message **match**

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

```

Interface Pattern<aType> with
  match [aType, Environment] → Nullable<Environment> !

```

```

Actor (anIdentifier:Identifier<aType>):Pattern<aType>
implements Pattern<aType> using
  match[anActor:aType, e:Environment]:Nullable<Environment> →
  e._bind[anIdentifier, type ⊆ aType, to ⊆ anActor] !

```

```

Actor ("_"):UniversalPattern<aType>
implements Pattern<aType> using
  match[anActor:aType, e:Environment]:Nullable<Environment> →
  Nullable e !

```

```

Actor ("∘" anExpression:Expression<aType>))
    :ValuePattern<aType>
implements Pattern<aType> using
    match[anActor, e:Environment]:Nullable<Environment> →
        anActor ◊
        anExpression.eval[e] : Nullable e,
        else : Null Environment ?!

```

Message sending, e.g.,

```

Actor (procedure:Expression<argumentsType→returnType>
    ." "[" arguments:Arguments<argumentsType> "]" )
    :ProcedureSend<returnType>
uses BasicExpression<returnType>[] |
partially implements Expression<returnType> using
    eval[e:Environment]:returnType →
        (procedure.eval[e]).[∀(expressions.eval[e])]!

```

```

Actor (recipient:Expression<recipientType>
    ." name:MessageName
    "[" arguments:Arguments<argumentsType> "]" )
    :NamedMessageSend<returnType>
uses BasicExpression<returnType>[] |
partially implements Expression<returnType> using
    eval[e:Environment]:returnType →
        (aRecipient ← recipient.eval[e],
        aRecipient.SimpleMessage[QualifiedName[name, recipientType],
        [Arguments.eval[e]]])!

```

```

Actor (recipient:Expression<recipientType>
    ." aMessage:Message<messageType> )
    :UnnamedMessageSend<returnType>
uses BasicExpression<returnType>[] |
partially implements Expression<returnType> using
    eval[e:Environment]:returnType →
        recipientType.send[recipient.eval[e], aMessage.eval[e]]!

```

List Expressions and Patterns

```

Actor ("[" first:Expression<aType> ","
      second:Expression<aType>"]"):Expression<[aType⊙]>
uses BasicExpression<[aType⊙]>[] |
partially implements Expression<[aType⊙]> using
eval[e:Environment]:[aType⊙] →
[first.eval[e], second.eval[e]] §I

```

```

Actor ("[" first:Expression<aType> ","
      "v" rest:Expression<aType>"]"):Expression<[aType⊙]>
uses BasicExpression<[aType⊙]>[] |
partially implements Expression<[aType⊙]> using
eval[e:Environment]:[aType⊙] →
[first.eval[e], v rest.eval[e]] §I

```

```

Actor ("[" first:Pattern<aType> ","
      "v" rest:Pattern<aType⊙ "&"]"):Pattern<[aType⊙]>
implements Pattern<[aType⊙]> using
match[anActor:[aType⊙],
      e:Environment]:Nullable<Environment> →
anActor ⚡
[first, vrest] :
  first.match[first, e] ⚡
  TheNull : Null Environment,
  m⊙aNewEnvironment :
    rest.match[restValue, aNewEnvironment] [?],
  else : Null Environment[?] §I

```


Exceptions

```
Actor ("Try" anExpression:Expression<aType>
      "catch" exceptions:ExpressionCases<Exception, aType> "?")
      :TryExpression<aType>

uses BasicExpression<aType>[ ] |
partially implements Expression<aType> using
eval[e:Environment]:aType →
  Try anExpression.eval[e] catch
  anException:Exception :
    CasesEval.[anException, exceptions, e] ?$!
```

```
Actor ("Try" anExpression:Expression<aType>
      "cleanup" aCleanup:Expression<aType>))
      :TryExpression<aType>

uses BasicExpression<aType>[ ] |
partially implements Expression<aType> using
eval[e:Environment]:aType →
  Try anExpression.eval[e]
  catch
  _ : (aCleanup.eval[e]
      Rethrow) ?$!
```

Continuations using perform

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

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

```
Actor Execute<aType>
[aConstruct:Construct,
 e:Environment,
 c:CheeseQ]:aType →
  aConstruct ◆ aContinuation ↓ Continuation<aType> :
    aContinuaton.perform[e, c],
  anExpression ↓ Expression<aType> :
    anExpression.eval[e] ?$!
```

Atomic compare and update

```
Actor ("Atomic" location: Expression<Location<anotherType>>,
      "compare" comparison: Expression<anotherType>
      "update" update: Expression<anotherType> "⚡"
      "updated" "§"
      compareIdentical: ContinuationList<aType> ", "
      "notUpdated" "§"
      compareNotIdentical: ContinuationList<aType>)
      :Atomic<aType>

implements Continuation<aType> using
perform[e: Environment, c: CheeseQ]: aType →
(location. eval[e])
.compareAndConditionallyUpdate[comparison. eval[e],
                               update. eval[e]] ⚡
  True § compareIdentical. perform[e, c],
  False §
    compareNotIdentical. perform[e, c] ? § |

Actor SimpleLocation<anotherType>[initialContents]
  locals contents := initialContents |
  implements Location<anotherType> using
    compareAndConditionallyUpdate[comparison, update]: Boolean →
      (contents = comparison) ⚡
      True § True ∪ contents := update,
      False § False ? § |
```

Cases

```

Actor (anExpression: Expression <anotherType> "◆"
        cases: ExpressionCases <anotherType, aType> "[?]")
        : CasesExpression <aType>

uses BasicExpression <aType> [ ] |
partially implements Expression <aType> using
    eval [e: Environment]: aType →
        CasesEval.eval[anExpression.eval[e], cases, e] $!

Actor CasesEval
    [anActor: anotherType,
     cases: [ExpressionCase <anotherType, aType> ⊙],
     e: Environment]: aType →
    cases ◆
    [ ] : Throw NoApplicableCase [ ],
    [first, ∨rest] :
        first ◆ ((aPattern: Pattern <anotherType> "⊙"
                 anExpression: Expression <aType>)
                 : ExpressionCase <aType> :
        aPattern.match[anActor, e] ◆
        TheNull :
            CasesEval.eval[anActor, rest, e],
            ⊙ ⊙ newEnvironment :
                anExpression.eval[newEnvironment] [?],
            ("else" elsePattern: Pattern <anotherType> "⊙"
             elseExpression: Expression <aType>)
             : ExpressionElseCase <aType> :
        elsePattern.match[anActor, e] ◆
        TheNull :
            Throw ElsePatternMustMatch [ ],
            ⊙ ⊙ newEnvironment :
                elseExpression.eval[newEnvironment] [?],
            ("else" "⊙"
             elseExpression: Expression <aType>)
             : ExpressionElseCase <aType> :
        elseExpression.eval[e],
    else : Throw NoApplicableCase [ ] [?] $!

```

```

Actor (anExpression: Expression <anotherType> "◆"
        cases: ContinuationCases <anotherType, aType> "?")
        : CasesContinuation <aType>
implements Continuation <aType> using
    perform[e: Environment, c: CheeseQ]: aType →
        CasesPerform. [anExpression.eval[e], cases, e, c] $!

Actor CasesPerform
    [anActor: anotherType,
     cases: [ContinuationCase <aType> *],
     e: Environment,
     c: CheeseQ]: aType →
cases ◆
    [] : Throw NoApplicableCase [],
    [first, Vrest] :
        first ◆ (aPattern: Pattern <anotherType> "§"
                aContinuation: Continuation <aType>)
                : ContinuationCase <aType> :
                aPattern.match[anActor, e] ◆
                TheNull :
                    CasesPerform. [anActor, rest, e, c],
                    M⊙newEnvironment :
                    aContinuation.perform[newEnvironment, c] ?,
                ("else"
                 elsePattern: Pattern <anotherType> "§"
                 elseContinuation: Continuation <aType>)
                 : ContinuationElseCase <aType> :
                 elsePattern.match[anActor, e] ◆
                 TheNull :
                     Throw ElsePatternMustMatch [],
                     M⊙newEnvironment :
                     elseContinuation.eval[newEnvironment] ?,
                ("else" "§"
                 elseContinuation: Continuation <aType>)
                 : ContinuationElseCase <aType> :
                 elseContinuation.perform[e, c],
                else : Throw NoApplicableCase [] ? ? !

```

Holes in the cheese

```
Actor (anExpression: Expression<aType>
      "⌞" someAssignments: Assignments)
      :Afterward<aType>
implements Continuation<aType> using
perform[e: Environment, c: CheeseQ]: aType →
(anActor ← anExpression.eval[e] ●
 someAssignments.carryOut[e, c] ●
 c.release[] ●
 anActor)§
```

```
Actor (aVariable: Variable<aType>
      "!=" anExpression: Expression<aType>): Assignment
implements Assignment using
carryOut[e: Environment]: Void →
e.assign[aVariable, to ⌘ anExpression.eval[e]]§
```

```
Actor ("Hole" anExpression: Expression<aType>): Hole<aType>
implements Continuation<aType> using
perform[e: Environment, c: CheeseQ]: aType →
(frozenEnvironment ← e.freeze[] ●
 // create frozen environment so that subsequent assignments
 // subsequent assignments do not affect evaluating anExpression
 c.release[] ●
 anExpression.eval[frozenEnvironment])§
```

```

Actor ("(" aPreparations:Preparations
      anExpression:Expression <aType>")")
      :CompoundExpression <aType>
implements Continuation <aType> using
perform[e:Environment, c:CheeseQ]:aType →
(frozenEnvironment ← e.freeze[] ●
 // create frozen environment so that
 // preparation does not affect evaluating anExpression
aPreparation.carryOut[e, c] ●
c.release[] ●
anExpression.eval[frozenEnvironment])$!

```

```

Actor ("Hole" anExpression:Expression <anotherType>
      "⊔" anAfterward:AfterwardContinuation <aType> "?"")
      :Hole <aType>
implements Continuation <aType> using
perform[e:Environment, c:CheeseQ]:aType →
(frozenEnvironment ← e.freeze[] ●
c.release[] ●
Try (anActor ← anExpression.eval[frozenEnvironment] ●
    Holding c in anAfterward.perform[e, c] ●
    anActor)
catch ◆
    _ ∴ (Holding c in anAfterward.perform[e, c] ●
        Rethrow) ?$!

```

```

Actor ("Holding" resourceExpression:Expression<Resource> "in"
      anExpression Expression<aType> "?")
      :HoldingExpression<aType>
uses BasicExpression<aType> |
partially implements Expression<aType> using
eval[e:Environment]:aType →
(resource ← resourceExpression.eval[e],
 resource.acquire[] ●
 Try (anActor ← anExpression.eval[e],
      resource.release[] ,
      anActor)
 catch
  _ ⚡ (resource.release[] ●
      Rethrow) ? § !

```

```

("Hole" anExpression:Expression<anotherType>
 "returned"
 returnedCases:ContinuationCases<anotherType, aType> "?")
 "threw"
 threwCases:ContinuationCases<anotherType, aType> "?")
      :Hole<anotherType, aType>
implements Continuation<aType> using
perform[e:Environment, c:CheeseQ]:aType →
(frozenEnvironment ← e.freeze[] ●
 c.release[] ●
 Try (anActor ← anExpression.eval[frozenEnvironment] ●
      c.acquire[] ●
      CasesPerform.[anActor, returnedCases, e, c])
 cleanup
 (c.acquire[] ●
  CasesPerform.[anException, threwCases, e, c]) ? § !

```

```

Actor ("Enqueue" anExpression:QueueExpression "●"):Enqueue
implements Continuation using
perform[e:Environment, c:CheeseQ]:Void →
anExpression.eval[e].enqueueAndLeave[] § !

```

```

Actor ("Enqueue" anExpression: QueueExpression "●"
      aContinuation: Continuation <aType>): Enqueue <aType>
implements Continuation <aType> using
perform[e: Environment, c: CheeseQ]: aType →
(anInternalQ ← anExpression.eval[e],
 anInternalQ.enqueueAndLeave[] ●
 aContinuation.perform[e, c]) §!

```

Simple Implementation of Actor

The implementation below does not implement queues, holes, and relaying.

```

Actor ("Actor" declarations: ActorDeclarations
      "implements" Identifier <aType>
      "using" handlers: Handlers <anInterface> "$"): Definition
implements Expression <anInterface> using
eval[e: Environment]: aType →
  Initialized <aType>.[anInterface.eval[e],
                    handlers,
                    declarations.initialize[e],
                    CheeseQ.[ ]] §!

```

```

Actor Initialized <aType>
[anInterface: aType,
 handlers: [Handler⊕],
 e: Environment,
 c: CheeseQ]: aType →
  Actor implements anInterface using
  receivedMessage: Type <Message> →
    // receivedMessage received for anInterface
    (c.acquire[] ●
     aReturned ← Try Select.[receivedMessage, handlers, e, c]
     cleanup c.release[] ●
     // release cheese and rethrow exception
     c.release[] ●
     aReturned) §!

```


Actor Select

```
[receivedMessage:Message,  
handlers:[Handler⊗],  
e:Environment,  
c:CheeseQ]:aType →  
handlers ⚡  
[] : Throw MessageRejected[ ],  
[(aMessageDeclaration:MessageDeclaration <aType>  
  ":" ReturnDeclaration <aType> "→"  
  body:Continuation <aType>))  
  :ContinuationHandler <aType>,  
VrestHandlers] :  
aMessageDeclaration.match[receivedMessage, e] ⚡  
TheNull :  
  Select.[receivedMessage, restHandlers, e, c],  
  // process next handler  
  Ⓜ⊗newEnvironment :  
  Execute <aType>.[body, newEnvironment, c] [??] █
```

An implementation of cheese that never holds a lock

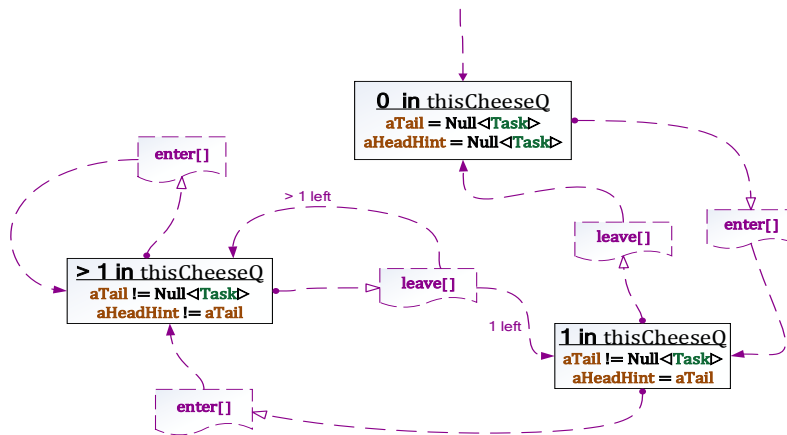
The following is an implementation of cheese that does not hold a lock:

```

Actor CheeseQ[]
  invariants aTail=Null Activity ⇒ previousToTail=Null Activity |
  locals aHeadHint := Null Activity,           // aHeadHint:Nullable<Activity>82
         aTail := Null Activity                // aTail:Nullable<Activity>83
  acquire[]:Void nonexclusive in myActivity →84
    myActivity.#[previous] = Null Activity ∧
    myActivity.#[nextHint] = Null Activity
  precondition // commentary for error checking
    Loop attempt.[]:Void is
      (myActivity.#[previous := aTail]) ● // set provisional tail of queue
      Atomic aTail compare aTail update myActivity ◊
        updated : // inserted myActivity in cheese queue with previous
          myActivity.#[previous] ◊
          TheNull: Void, // successfully entered cheese
          else : Suspend [], // current activity is suspended
        notUpdated : attempt.[] []? ◊ // make another attempt
  release[]:Void nonexclusive in myActivity →
    // release message received running myActivity
  aTail≠Null Activity85 precondition // commentary for error checking
    (ahead ← []SubCheeseQ.#[head]) ●
    ahead=myActivity
  precondition // commentary for error checking
    Atomic aTail compare ahead update Null Activity ◊
    updated : // last activity has left this cheese queue
    Void ∪ aHeadHint := Null Activity,
    notUpdated : // another activity is in this cheese queue
      MakeRunnable @ahead.#[nextHint]
      ∪ aHeadHint := ahead.#[nextHint] []? §
  internal SubCheeseQ using // internal interface
    #[head]:Activity nonexclusive →
    aTail≠Null Activity precondition // commentary for error checking
    Loop findHead.#[backIterator:Activity] ←
      aHeadHint ◊
      TheNull: @aTail,
      ∪ @anActivity : anActivity []]:Activity is
    backIterator.#[previous] ◊
    TheNull: // backIterator is head of this cheese queue
      (aHeadHint := Nullable backIterator) ●
      backIterator),
    ∪ @previousBackIterator :
      // backIterator is not the head of this cheese queue
      (previousBackIterator.#[nextHint := Nullable backIterator]) ●
      // set nextHint of previous to backIterator
    findHead.#[previousBackIterator] []? §
  
```

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:



As a consequence of the definition of **CheeseQ**:

Implementation CheeseQ has **acquire[]** \mapsto **Void**
release[] \mapsto **Void**!

The implementation **CheeseQ** uses activities to implement its queue where

Implementation Activity has

```

[[previous]]  $\mapsto$  Nullable<Activity>
    // if null then head of queue else, pointer to backwards list to head
[[previous := Nullable<Activity>]]  $\mapsto$  Nullable<Activity>
    // returns self so that updates can be chained
[[nextHint]]  $\mapsto$  Nullable<Activity>
    // if non-null then pointer to next activity to get cheese after this one
[[nextHint := Nullable<Activity>]]  $\mapsto$  Nullable<Activity>!
    // returns self so that updates can be chained
  
```

Implementation type **InternalQ** is defined on the next page where:

```

Implementation InternalQ has
  enqueueAndLeave[]  $\mapsto$  Void,
  enqueueAndDequeue[InternalQ]  $\mapsto$  Activity
  dequeue[]  $\mapsto$  Activity
  empty?[]  $\mapsto$  Boolean!
  
```

```

Actor InternalQ[c:CheeseQ]
  locals aQueue ← SimpleFIFO<Activity>[ ]
  enqueueAndLeave[ ]:Void in myActivity →
    // enqueueAndLeave message received in myActivity
    (aQueue.■add[myActivity])●
    c.■release[ ]● // myActivity is the head of aCheeseQ
    Suspend)¶
    // myActivity is suspended and when resumed returns Void ¶
  enqueueAndDequeue[anInternalQ:InternalQ]:Activity in myActivity →
    ¬anInternalQ.■empty?[ ] precondition
    // commentary for error checking
    (aQueue.■add[myActivity])●
    ..dequeue[ ]●
    Suspend)¶
  dequeue[ ]:Activity in myActivity →
    ¬..empty?[ ] precondition // commentary for error checking
    (c.■release[ ]●
    // myActivity is the head of aCheeseQ
    MakeRunnable aQueue.■remove[ ])¶
    // make runnable the removed activity
  empty?[ ]:Boolean → aQueue.■empty?[ ]$■

```

where

```

Interface FIFO<aType> has
  add[anActivity:aType] ↪ Void,
  remove[anActivity:aType] ↪ aType,
  empty?[ ] ↪ Boolean■

```

Appendix 3. ActorScript Symbols with IDE ASCII, and Unicode codes

Symbol	IDE ASCII ⁱ	Read as	Category	Matching Delimiters	Unicode (hex)
⏏	;;	end	top level terminator		25AE
:	:	of specified type	infix		
::	::	is a type	postfix		
⏏	[:]	this Actor with interface (aspect)	prefix		2360
⊙	\0 ⁸⁶	reduce (nullables, futures)	prefix		29BE
⊙	~\0 ⁸⁷	match reduced (nullables, futures)	prefix		
↓	\v/	down	infix		2193
↓?	\v/?	down query	infix		
↓	~\v/	match downed	infix		
↑	^^	up	infix		2191
↑	~^	match upped	prefix		
⊙	(.)	qualified by	infix		22A1
λ	/\	procedure	prefix	≡ and/or →	03BB
≡	===	defined as	infix	Define	2261
▪	.	is sent	infix		
▪▪	..	send to this Actor	prefix		2025
Ⓟ	\p ⁸⁸	necessarily concurrent	prefix		29B7
→	->	message type returns type ⁸⁹	infix		21A6
→	..>	cacheable →			
→	-->	message received ⁹⁰		λ and/or ¶	2192
→		pair	infix		21A0
←	<--	be ⁹¹	infix		2190
⚡	??	cases	separator	?	FFFD
⚡	???	end cases	terminator	⚡ and catch⚡	2370
¶	\p ⁹²	another message handler	separator for handlers	→	00B6
§	\s	end handlers	terminator	implements and extension	00A7
⋮	(:)	case	separator for case		2982
●	;	before	separator	binding, preparation and Enqueue	2BC3
		concurrently	separator	binding, preparation	2225

ⁱ These are only examples. They can be redefined using keyboard macros according to personal preference.

				and Enqueue	
\doteq	\doteq	is assigned	infix		2254
\supset	\supset	afterward	infix		21BA
\circ	$\backslash o^{93}$	matches value of ⁹⁴	prefix		2315
$=$	$=$	same as?	infix		
\neq	\neq	Different from?	infix		2260
\equiv	$[=]$	keyword or field	infix		2338
$:\equiv$	$:[=]$	assignable field	infix		
\triangleleft	$< $	begin type parameters	left delimiter	\triangleright (Unicode hex: 0077)	0076
\vee	$\backslash /$	spread ⁹⁵	prefix		2A5B
$\{$	$\{$	begin set	left delimiter	$\}$	
$[$	$[$	begin list	left delimiter	$]$	
$\{ $	$\{ $	begin multi-set	left delimiter	$\} $	2983
\llbracket	$[$	formatted message	left delimiter	\rrbracket	27E6
$"$	$\backslash"$	Left string structure	left delimiter	$"$	201C
$($	$($	begin grouping	left delimiter	$)$	
$(($	$($	begin syntax	left delimiter	$))$	2985
\otimes	$(*)$	zero or more	postfix		229B
\vdots	$:::$	uniformly of a type	infix		22EE
\ominus	$(-)$	nothing ⁹⁶	expression		229D
\sqcap	$\backslash.$	one-way send	infix		219E
\sqcup	\sqcup	join	infix		2294
\sqsubseteq	$[<=]$	constrained by	infix		2291
\sqsupseteq	$[>=]$	extends	infix		2292
\Rightarrow	\Rightarrow	logical implication	infix		21E8
\Leftrightarrow	\Leftrightarrow	logical equivalence	infix		21D4
\wedge	\wedge	logical conjunction	infix		00D9
\vee	\vee	logical disjunction	infix		00DA
\neg	$- $	logical negation	prefix		00D8
\vdash	$ -$	assert	prefix and infix		22A2
\Vdash	$ -$	goal	prefix and infix		22A9
$//$	$//$	begin 1-line comment	prefix	EndOfLine	
$/*$	$/*$	begin comment	prefix	$*/$	

Appendix 4. ActorScript Reserved Words

Prefix

Token	Separators	Terminator
Try	catch § cleanup	
Interface	extends with restricts with	
Discrimination	between	
Actor Structure	invariants uses queues implements using § internal using §	
Implementation	has	
Holding	in	
Loop	is	
Hole	returned ∪ threw ∪	
Enqueue		
Null		
Nullable		
MakeRunnable		
Suspend		
Atomic	compare update updated notUpdated	

Infix

Token
thatIs
postcondition
precondition
permit

Unary

Token
True
False
TheNull
Void

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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 be 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,

```
((x:Numerical "+" y:Numerical):Numerical |  
Numerical ⊆ Expression |
```

Also,

```
(Numerical "-" Numerical):Numerical |  
("-" Numerical):Numerical |  
(Numerical "*" Numerical):Numerical |  
(Numerical "/" Numerical):Numerical |  
("Remainder" Numerical "/" Numerical):remainder:Numerical |  
("QuotientRemainder" Numerical "/" Numerical)  
:[Numerical, Numerical] |  
("True" ⊔ "False"):Expression |  
(Expression ^ Expression):Expression |  
(Expression ∨ Expression):Expression |  
("¬" Expression):Expression |  
("Throw" Expression):Expression |
```

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
```

```
((Expression ⊔ Definition ⊔ Judgment)) " |"):Top |
```

⁵ `(Identifier ":" Type):Declaration`

```
// Identifier is declared to be of Type
```

```
(Identifier "::"):Declaration // Identifier is declared to be a type
```

```
(Type "→" Type):Signature |
```

```
(Type "→" "⊖"):Signature |
```

-
- ("[" Types "]):Type █
 (⊔ MoreTypes):Types █
 (Type ⊔ (Type ", " MoreTypes)):MoreTypes █
- ⁶ (Identifier "←" Expression):Definition █
 (Preparation ("," ⊔ "●") MorePreperations):Preparations █
 (Expression):MorePreperations █
- ⁷ Generalization of the notation of [Church 1932].
- ⁸ ("Define" ProcedureName " █ " "
 "[" ArgumentDeclarations "]" ":" Type "≡"
 Expression):Definition █
 ProcedureName ⊆ Expression █
 (⊔ MoreDeclarations):ArgumentDeclarations █
 (SimpleDeclaration (⊔ ("," MoreKeywordDeclarations))
 ⊔ (SimpleDeclaration ", " MoreDeclarations))
 :MoreDeclarations █
 // Comma is used to separate declarations.
 ((Identifier (⊔ "default" Expression)):SimpleDeclaration █
 (KeywordArgumentDeclaration
 ⊔ (KeywordDeclaration ", " MoreKeywordDeclarations))
 :MoreKeywordDeclarations █
 (Keyword "⊆" SimpleDeclaration)):KeywordDeclaration █
 Keyword ⊆ Word █
- ⁹ The symbol █ is fancy typography for an ordinary period when it is used to denote message sending.
- ¹⁰ (Recipient:Expression " █ " "[" Arguments "]"):ProcedureSend █
 ProcedureSend ⊆ Expression █
 // Recipient is sent a message with Arguments
 (⊔ MoreArguments):Arguments █
 ((Expression (⊔ ("," MoreKeywordArguments)))
 ⊔ (Expression ", " MoreArguments)):MoreArguments █
 (KeywordArgument
 ⊔ (KeywordArgument
 ", " MoreKeywordArguments)):MoreKeywordArguments █
 (Keyword "⊆" Expression):KeywordArgument █
 (Identifier "[" ArgumentDeclarations "]" ":" Type "→"
 Preparations " █ "):Definition █
- ¹¹ █ solves the infamous "dangling else" problem [Abrahams 1966].
- ¹² (test:Expression "◆" ExpressionCases "█"):Expression █
 (ExpressionCase ⊔ MoreExpressionCases):ExpressionCases █
 (ExpressionCase ⊔ (ExpressionCase ", " MoreExpressionCases))
 ⊔ ExpressionElseCases):MoreExpressionCases █

```

( ⊔ ExpressionElseCase ⊔ (ExpressionElseCase
  ", " MoreExpressionElseCases)):ExpressionElseCases ⊐
(ExpressionElseCase
  ⊔ (ExpressionElseCase
    ", " MoreExpressionElseCases )):MoreExpressionElseCases ⊐
( ("else" ":" Preparations)
  ⊔ ("else" Pattern ":" Preparations)):ExpressionElseCase ⊐
  // The else case is executed only if the patterns before
  // the else case do not match the value of test.
(Pattern ":" Preparations):ExpressionCase ⊐
13 ("(" Preparations Expression")):CompoundExpression
Binding ⊑ Preparation ⊐
  // A let binding is a preparation
( ):Preparations
(Binding ← Expression ("●" ⊔ ",") Preparations)):Preparations
(Expression ("●" ⊔ "||") Preparations)):Preparations
(Pattern ← Expression):Binding ⊐
14 (recipient:Expression
  "." MessageName "[" Arguments "]"):NamedMessageSend ⊐
NamedMessageSend ⊑ Expression ⊐
  // Recipient is sent message MessageName with Arguments
MessageName ⊑ Word ⊐
("Interface" Identifier▷ "with"
  MessageHandlerSignatures "⊐"):InterfaceDefinition ⊐
InterfaceDefinition ⊑ Definition ⊐
( ⊔ MoreMessageHandlerSignatures))
  :MessageHandlerSignatures ⊐
(MessageHandlerSignature
  ( ⊔ MoreMessageHandlerSignatures))
  :MoreMessageHandlerSignatures ⊐
(MessageName "[" ArgumentTypes "]" ("↳" ⊔ "⊐"))
  returnType:Type ):MessageHandlerSignature ⊐
MessageHandlerSignature ⊑ Expression ⊐
15 equivalent to [1, ⊐[2, 3]:Integer, 4]:Integer
16 ("[" ComponentExpressions "]"
  ( ⊔ (":" aType:Type)
    ⊔ ("::" "[" someTypes:Types"]"))):Expression
  // An ordered list with elements ComponentExpressions
  // : means uniformly of type aType
  // :: means each element is of the
  // corresponding type in someTypes
( ⊔ MoreComponentExpressions ):ComponentExpressions ⊐

```

```

((( ⊔ "V") Expression) ⊔ (( ⊔ "V") Expression
  ", " MoreComponentExpressions)):MoreComponentExpressions ⊐
([" TypeExpressions "]):TypeExpression ⊐
( ⊔ MoreTypeExpressions):TypeExpressions ⊐
(TypeExpression ⊔ (TypeExpression ", " MoreTypeExpressions))
  :MoreTypeExpressions ⊐

```

¹⁷ Equivalent to the following:

```

Define Reverse<aType>. [aList:[aType⊗]]:[aType⊗] ≡
  aList ↻
  [] ⊘ [],
  [first, vrest] ⊘ [vrest, first] ⊐ ⊐

```

```

18 ("_"):UnderscorePattern ⊐
UnderscorePattern ⊑ Pattern ⊐
Identifier ⊑ Pattern ⊐
(Pattern "thatIs" Expression):ThatIs ⊐
ThatIs ⊑ Pattern ⊐
("∅" Expression):Pattern ⊐
([" ComponentPatterns "]):Pattern ⊐
  // A pattern that matches a list whose elements match
  // ComponentPatterns
( ⊔ MoreComponentPatterns):ComponentPatterns ⊐
(Pattern ⊔ ( "V" Pattern
  ⊔ (Pattern ", " MoreComponentPatterns)))
  :MoreComponentPatterns ⊐

```

¹⁹ 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.

²⁰ 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 has 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.

```

21 ("Actor" ConstructorDeclaration ActorBody):Expression ⊐
  // The above expression creates an Actor with
  // declarations for variables and message handlers
  ( ⊔ ( "uses" ConstructorList " " ))
  ( ⊔ "management" Expression )
  MessageHandlers
  InterfaceImplementations):ActorBody ⊐
(Identifier "<" ParametersDeclarations ">"
  ( ⊔ ([" ArgumentDeclarations "]))):ConstructorDeclaration ⊐

```

```

(Constructor "," MoreConstructors "|"):ConstructorList |
(Constructor
  ( (Constructor "," MoreConstructors )):MoreConstructors |
  ( ( "locals" Local&Declarations "|" ):Local&Declaration |
  (QueuesDeclaration Local&Declaration ):Declaration |

(LocalDeclaration
  "," MoreLocalDeclarations ):MoreLocalDeclarations |
(Identifier "←" Expression ):IdentifierDeclaration |
IdentifierDeclaration ⊆ LocalDeclaration |
(Variable "==" Expression InstanceVariableAQualifications )
                                     :VariableDeclaration |
VariableDeclaration ⊆ LocalDeclaration |
Variable ⊆ Word |
InstanceVariableQualifications ⊆ InstanceQualifications |
( ( InstanceVariableQualification
  ( ( InstanceVariableQualification
    InstanceVariableQualifications )
                                     :InstanceVariableQualifications |
"nonpersistent" ⊆ InstanceVariableQualification |
  // A nonpersistent variable must be Nullable,
  // and can be nulled out before a message is received
( "queues" QueueName ):QueueDeclaratoins |
QueueName ⊆ Word |
QueueName ⊆ Expression |
("Void"):Expression |
(InterfaceImplementation
  ( ( MoreInterfaceImplementations ))
                                     :InterfaceImplementations |
("also" InterfaceImplementation
  ( ( MoreInterfaceImplementations ))
                                     :MoreInterfaceImplementations |
(( ( "partially"
  ("implements" ( "reimplements" )
    ( ( "exportable" ) Type "using"
      (MessageHandlers "§" ) ( UniversalMessageHandler )
                                     :InterfaceImplementation |
(MessagePattern ":" Type ( ( "sponsor" Identifier ))
  "→" ExpressionsContinuation ):UniversalMessageHandler |
( ( MoreMessageHandlers ):MessageHandlers |

```

```

(MessageHandler
  ⌊ (MessageHandler "$" MoreMessageHandlers))
                                     :MoreMessageHandlers ─
  // The message handler separator is ¶.
(MessageName "[" ArgumentDeclarations "]" ":" Type
  ( ⌊ ("sponsor" Identifier)))
  "→" ExpressionsContinuation):MessageHandler ─
  // For a message with MessageName with arguments,
  // the response is ExpressionsContinuation
(Expression "⊔" Afterward):Continuation ─
  // Return Expression and afterward perform
  // MoreVariableAssignments
VariableAssignments ⊆ Afterward ─
(VariableAssignment
  "," MoreVariableAssignments):VariableAssignments ─
(VariableAssignment
  ⌊ (VariableAssignment
    "," MoreVariableAssignments))
                                     :MoreVariableAssignments ─
(Variable "!=" Expression):VariableAssignment ─
22 ("(" MoreAntecedents Continuation ")"):CompoundContinuation ─
(Antecedent):MoreAntecedents ─
(Antecedent ("||" ⌊ "●") MoreAntecedents):MoreAntecedents ─
(Binding ("," ) MoreAntecedents):MoreAntecedents ─
Expression ⊆ Antecedent ─
StructureAssignment ⊆ Antecedent ─
ArrayAssignment ⊆ Antecedent ─

```

²³ For example, consider the following:

```
Actor NeedTwo[]
  queues waiting|
  locals hasOne := False|
  go[]:Void → hasOne ⇨ True ∃ Void permit waiting,
              False ∃ (hasOne := True●
                       enqueue waiting●
                       Void)∃!|
```

The following expression must return **Void** because of mandatory concurrency:

```
(aNeedTwo ← NeedTwo.[] ,
 @aNeedTwo.go[]●
 aNeedTwo.go[])|
```

However following expression might never return because of optional concurrency:

```
(aNeedTwo ← NeedTwo.[] ,
 aNeedTwo.go[]●
 aNeedTwo.go[])|
```

²⁴ ("@" anExpression:Expression (⊔ ("sponsor" Expression)))
:Expression |

```
// Execute anExpression in parallel and respond with the outcome.
// In every case, anExpression must complete before execution leaves
// the lexical scope in which it appears.
```

²⁵ cf. [Crahen 2002, Amborn 2004, Miller, et. al. 2011]

²⁶ The ability to extend implementation is important because it helps to avoid code duplication.

²⁷ note the absence of "." in the **implementation** subexpression

²⁸ equivalent to the following:

```
myBalance ◦ SimpleAccount :=
  myBalance ◦ SimpleAccount - anAmount
```

²⁹ ignoring exceptions in this way is *not* a good practice

³⁰ (**"Enqueue"** *QueueExpression* "●" *Continuation*):*Continuation* |
 /*
 1. Enqueue activity in *QueueExpression*
 2. Leave the cheese
 3. When the cheese is re-entered perform *Continuation*. */
 ("(*Antecedents*
 "enqueue" *QueueExpression* "●" *Continuation*"))
 :*Continuation* |
 /*
 1. Perform the *Antecedents*
 2. Enqueue activity in *QueueExpression*
 3. Leave the cheese
 4. When the cheese is re-entered perform *Continuation*. */

Cases can be continuations:

```
(test:Expression "◆"  

  ContinuationCases "[?]):Continuation |  

(ContinuationCase  

  ⊔ ((ContinuationCase ", " MoreContinuationCases))  

  ContinuationElseCases):ContinuationCases |  

(ContinuationCase  

  ⊔ ((ContinuationCase ", " MoreContinuationCases))  

  :MoreContinuationCases |  

(Pattern": " ExpressionsContinuation):ContinuationCase |  

( ⊔ MoreContinuationElseCases ):ContinuationElseCases |  

(ContinuationElseCase  

  ⊔ ((ContinuationElseCase ", " MoreContinuationElseCases))  

  :MoreContinuationElseCases |  

(("else" ": " ExpressionsContinuation)  

  ⊔ ("else" Pattern": " ExpressionsContinuation))  

  :ContinuationElseCase |  

(Continuation):ExpressionsContinuation |  

(preparation (" " ⊔ "●") MoreExpressionsContinuation))  

  :ExpressionsContinuation |  

((Continuation)  

  ⊔ (Expression " " MoreExpressionsContinuation))  

  : MoreExpressionsContinuation |
```

³¹ Equivalent to the following:

```
Define Fringe[aTree:Tree]:[String⊕]  

  aTree ◆  

  Leaf[aString] ⊗ [aString],  

  Fork[left, right] ⊗  

  [∀Fringe.[left], ∀Fringe.[right]] ? |
```

³² Equivalent to the following:

```
Fringe.[Fork[Leaf["The"]↑Tree&Leaf["boy"]↑Tree]↑Tree]
```

³³ Swiss cheese was called "serializers" in the literature.

```
34(".." Message):Expression |
  // Delegate message to this Actor.
  ("(" Antecedents "hole" Expression>")"):Continuation |
  /*
    1. Carry out Antecedents
    2. Leave the cheese
    3. The result is the result of evaluating Expression */
```

³⁵ 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]
  locals writing := False,
         numberReading := 0 |
  implements ReadersWriter using
  read[aQuery:Query]:QueryAnswer
    ¬writing precondition // commentary for error checking
    (numberReading++ ●
     hole theResource.read[aQuery]
     ∪ numberReading--) ¶
  write[anUpdate:Update]:Void →
    numberReading=0 ∧ ¬writing precondition
    (writing := True ●
     hole theResource.write[anUpdate]
     ∪ writing := False) § |
```

³⁶ A downside of this policy is that readers may not get the most recent information.

³⁷ A downside of this policy is that writing and reading may be delayed because of lack of concurrency among readers.

³⁸ (((" *Antecedents*
"enqueue" *QueueExpression* (\sqcup **"backout"** *Preparations*)
Continuation"))):*Continuation* **■**
/*
1. Perform *Antecedents*
2. Enqueue activity in *QueueExpression*.
3. Leave the cheese
4. If an exception is generated by the activity while in the queue,
then reenter the cheese, perform *Preparations*, and release
the cheese.
5. If no exception is generated by the activity while in the queue,
then when allowed to continue, re-acquire the cheese to
perform *Continuation*. */

Cases can be continuations:

```
((test:Expression "◆" ContinuationCases"□")):Continuation ■
((ContinuationCase  $\sqcup$  MoreContinuationCases):ContinuationCases ■
(ContinuationCase  $\sqcup$ 
(ContinuationCase "," MoreContinuationCases)
 $\sqcup$  ContinuationElseCases):MoreContinuationCases ■
(  $\sqcup$  ContinuationElseCase  $\sqcup$ 
(ContinuationElseCase "," MoreContinuationElseCases))
:ContinuationElseCases ■
(ContinuationElseCase
 $\sqcup$  (ContinuationElseCase "," MoreContinuationElseCases))
:MoreContinuationElseCases ■
(("else" ":" ContinuationList)
 $\sqcup$  ("else" Pattern ":" ExpressionsContinuation))
:ContinuationElseCase ■
// The else case is executed only if the patterns before
// the else case do not match the value of test.
(Pattern ":" ExpressionsContinuation):ContinuationCase ■
```

The following are allowed in the cheese for a response to message affecting the next message:

```
((Expression
(  $\sqcup$  ("permit" aQueue:Expression))
(  $\sqcup$  ("U" Afterward))):Continuation ■
/* If there are activities in aQueue, then the one of them gets the
cheese next and also perform Afterward, then release the
cheese and return the value of Expression. */
VariableAssignments:Afterward ■
("Permit" aQueue:Expression
(  $\sqcup$  ("also" VariableAssignments))):PermitAlso ■
```

The following can be used temporarily release the cheese:

```
(("Hole" Expression):Continuation |
/*
  1. Leave the cheese
  2. The response is the result of evaluating Expression */
```

```
(((" Antecedents
hole Expression ( | ("⊔" Afterward) ")):Continuation |
/*
  1. Carry out Antecedents
  2. Leave the cheese
  3. Evaluate Expression
```

4. When a response is received, reacquire the cheese, carry out
Afterward and the result is the result of evaluating Expression */

```
(((" Antecedents
hole Expression
  ( | ("returned" ContinuationCases "?")
    ( | ("threw" ContinuationCases "?") ) ):Continuation |
/*
  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 normal.
    • If Expression throws an exception, continue using the
      exception with exceptional. */
```

³⁹ -- is postfix decrement

⁴⁰ Joe Armstrong interviews Alan Kay Erlang Conference on YouTube.
November 22, 2016.

⁴¹ (Identifier "<" ParametersDeclarations ">" Preparations)
:ParameterizedDefinition |

ParameterizedDefinition \sqsubseteq Definition |

// Parameterize definition with ParametersDeclarations |

(| MoreParameterDeclarations):ParametersDeclarations |

(ParameterDeclaration

| (ParameterDeclaration

"," MoreParameterDeclarations))

:MoreParameterDeclarations |

(Identifier (| Qualifier)):ParameterDeclaration |

(| ("extends" Type)):TypeQualifier |

(Identifier "<" Parameters ">"):TypeExpression |

(Identifier | (| (Identifier "," Parameters)):Parameters |

⁴² ("**Discrimination**" Identifier MoreTypeDiscriminations "I")

:Definition |

```

(Identifier ⊔ (Identifier ", " MoreTypeDiscriminations))
                                     :MoreTypeDiscriminations ⊔
(Expression "↓" Type):Expression ⊔
    // Discriminate to be of Type if possible.
    // Otherwise, an exception is thrown.
(Expression "↓?" Type):Expression ⊔
    // If Expression discriminates to be of Type,
    // then True, else False.
(Pattern "↯↓" TypePattern):Pattern ⊔
    // If matching Actor is a discrimination that can be discriminated
    // then Pattern must match the discriminate.
(("↯↯↓" StructurePattern):Pattern ⊔
    // Matching Actor must be discrimination that
    // can be downed as StructurePattern which matches
43 Equivalent to the following:
    (x ← 3,
     TrieFork<Integer>[Terminal<Integer>[x]↑Trie<Integer>,
     Terminal<Integer>[x+1]↑Trie<Integer>]) ⊔
44 (Identifier "[" Arguments "]"):Expression ⊔
    (Identifier "[" Patterns "]"):Pattern ⊔
45 ("Nullable" Expression):Expression ⊔
    ("⊙" Expression):Expression ⊔
    // reduce Expression if not null.
    // Otherwise, an exception is thrown.
    ("↯⊙" Pattern):Pattern ⊔
    // If matching Actor is a non-null nullable
    // then Pattern must match the Actor in the nullable.
    ("TheNull"):Pattern ⊔
    // matches only the null
46 ("Try" anExpression:Expression "catch⊙" ExpressionCases"[?]")
                                     :Expression ⊔
/*
• 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 the value of
  TryExpression is the value computed by anExpression. /*

```

```

(("Try" anExpression:Expression "catch" ContinuationCases "?")
                                     :Continuation)

```

```

/*
  • 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 anExpression doesn't throw an exception, then the response
    of TryExpression is the response computed by anExpression.
*/

```

```

(("Try" anExpression:Expression "cleanup" cleanup:Expression)
                                     :Expression)

```

```

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

```

```

47 (test:Expression "precondition" Preparations):Expression)
    // test must evaluate to True or an exception is thrown
(test:Expression "precondition" ExpressionsContinuation)
                                     :Continuation)

```

```

    // test must evaluate to True or an exception is thrown
(value:Expression "postcondition" pre:Expression):Expression)
    // The expression pre must evaluate to True when sent value
    // or an exception is thrown

```

⁴⁸ ° is a reserved postfix operator for degrees of angle

⁴⁹ Using parameterized procedures like the ones below can improve the simplicity and effectiveness of types by comparison with other approaches

⁵⁰ Equivalent to the following:

```

Define Times[u:Complex, v:Complex]:Complex →
  Cartesian[u.[real]*v.[real] - u.[imaginary]*v.[imaginary],
            u.[imaginary]*v.[real]
            + u.[real]*v.[imaginary]]↑Complex)

```

⁵¹ Equivalent to the following:

```

Define Times[Polar[angle aAngle, magnitude aMagnitude],
             Polar[angle anotherAngle,
                  magnitude anotherMagnitude]]:Complex →
  Polar[angle aAngle+anotherAngle,
        magnitude aMagnitude*anotherMagnitude]↑Complex)

```

52 ("Structure" Identifier "[" FieldDeclarations "]"
 ((("uses" ConstructorList "|"))
 NamedDeclaration
 MessageHandlers
 MoreInterfaceImplementations):Definition |
 // Structure definition with StructureImplementation
 (anExpression:Expression "↓" Type):Expression |
 (anExpression:Expression "↓?" Type):Expression |
 // If anExpression is an extension of Type, then True else False
 (aPattern:Pattern "↓" Type):Pattern |
 // Matching Actor must be an extension of Type which
 // matches aPattern
 ((MoreFieldDeclarations):FieldDeclarations |
 ((SimpleFieldDeclaration
 ((("," MoreNamedFieldDeclarations)))
 (SimpleFieldDeclaration
 "," MoreFieldDeclarations)):MoreFieldDeclarations |
 ((Identifier (("default" Expression)):SimpleFieldDeclaration |
 (NamedFieldDeclaration
 ((NamedFieldDeclaration
 "," MoreNamedFieldDeclarations))
 :MoreNamedFieldDeclarations |
 (FieldName
 ("⊘" ("⊘") SimpleFieldDeclaration))
 :NamedFieldDeclaration |
 FieldName ⊆ QualifiedName |
 // "⊘" is used for assignable fields.
 (((Identifier) ActorBody):StructureImplementation |
 (Expression "[" FieldName "]"):FieldSelector |
 // FieldName of Expression which must be a structure
 FieldSelector ⊆ Expression |
 (StructureName "[" FieldExpressions "]"):StructureExpression |
 StructureExpression ⊆ Expression |
 ((MoreFieldExpressions):FieldExpressions |
 ((SimpleFieldExpression ((("," MoreNamedFieldExpressions))))
 (SimpleFieldExpression
 "," MoreFieldExpressions)):MoreFieldExpressions |
 (NamedFieldExpression
 ((NamedFieldExpression
 "," MoreNamedFieldExpressions))
 :MoreNamedFieldExpressions |

```

((FieldName
  ("⊖" ⊔ ":"⊖") SimpleFieldExpression))
                                     :NamedFieldExpression █
(StructureName "[" FieldPatterns "]" ):StructurePattern █
StructurePattern ⊆ Pattern █
( ⊔ MoreFieldPatterns ):FieldPatterns █
(((SimpleFieldPattern( ⊔ (";" MoreNamedFieldPatterns))))
  ⊔ ( SimpleFieldPattern ";" MoreFieldPatterns))
                                     :MoreFieldPatterns █

(NamedFieldPattern
  ⊔ ( NamedFieldPattern
      ";" MoreNamedFieldPatterns))
                                     :MoreNamedFieldPatterns █
(FieldName ("⊖" ⊔ ":"⊖") SimpleFieldExpression))
                                     :NamedFieldPattern █
53 ("{" ComponentExpressions "}"):Expression▷ █
    // A set of Actors without duplicates
    ("{" ComponentPatterns "}"):Pattern █
54 ("{" ComponentExpressions "}"):Expression █
    // A multiset of the Actors with possible duplicates
    ("{" ComponentPatterns "}"):Pattern █
55 ("[" Expressions "]" "→" Expression):Expression █
    ("{" ComponentPatterns "}"):Pattern █
56 Optimization of this program is facilitated because:
    • The records are cacheable because their type is {ContactRecord*}
    • All of the operators are cacheable
    • The operators are annotated as cacheable using "|.>"
57 ("Encrypt" Expression):Expression
    Define ("Encrypt" anExpression:Expression) ≡
        (aType "." "encrypt" "[" anExpression "]")
58 It is possible to define a procedure that will produce a "bottomless" future.
    For example,
    Actor f.[.]:Future<BottomLessFuture> → Future f. █
    Define BottomLessFuture ([ ] ↦ BottomLessFuture) █

```

-
- 59 (**"Future"** aValue:Expression (\sqcup ("sponsor" Expression)))
:Expression **|**
// A future for aValue.
("⊙" Expression):Expression **|**
// Reduce a future
- 60 A **Postpone** expression does not begin execution of Expression₁ until a request is received as in the following example:
Define IntegersBeginningWith[n:Integer]:[Integer[⊙]]
[n, \forall IntegersBeginningWith._{n+1}]**|**
Note: A **Postpone** expression can limit performance by preventing concurrency
- 61 ("(" MoreGrammars ")"):Grammar **|**
("(" Grammar " \sqcup " Grammar ")"):Grammar **|**
(ReservedWord (\sqcup StartsWithIdentifier)):StartsWithReserved **|**
StartsWithReserved \sqsubseteq MoreGrammars **|**
(Identifier (\sqcup StartsWithReserved)):StartsWithIdentifier **|**
StartsWithIdentifier \sqsubseteq MoreGrammars **|**
("\ "" Word "\""):ReservedWord **|**
// The use of \ escapes the next character in a string so
// that "\" has just one character that is "
(Grammar ":" GrammarIdentifier "**|**"):Judgment **|**
(Identifier " \sqsubseteq " Identifier "**|**"):Judgment **|**
- 62 Equivalent to the following:
Loop OneOfTen.<sub>[n:Integer \leftarrow 10]:Integer **is**
n=1 \diamond True $\%$ P._[],
False $\%$ \odot P._[] **either** \odot OneOfTen._[n-1] ? **|**</sub>
- 63 ("**Loop**" LoopName:Identifier " " [" Initializers "] " ":" Type)
"is" Expression):Expression **|**
(\sqcup MoreInitializers):Initializers **|**
(Initializer \sqcup (Initializer " " MoreInitializers))
:MoreInitializers **|**
(Identifier " \leftarrow " Expression):Initializer **|**
- 64 The implementation below requires careful optimization.
- 65 (" " ComponentExpressions ""):Expression **|**
(" " ComponentPatterns ""):Pattern **|**
- 66 (recipient:Expression " " message:Expression):Expression **|**
// Send recipient the message
- 67 The implementation below can be highly inefficient.

-
- 68 (**"Atomic"** aLocation:Expression
 "compare" comparison:Expression
 "update" update:Expression "◆"
 "updated" "§"
 compareIdentical:ExpressionsContinuation ","
 "notUpdated" "§"
 compareNotIdentical:ExpressionsContinuation "⊙")
 :Continuation **█**
- /* Atomically compare the contents of aLocation with the value of
 comparison. If identical, update the contents of aLocation with the
 value of update and execute compareIdentical.
- 69 (Identifier "" Qualifier):QualifiedName **█**
 QualifiedName ⊆ Expression **█**
 Identifier ⊆ QualifiedName **█**
- ((Identifier ⊔ (Identifier "" Qualifier)):Qualifier **█**
- 70 (**"Enumeration"** Identifier
 MoreEnumerationNames " | "):Definition **█**
 (EnumerationName
 ⊔ (EnumerationName
 ", " MoreEnumerationNames)):MoreEnumerationNames **█**
 EnumerationName ⊆ Word **█**
- 71 equivalently (**HTTPS**[en.wikipedia.org]) **█ █**
- 72 Declarations provide version number, encoding, schemas, etc.
- 73 (recipient:Expression
 " □ MessageName [" Arguments "]):Expression **█**
 /* recipient is sent one-way message with MessageName and
 Arguments. Note that Expression cannot be used to produce a
 value. */
 (MessageName [" ArgumentDeclarations "] " ":" "⊙"
 (⊔ ("sponsor" Identifier))
 "→" ExpressionsContinuation):MessageHandler **█**
 /* one-way message handler implementation with
 ArgumentDeclarations that has a one-way continuation
 that returns nothing */
 ("⊙" (⊔ ("permit" aQueue:Expression))
 (⊔ ("⊕" Afterward))):Continuation **█**
- 74 note the absence of " . " in the **implementation** subexpressions.
Male[aMagnitude] is invoked concurrently with **Human**[aLength].

⁷⁵ [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.

⁷⁶ A ground-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].

⁷⁷ Execution can proceed differently depending on how sets fit into computer storage units.

⁷⁸ /* 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]:

```
Define (Eval expression environment)
    // Eval of expression using environment defined to be
    (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 evaluate an **if** expression! */

⁷⁹ For example, the message could be of type

```
Message<DepositOnlyAccount, deposit[Euro] → Void>
```

where

```
Interface DepositOnlyAccount restricts Account with deposit[Euro] → Void
```

⁸⁰ the device may have *no* access to anAccount or **Account**

⁸¹ the device may have *no* access to anAccount, x, **et1**, or **Account**

⁸² If non-null points to head with current holder of cheese

⁸³ If non-null, pointer to backwards list ending with head that holds cheese

⁸⁴ // **acquire** message received running myActivity

⁸⁵ /* this cheese queue is not empty because myActivity is at the head of the queue */

⁸⁶ Not to be confused with \0 which is the null character or with \o which is ∅.

-
- ⁸⁷ Not to be confused with `\0` which is the null character or with `\o` which is `␣`.
- ⁸⁸ Not to be confused with `\p` which is `¶`.
- ⁸⁹ Used in type specifications for interfaces.
- ⁹⁰ Used in message handlers.
- ⁹¹ Used to bind identifiers.
- ⁹² Not to be confused with `\P` which is `Ⓟ`.
- ⁹³ Not to be confused with `\0` which is the null character or with `\O` which is `Ⓞ`.
- ⁹⁴ Used in patterns.
- ⁹⁵ Used in structures.
- ⁹⁶ Used in one-way message passing.