



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

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. It is differentiated from previous languages by the following:

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

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

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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 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 (e.g., **Integer**)
- program variables (e.g., **aBalance**)
- message names (e.g., **getBalance**)
- reserved words² for language constructs (e.g., **Actor**)
- structures (e.g., **[** and **]**)
- argument keyword (e.g., **to**)
- logical variables (e.g., *x*)
- comments in programs (e.g. */* this is a comment */*)

There is a diagram of the syntax categories of ActorScript in an appendix of this paper in addition to an appendix with an index of symbols and names along with an explanation of the notation used to express the syntax of ActorScript.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 physical laws. The advent of massive concurrency through client-cloud

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.*

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.*

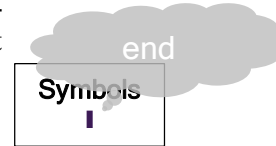
The Actor Model is designed to provide a foundation for inconsistency robust information coordination.

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. In this paper, Type names are shown in green, e.g., **Integer**.

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

ⁱ sometimes called “names”

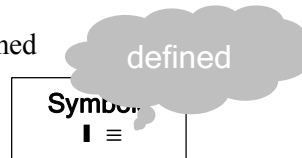
ⁱⁱ Furthermore, all special symbols have ASCII equivalents for input with a keyboard. An IDE can convert ASCII for a symbol equivalent into the symbol. See table in an appendix to this article.

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

Definitions, *i.e.*, \equiv

An identifier definition has an identifier to be defined followed by “ \equiv ” followed by the definition. For example, $x \equiv 3$ defines the identifier x to be the Actor 3.



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

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 a procedure name followed by “ \cdot ”, a list of formal arguments, and return type. For example,

$\text{Double} \cdot [v:\text{Integer}]:\text{Integer} \equiv v+v$

The formal syntax of a procedure definition is in the end note: 7.

Sending messages to procedures, *i.e.*, $\cdot [\]$

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 “ \cdot ”⁸ followed by a message with arguments delimited by “[” and “]”. For example, $\text{Square} \cdot [2+1]$ means send Square ⁱ the message $[3]$. Thus $\text{Square} \cdot [2+1]$ is equivalent to 9 .

The formal syntactic definition of procedural message sending is in the end note: 9.

ⁱ As a convenience, the procedure Square can be defined to as follows:
 $\text{Square} \cdot [x:\text{Integer}]:\text{Integer} \equiv x*x$

Patterns

Patterns are fundamental to ActorScript. For example,



- 3 is a pattern that matches 3
- “abc” is a pattern that matches “abc”.
- `_` is a pattern that matches anythingⁱ
- `$$x` is a pattern that matches the value of `x`.
- `$(x+2)` is a pattern that matches the value of the expression `x+2`.
- `< 5` is a pattern that matches an integer less than 5
- `x suchThat Factorial.x > 120` is a pattern that matches an integer whose factorial is greater than 120




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

- `x` is a pattern that matches “abc” and binds `x` to “abc”

ⁱ e.g., `_` matches 7















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

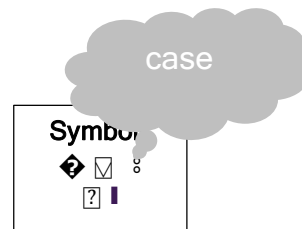
Cases, i.e.,  , % 

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 “”ⁱ and then followed by a number of cases separated by “” terminated by “”.¹⁰ 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 casesⁱⁱ 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 0iii
Throwiv 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: **11**.

ⁱ “” is fancy typography for “?”

ⁱⁱ *including* patterns in previous **else** cases

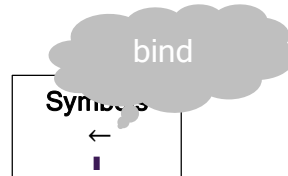
ⁱⁱⁱ As is standard, ActorScript uses the token “//” to begin a one-line comment.

^{iv} Reserved words are shown in bold black.

Binding locals, *i.e.*, **Let** \leftarrow .

Local identifiers can be bound using “**Let**” followed by a list of bindings separated by commas and terminated with “.” Each binding consists of a pattern, “ \leftarrow ”, and an expression for the Actor to be matched. For example, `aProcedure.["G", "F", "F"]` is equivalent to the following:

```
Let x  $\leftarrow$  "F".           // x is "F"  
  aProcedure.["G", x, x]
```



Dependent bindings (in which each can depend on previous ones) can be accomplished by nesting **Let**. For example:

```
Let x  $\leftarrow$  "F".           // x is "F"  
  Let y  $\leftarrow$  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: **12**.

General Message-passing interfaces

Procedure interfaces are a special case of general message-passing interfaces.

A message handler signature consists of a message name followed by argument types delimited by “[” and “]”, “ \mapsto ”, and a return type. For example

```
Interface Account with getBalance[ ]  $\mapsto$  Currency,  
                        deposit[Currency]  $\mapsto$  Void,  
                        withdraw[Currency]  $\mapsto$  Void
```

The formal syntactic definition of named-message sending is in the following end note: **13**

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

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

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

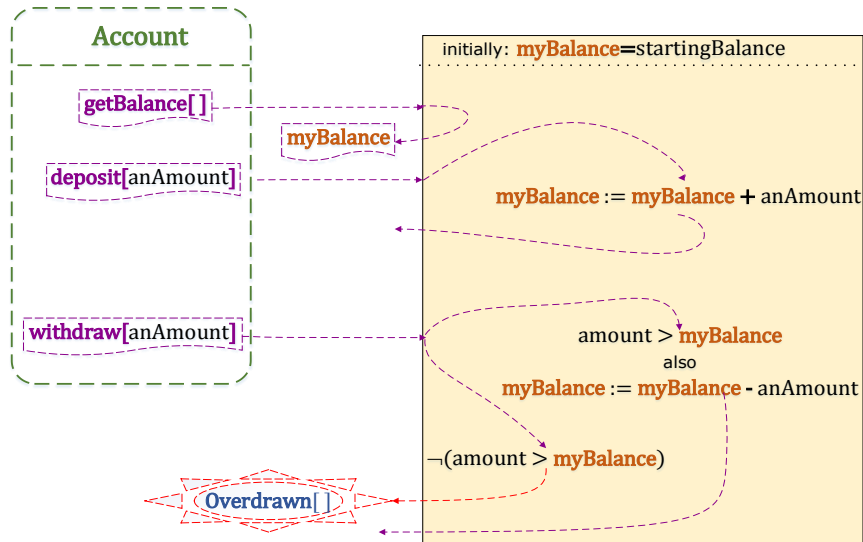
- constructor name with formal arguments delimited using brackets
- declarations of variablesⁱ terminated by “.”
- implementations of interface(s).

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.¹⁴

ActorScript is referentially transparent in the sense that a variable never changes while in a continuous part of the cheese.¹⁵ For example, in the **deposit** message handler change is accomplished using the following:

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

Below is a diagram for an Actor, which implements **Account**:



ⁱ variable declarations separated by commas

Variable races are impossible in ActorScript

The implementation of **Account** above can be expressed as follows:



Actor SimpleAccount. [startingBalance: **Euro**]

// SimpleAccount is a constructor and *not* a typeⁱ

myBalance := startingBalance.

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

implements **Account** using

getBalance[] → **myBalance**¶

deposit[anAmount] →

Void

// return **Void**

afterward **myBalance** := **myBalance** + anAmount¶

// the *next* message is processed with

// **myBalance** reflecting the deposit

withdraw[anAmount] →

(amount > **myBalance**) ◆

True : **Throw** **Overdrawn**[] ☒

False : **Void**

// return **Void**

afterward **myBalance** := **myBalance** - anAmount ¶\$¶

// the *next* message is processed with updated **myBalance**

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

ⁱ SimpleAccount: [**Euro**] → **Account**

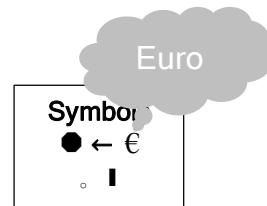
Antecedents, Preparations, and Necessary Concurrency, *i.e.*, \square

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:

```
Let anAccount ← SimpleAccount.[€6]. //€ is a reserved prefix operator
  Prep anAccount.withdraw[€1],
      anAccount.withdraw[€2] ●.
      // proceed only after both of the
      // withdrawals have been acknowledged
  anAccount.getBalance[]
```

The above expression returns €3.



Operations are quasi-commutative to the extent that it doesn't matter in which order they occur.

Quasi-commutativity can be used to tame indeterminacy 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: **17**

An expression can be annotated for concurrent execution by preceding it with “ \square ” indicating that the following expression must be considered for concurrent execution if resources are available. For example \square Factorial.[1000]+ \square 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.¹⁸

The formal syntax of explicit concurrency is in the following end note: **19**.

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., `Account` and also implements

The above implementation of `Account` can be extended as follows to provide the ability to revoke some abilities to change an account.²⁰ For example, `AccountSupervisor` below implements both the `Account` and `AccountRevoker` interfaces as an extension of the implementation `SimpleAccount`:

As illustrated below, a qualified address of an Actor can be expressed using “`Account`” followed by the name of the qualifier.²¹

```

Actor SimpleAccountSupervisor.[initialBalance:Euro]
    // SimpleAccountSupervisor is a constructor and not a typei
    extends SimpleAccount[initialBalance]
        // extends implementation SimpleAccount[initialBalance]22
    withdrawableIsRevoked := False,
    depositableIsRevoked := False.
    implements AccountSupervisor using
        getRevoker[ ] → AccountRevoker
        getAccount[ ] → Account
        withdrawFee[anAmount] →
            Void afterward myBalance := myBalance - anAmount$
            // withdraw fee even if balance goes negative23
    also partially reimplements exportable Account using
        withdraw[anAmount] →
            withdrawableIsRevoked
            True : Throw Revoked[ ]
            False : SimpleAccount.withdraw[anAmount]
        deposit[anAmount] →
            depositableIsRevoked
            True : Throw Revoked[ ]
            False : SimpleAccount.deposit[anAmount]
    also implements exportable AccountRevoker using
        revokeDepositable[ ] →
            Void afterward depositableIsRevoked := True
        revokeWithdrawable[ ] →
            Void afterward withdrawableIsRevoked := True

```

ⁱ SimpleAccountSupervisor:[Euro]→AccountSupervisor

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

```

Let anAccountSupervisor ← SimpleAccountSupervisor.[€3]。
Let anAccount ← anAccountSupervisor.getAccount[ ],
    aRevoker ← anAccountSupervisor.getRevoker[ ]。
Prep anAccount.withdraw[€2] ● // the balance is €1
    aRevoker.revokeWithdrawable[ ] ●
                                // withdrawableIsRevoked is True
Try anAccount.withdraw[€5] // try another withdraw
    catch _ : Void ? ● // ignore the thrown exception24
                        // the balance remains €1
    anAccountSupervisor.withdrawFee[€4] ●。
    // €4 is withdrawn even though withdrawableIsRevoked
anAccount.getBalance[ ] ! // the balance is negative €3

```

The formal syntax of the programs below is in the following end note: **25**

Swiss cheese

Swiss cheese [Hewitt and Atkinson 1977, 1979; Atkinson 1980]²⁶ 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.

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**ⁱ with the following variables:

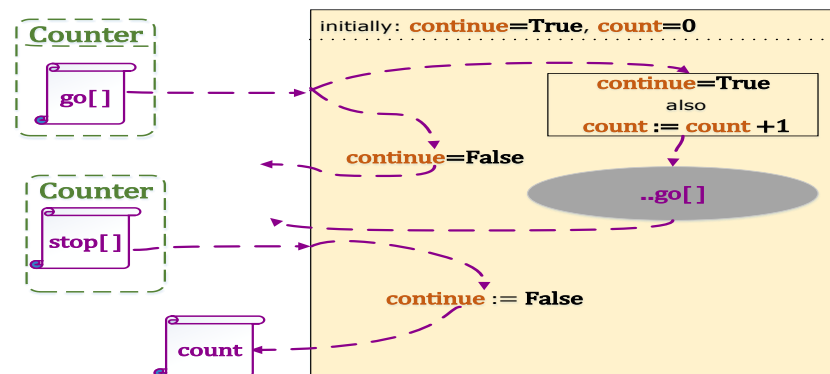
- **count** initially 0
- **continue** initially **True**

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.



ⁱ Interface **Counter** with `go[]` \rightarrow Void,
`stop[]` \rightarrow Integer[!]


```

CreateUnbounded.[]:Integer ≡
  Let aCounter ← SimpleCounter.[]。 // let aCounter be a new Counter
  Prep □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 SimpleCounter:

```

Actor SimpleCounter.[]
  count := 0, // the variable count is initially 0
  continue := True。
  implements Counter using
    stop[] →
      count // return count
      afterward continue := False!
      // continue is updated to False for the next message received
    go[] →
      continue ⚡
      True : Prep count := count+1●。 // increment count
      hole ..go[] □ // send go[] to this counter
      False : Void ?$! // if continue is False, return Void

```

Symbols

≡ → :

。 ? \$!

The formal syntax of the programs above is in the following end note: 27

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.

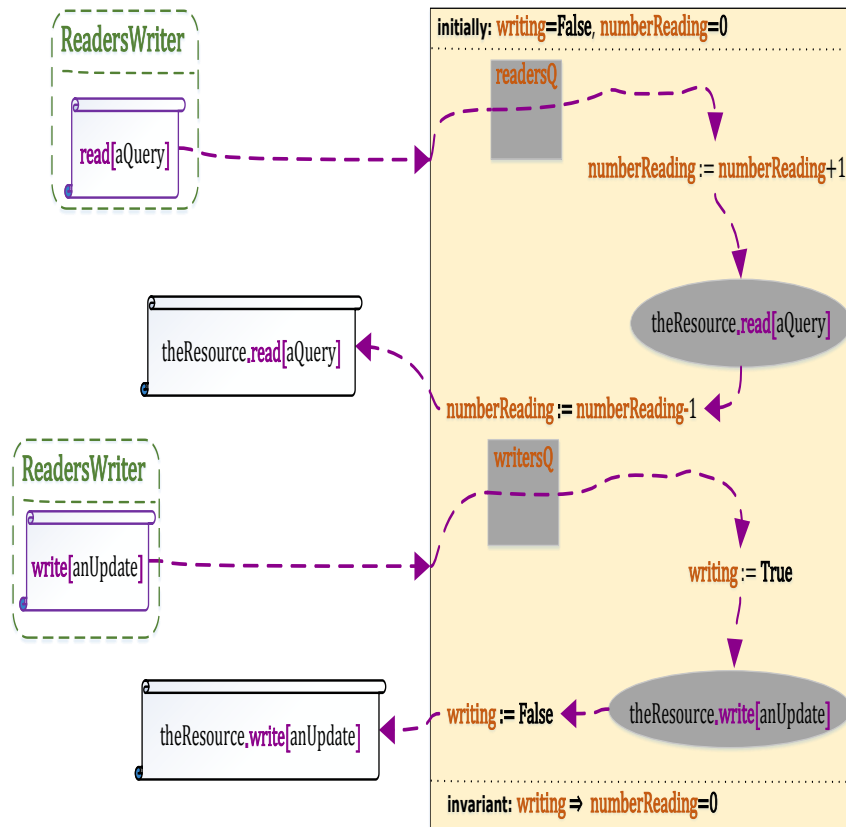
Below are two implementations of readers/writer guardians for a shared resource that implement different policies:²⁸

1. *ReadingPriority*: The policy is to permit maximum concurrency among readers without starving writers.²⁹
 - 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.³⁰
 - 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: **31**

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 **writing** \Rightarrow **numberReading**=0.
queues **readersQ**, **writersQ**. // **readersQ** and **writersQ** are initially empty
writing := False,
numberReading:PositiveInteger := 0.
// PositiveInteger \equiv Integer thatIs ≥ 0
implements ReadersWriter using
read[query] \rightarrow

Symbols

$\equiv \rightarrow \diamond \circ \square \wedge \vee \neg$

$?$ \uparrow $\$$ $\mathbf{!}$

Prep (**writing** \vee \neg IsEmpty **writersQ**) \diamond
True : **Enqueue** **readersQ** \bullet // leave cheese while in **readersQ**
backout (\neg **writing** \wedge **numberReading**=0 \wedge IsEmpty **readersQ**) \diamond
True : Void **permit** **writersQ** \square
False : Void $?$
Void \square
False : Void $?$ \bullet .
Preconditions \neg **writing**. // commentary for error checking
Prep **numberReading**++ \bullet . // increment **numberReading**
permit **readersQ**
hole theResource.**read**[query] // leave cheese while reading
afterward
(IsEmpty **writersQ**) \diamond
True : **Permit** **readersQ** also **numberReading**-- \square ³²
False : **numberReading**=1 \diamond
True : **Permit** **writersQ** also **numberReading**-- \square
False : **numberReading**-- $?$ $?$ \uparrow
write[update] \rightarrow
Prep (**numberReading**>0 \vee \neg IsEmpty **readersQ** \vee **writing** \vee \neg IsEmpty **writersQ**) \diamond
True : **Enqueue** **writersQ** \bullet // leave cheese while in **writersQ**
backout (IsEmpty **writersQ** \wedge \neg **writing**) \diamond
True : Void **permit** **readersQ** \square
False : Void $?$
Void \square
False : Void $?$ \bullet .
Preconditions³³ **numberReading**=0, \neg **writing**. // commentary for error checking
Prep **writing** := True \bullet . // record that writing is happening
hole theResource.**write**[update] // leave cheese while writing
afterward (IsEmpty **readersQ**) \diamond
True : **Permit** **writersQ** also **writing** := False \square
False : **Permit** **readersQ** also **writing** := False $?$ $\$$ $\mathbf{!}$

Illustration of writing-priority:

Actor WritingPriority._[theResource:ReadersWriter]

invariants $\text{writing} \Rightarrow \text{numberReading} = 0$.

queues readersQ , writersQ .

$\text{writing} := \text{False}$,

$\text{numberReading} : \text{PositiveInteger} := 0$.

implements ReadersWriter using

$\text{read}[\text{query}] \rightarrow$

Prep ($\text{writing} \vee \neg \text{Empty writersQ}$) \diamond

True : $\text{Enqueue readersQ} \bullet$ // leave cheese while in readersQ

backout $\neg \text{writing} \wedge \text{numberReading} = 0 \wedge \text{IsEmpty readersQ} \diamond$

True : Void $\text{permit writersQ} \boxtimes$

False : Void $?$

Void \boxtimes

False : Void $?$ \bullet .

Preconditions $\neg \text{writing}$. // commentary for error checking

Prep $\text{numberReading}++$.

permit $\text{IsEmpty writersQ} \diamond$

True : $\text{readersQ} \boxtimes$

False : Void $?$ \bullet

hole $\text{theResource.read}[\text{query}]$ // leave cheese while reading

afterward

(IsEmpty writersQ) \diamond

True : $\text{Permit readersQ also numberReading--} \boxtimes$

False : $\text{numberReading} = 1 \diamond$

True : $\text{Permit writersQ also numberReading--} \boxtimes$

False : $\text{numberReading--} ? ? \uparrow$

$\text{write}[\text{update}] \rightarrow$

Prep ($\text{numberReading} > 0 \vee \neg \text{IsEmpty readersQ} \vee \text{writing} \vee \neg \text{IsEmpty writersQ}$) \diamond

True : $\text{Enqueue writersQ} \bullet$ // leave cheese while in writersQ

backout ($\text{IsEmpty writersQ} \wedge \neg \text{writing}$) \diamond

True : Void $\text{permit readersQ} \boxtimes$

False : Void $?$

Void \boxtimes

False : Void $?$ \bullet .

Preconditions $\text{numberReading} = 0, \neg \text{writing}$.³⁴

Prep $\text{writing} := \text{True}$.

hole $\text{theResource.write}[\text{update}]$ // leave cheese while writing

afterward

(IsEmpty readersQ) \diamond

True : $\text{Permit writersQ also writing} := \text{False} \boxtimes$

False : $\text{Permit readersQ also writing} := \text{False} ? ? \S \uparrow$

Symbols	
$\equiv \rightarrow \diamond \boxtimes \boxtimes \wedge \vee \neg$	
$?$	$\uparrow \S \uparrow$

Conclusion

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

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

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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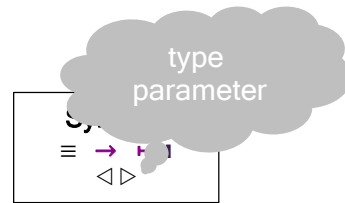
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Appendix 1. Extreme ActorScript

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

Parameterized Types are specialized using other types delimited by “◁” and “▷”:



```
Double<aType  $\models$  Arithmetic>[x:aType]:aType  $\equiv \rightarrow$  x+x$!
// addition for aType that is Arithmetic
```

The formal syntax of parameterized types is in the following end note: **35**.

Type Discrimination, *i.e.*, Discrimination, \otimes and \otimes

A discrimination definition is a type of alternatives differentiated by type using “**Discrimination**” followed by a type name, “**between**”, types separated using “,” terminated by “**I**”.

A discriminate can be injected into a discrimination using an expression for the discriminate followed by “ \otimes ” and the discrimination.

A discriminate can be projected as follows:

- In an expression, by using an expression for a discrimination followed by “ \ominus ” and the type to be projected. Also, a discrimination can be tested if it holds a discrimination of a certain type with a expression for the discrimination followed by “ $\ominus?$ ” and the type to be tested.
- In a pattern, by using a pattern followed by “ \ominus ” and the type to be projected

For example, consider the following definition:

Discrimination IntegerOrFloat between Integer, Float

Consequently,

- $(3 \odot \text{IntegerOrFloat}) \odot \text{Integer} \mathbf{!}$ is equivalent to $3 \mathbf{!}$.
- $(3.0 \odot \text{IntegerOrFloat}) \odot \text{Integer} \mathbf{!}$ throws an exception because **Integer** is not the same as the discriminant **Float**.
- $(3 \odot \text{IntegerOrFloat}) \odot ?\text{Integer} \mathbf{!}$ is equivalent to **True** $\mathbf{!}$.
- The pattern $x \odot \text{Float}$ matches $3.0 \odot \text{IntegerOrFloat}$ and binds x to 3.0 .
- The expression below is equivalent to $4.0 \mathbf{!}$:

$$3.0 \odot \text{IntegerOrFloat} \blacklozenge y \odot \text{Integer} : y-1 \mathbf{?}$$

$$x \odot \text{Float} : x+1 \mathbf{?} \mathbf{!}$$

A nullable is a discrimination:

Discrimination **Nullable** $\langle aType \rangle$ **between** $aType$, **Null** $\langle aType \rangle$ **!**

A nullable can be created as follows:

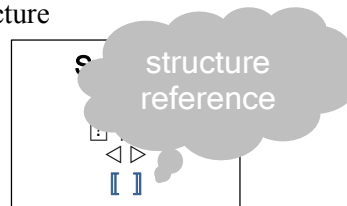
Nullable $x:aType \equiv x \odot \text{Nullable}\langle aType \rangle$

The formal syntax of type discrimination is in the following end note: **36**.

Structures, i.e., Structure

A structure can be defined using a structure identifier by “[”, parts separated by “,” and “]”.

For example, the structure **Leaf** can be defined as follows:



Structure **Leaf** $\langle aType \rangle [aType]$ **extends** **Tree** $\langle aType \rangle$ **!**
 // a terminal must be of $aType$

For example,

- The expression **Let** $x^i \leftarrow 3$. **Leaf** $\langle Integer \rangle [x]$ **!** is equivalent to **Leaf** $\langle Integer \rangle [3]$ **!**
- The pattern **Leaf** $\langle Integer \rangle [x]$ matches **Leaf** $\langle Integer \rangle [3]$ and binds x to 3.

The formal syntax of structures is in the following end note: **37**

ⁱ x is of type **Integer**

Structures with named fields, i.e., `≡` and `:≡`

The structure **Fork** can be defined as follows:

```
Structure Fork<aType>[left≡Tree<aType>, right≡Tree<aType>]
  extends Tree<aType>
  flip[ ]:Fork<aType> → // flip the branches
    Fork<aType>[left≡right, right≡left]■
```

For example,

- The expression
`Let x ← 3. Fork<Integer>[left≡Leaf<Integer>[x],`
`right≡Leaf<Integer>[x+1]])■`
 is equivalent to the following:
`Fork<Integer>[left≡Leaf<Integer>[3],`
`right≡Leaf<Integer>[4]]■`
- The pattern `Fork<Integer>[left≡x, right≡y]` matches
`Fork<Integer>[Leaf<Integer>[6], Leaf<Integer>[6]]` and binds x
 to `Leaf<Integer>[5]` and y to `Leaf<Integer>[6]`.

The formal syntax structures with named fields is in the following end note: **38.**

Processing Exceptions, i.e., Try catch \blacklozenge : , : \boxtimes 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 $\blacklozenge$ 
  Exception[aString] : aString  $\boxtimes$ ■
```

The following illustration performs `Reset.[]` and then rethrows
`Exception["This is another test."]:`

```
Try Throw Exception["This is another test." ] cleanup Reset.[ ]■
```

The formal syntax of processing exceptions is in the following end note: **39.**

Runtime Requirements, *i.e.*, **Preconditions** 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:

```
Let x ← -1.  
  Preconditions  $x \geq 0$ . // commentary for error checking  
  SquareRoot.[x]■
```

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.[2] postcondition [y:Float] → y < 1■
```

The formal syntax requirements is in the following end note: 40.

Multiple implementations of a type

For example, **Cartesian** Actors that implement **Complex**ⁱ can be defined as follows:

```
Actor Cartesian.[myReal:Float default 0, myImaginary:Float default 0]
implements Complex using // construct a Cartesian of type Complex
  realPart[ ] → myReal¶
  imaginaryPart[ ] → myImaginary¶
  magnitude[ ] →
    SquareRoot.[myReal*myReal + myImaginary*myImaginary]¶
  angle[ ] →
    Let theta ← Arcsine.[myImaginary/..magnitude[ ]].
    // ..magnitude[ ] is the result of sending magnitude[ ] to this Actor
    myReal>0 ◆
    True % theta¶
    False % myImaginary >0 ◆
    True % 180°-theta¶41
    False % 180°+theta ¶ ? ?¶

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

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

  equivalent[z] → // test if x is an equivalent complex number
    myReal=z..realPart[ ] ^ myImaginary=z..imaginaryPart[ ]§
```

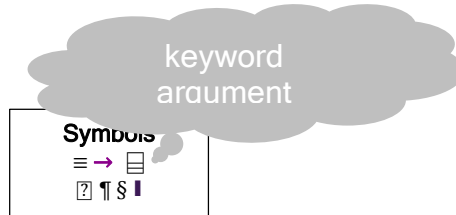
ⁱ Interface **Complex** with **realPart[]** |>> **Float**,
imaginaryPart[] |>> **Float**,
magnitude[] |>> **Float**,
angle[] |>> **Degrees**,
plus[Complex] |>> **Complex**,
times[Complex] |>> **Complex**,
equivalent[Complex] |>> **Boolean**■

Consequently,

- `Cartesian.[1, 2].realPart[]` is equivalent to `1`
- `Cartesian.[3, 4].magnitude[]` is equivalent to `5.0`
- `Cartesian.[0, 1].times[Cartesian.[0, 1]]` is equivalent to `Cartesian.[-1, 0]`⁴²

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

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



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

Consequently,

- `Polar.[theAngle ⊞ 0°, theMagnitude ⊞ 1].realPart[]` is equivalent to `1`
- `(Polar.[theMagnitude ⊞ 1]).equivalent[Cartesian.[1, 0]]` is equivalent to `True`

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

A list expression begins with “**List**” followed by the type of list elementⁱ and expressions for list elementsⁱⁱ. Similarly “**Lists**” is used for a list of lists. The prefix operator “**V**” can be used to spread the elements of a list. For example

- `[1, V[2, 3], 4]` 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 `[1, 2, [5, 6], 5, 6]`
- `[1, 2]` is the list of integers of type **Integer** with just 1 and 2.

The formal syntax of list expressions is in the following end note: **43**.

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

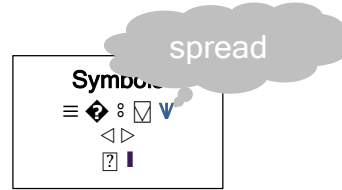
- `[[x, 2], Vy:[Integer*]]` is a pattern that matches `[[1, 2], 3, 4]` and binds `x` to 1 and `y` to `[3, 4]`
- if `y` is `[3, 4]` then `[[1, 2], V$$y]` matches `[[1, 2], 3, 4]`
- `[Vx, Vy]` is an illegal pattern because it can match ambiguously

The formal syntax of patterns is in the following end note: **44**.

ⁱ delimited by `<` and `>`

ⁱⁱ delimited by `[` and `]`

As an example of the use of spread, the following procedure returns every other element of a list beginning with the first:



```

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

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

A set is an unordered structure with duplicates removed.

The formal syntax of sets is in the following end note: **45.**

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

A set is an unordered structure with duplicates allowed.

The formal syntax of multisets is in the following end note: **46.**

Maps, i.e., `Map{ }`

A map is composed of pairs. For example `Map{ [3, "a"], ["x", "b"] }`!

Pairs in maps are unordered, e.g., `Map{ [3, "a"], ["x", "b"] }` is equivalent to `Map{ ["x", "b"], [3, "a"] }`!

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

Age \equiv **Integer** that $Is \geq 0 \leq 130$!

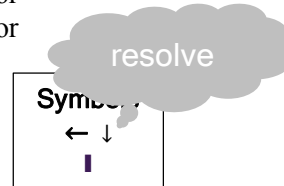
```
AgeToAverageOfNumberOfContactsPairsSortedByAge
  .[[records: Set<ContactRecord>]: [[Age, Float]*]  $\equiv^{47}$ 
  records.filterii[[aRecord: ContactRecord] ..>
    aRecord[[citizenship]  $\diamond$ 
      "US"  $\circ$  True  $\square$ 
      else  $\circ$  False  $\square$ ]
  .collectiii[[aRecord: ContactRecord] ..>
    [aRecord[[yearsOld],
      aRecord[[numberOfContacts]]
  .reduceRangeiv
    [[aSetOfNumberOfContacts: {Integer*}] ..>
      aSetOfNumberOfContacts.averagev[ ]
  .sortvi[LessThanOrEqual]!
```

-
- ⁱ **Structure** **ContactRecord**[**yearsOld** \sqsubseteq **Age**,
 numberOfContacts \sqsubseteq **Integer**,
 citizenship \sqsubseteq **String**]!
- ⁱⁱ {**ContactRecord***} has **filter**[[**ContactRecord**] |..> **Boolean**]
 |..> {**ContactRecord***}]!
- ⁱⁱⁱ {**ContactRecord***} has
 collect [**SingleArgumentToPair**<**ContactRecord**, **Age**, **Integer**>] |..>
 Map<**Age**, **Set**<**Integer**>>!
- Interface** **SingleArgumentToPair**<**Type1**, **Type2**, **Type3**> with
 [**Type1**] |..> [**Type2**, **Type3**]!
- ^{iv} **Map**<**Age**, **Set**<**Integer**>> has
 reduceRange[**FromTo**<{**Integer***}, **Float**>] |..> **Map**<**Age**, **Float**>!
- Interface** **FromTo**<**Type1**, **Type2**> with [**Type1**] |..> **Type2**!
- ^v {**Number***} has **average**[] |..> **Float**!
- ^{vi} **Map**<**Age**, **Float**> has **sort**[**PairTo**<**Age**, **Age**, **Boolean**>] |..> [[**Age**, **Float**]*]!
Interface **PairTo**<**Type1**, **Type2**, **Type3**> with [**Type1**, **Type2**] |..> **Type3**!

The formal syntax of maps is in the following end note: 48.

Futures, *i.e.*, Future and ↓

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



```
Let aFuturei ← Future Factorial.[9999].
↓aFutureii // do not proceed until Factorial.[9999] has
           // resolvediii
```

Futures allow execution of expressions to be adaptively executed indefinitely into the future.⁴⁹ For example, the following returns a future

```
Let aFuture ← Future Factorial.[9999],
g ← ([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:

- `↓Future (4+Factorial.[9999])`
- `4+↓Future Factorial.[9999]`
- `4+□Factorial.[9999]`
- `□(4+Factorial.[9999])`

Also `□Factorial.[9999]+□Fibonacci.[9000]` is equivalent to the following:

```
Let niv ← □Factorial.[9999],
m ← □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.

^{iv} n is of type `Integer`

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

```

Let aFuture  $\leftarrow$  Future Factorial.[9999].
  readCharacter.[ ]
    'x'  $\ni$  1 // readCharacter.[ ] returned 'x'
  else  $\ni$  1 + !aFuture
    // readCharacter.[ ] returned something other than 'x'

```

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

The procedure `Size` below can compute the size of a `FutureList<String>`ⁱ concurrently with its being created:

```

Size.[aFutureList:FutureList<String>]:Integer  $\equiv$ 
  aFutureList
    []  $\ni$  0
    [first,  $\vee$ rest]  $\ni$  first.length + !Size.[rest]
    // resolving a FutureList resolves only the head

```

Below is the definition of a procedure that computes a `FutureList` that is the “fringe” of the leaves of tree.ⁱⁱ

```

Fringe<aType>.[aTree: $\ni$ Tree<aType>]:FutureList<aType>  $\equiv$ 
  aTree
    Leaf<aType>[x]  $\ni$  [x]
    Fork<aType>[tree1, tree2]  $\ni$ 
      [ $\vee$ Fringe.[tree1],  $\vee$ Postpone50 Fringe<aType>.[tree2]]

```

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

```

SameFringe<aType>
  .[aTree: $\ni$ Tree<aType>, anotherTree: $\ni$ Tree<aType>]:Boolean  $\equiv$ 
    // test if two trees have the same fringe
    Fringe<aType>.[aTree]  $\equiv$  Fringe<aType>.[anotherTree]
    // = resolves futures in the fringes

```

ⁱ An instance of `FutureList<aType>` is *either*

1. the empty list of type `FutureList<aType>` *or*
2. a list whose first element is of `aType` and whose rest is of `Future<FutureList<aType>>`.

ⁱⁱ See definition of `Tree` above in this article.

The procedure below given a list of futures returns a **FutureList** with the same elements resolved:

```
FutureListOfResolvedElements<aType>
  .[aListOfFutures:[<Future<aType>*>]:FutureList<aType> ≡
aListOfFutures ◆
  [] § [] □
  [aFirst, ∀aRest] §
  [↓aFirst,
    ∀Future FutureListOfResolvedElements<aType>. [↓aRest]] ? ■
```

The formal syntax of futures is in the following end note: **51**.

In-line Recursion (e.g., looping), i.e. ■[← , ←] ≡

Inline recursion (often called looping) is accomplished using an initial invocation with identifiers initialized using “←” followed by “≡” 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.

```
Factorial. [n ← 9, accumulation ← 1] ≡
  n ◆ 1 § accumulation □
  (> 1) § 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].

ⁱ This construct takes the place of **while**, **for**, *etc.* loops used in other programming languages.

ⁱⁱ equivalent to the following:

```
Factorial. [n:Integer ← 9, accumulation:Integer ← 1]:Integer ≡
  n ◆ 1 § accumulation □
  (> 1) § Factorial. [n-1, n* accumulation] ? ■
```

The following expression returns a list of ten times successively calling the parameterless procedure P^i (of type $\text{To}\langle\text{Integer}\rangle^{ii}$):

```
FirstTenSequentially.n[n ← 10]:[Integer*] ≜
  n=1 ♦ True ∶ P..[ ] □
  False ∶ Let x ← P..[ ] ●.
  [x, vFirstTenSequentially.n[n-1]] ? !
```

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

```
OneOfTen.n[n ← 10]:[Integer*] ≜
  n=1 ♦ True ∶ P..[ ] □
  False ∶ □P..[ ] either □OneOfTen.n[n-1]] ? !
```

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

Strings

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

- **String**[‘1’, ‘23’, ‘4’]! is equivalent to “1234”!
- **String**[‘1’, ‘2’, ‘34’, ‘56’]! is equivalent to “123456”!
- **String**[**String**[‘1’, ‘2’], ‘34’]! is equivalent to “1234”!
- **String**[]! is equivalent to “”!

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

For example:

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

ⁱ The procedure P may be indeterminate, *i.e.*, return different results on successive calls.

ⁱⁱ **Interface** $\text{To}\langle\text{aType}\rangle$ **with** [] \mapsto **aType**!

ⁱⁱⁱ The procedure P may be indeterminate, *i.e.*, return different results on different calls.

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

The following is an illustration of language extension that illustrates postponed execution:⁵⁶

```
(("Postpone" anExpression:Expression <aType>):Postpone<aType> ≡  
  Actor implements Expression<Future<aType>> using  
    eval[anEnvironment]→  
      Future Actor implements aType using  
        aMessagei→ // aMessage received  
        Let postponed ← anExpression.eval[anEnvironment].  
        postponed.aMessage  
        // return result of sending aMessage to postponed  
        become postponed$  
        // become the Actor postponed for  
        // the next message receivedii
```

The formal syntax of language extension is in the following end note: 57.

ⁱ aMessage:Message<aType>

ⁱⁱ this is allowed because postponed is of type aType

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

For example, the following example implements a lockable that spins to lock:⁵⁸

```

Actor SpinLock.[ ]
  locked := False.           // initially unlocked
  implements Lockablei using
    lock[ ] → Attempt.[ ] ≡    // perform the loop Attempt as follows
      Atomic locked compare False update True ⚡
      // attempt to atomically update locked from False to True
      updated % Preconditions locked=True.
      // locked must have contents True
      Void □ // if updated return Void
      notUpdated % Attempt.[ ] ? ! // if not updated, try again
    unLock[ ] →
      Preconditions locked=True. // locked must have contents True
      Void afterward locked := False § ! // reset locked to False

```

Symbols

≡ → ⚡ □ %

? ! § !

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

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 structure for namespaces.

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

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

UsingNamespace DayName!

FollowingDay.[aDay:DayName]:DayName ≡

aDay ◆ **Monday** : **Tuesday**,
 Tuesday : **Wednesday**,
 Wednesday : **Thursday**,
 Thursday : **Friday**,
 Friday : **Saturday**,
 Saturday : **Sunday**,
 Sunday : **Monday** ?!

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

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

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

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

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

```
setTimeoutJavaScript.[1000,  
    Function [] →  
        consoleJavaScript.[ "log" ].["later"]]
```

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

Native types can also be used from Java. For example
(s:StringJavaScript).substring[3, 5]ⁱⁱⁱ is the substring of s from the 3rd to the 5th characters inclusive.

Java types can be imported using **Import**, e.g.:

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

After the above, **BigInteger.new**["123"].instanceof[**Number**] is equivalent to **True**.

ⁱ aRectangle is of type **Object**JavaScript

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

ⁱⁱⁱ **substring** is a method of the **String** class in Java

The following notation is used for XML.⁶²

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

and could print as:

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

XML Attributes are allowed so that the expression

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

and could print as:

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

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

- **XML** <"doc"> 1, 2, **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 , \leftarrow , and \rightarrow

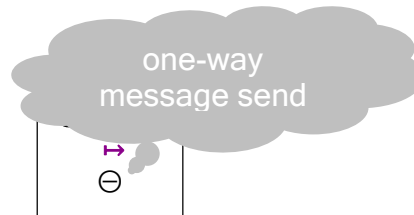
One-way messaging is often used in hardware implementations.

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

The following is an interface for a customer that is used in request/response message passing for return type **aType**.⁶³

Interface Customer<aType> with
 return [aType] $\rightarrow \Theta$,
 throw [anException] $\rightarrow \Theta$!

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



The formal syntactic definition of one-way named-message sending is in the end note: **64**

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

The formal syntactic definition of one-way named-message implementation is in the following end note: **65**

one-way message receive

Symbols

◊ ? ◻ ◻ ? | ? | \$

Arrays

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

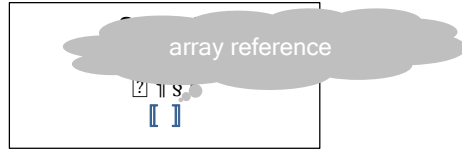
- i **Interface** **ALU** \langle **aType** \rangle with **jumpGreater** [**aType**,] $\mapsto \ominus$,
addJumpPositive [**anException**] $\mapsto \ominus$ **!**
- ii **VariableLocation** \langle **aType** \rangle has **store**[**aType**] \mapsto **Void** **!**
- iii **TemporaryLocation** \langle **aType** \rangle has **write**[**aType**] $\mapsto \ominus$ **!**

of the subarray (inclusive), and the number of elements in the subarray is $\text{right} - (\text{left} + 1)$.

```

QuickSort.[anArray:Array<Number>, left:Integer, right:Integer]:Void  $\equiv$ 
  Preconditions anArray.lower[ ]  $\leq$  left  $\leq$  right  $\leq$  anArray.upper[ ].
  (left < right)  $\Leftarrow$  True : // If the array has 2 or more items
    Let pivotIndex  $\leftarrow$ 
      Partition.[anArray, left, right, left + (right - left) / 2]  $\bullet$ .
    Preconditions left  $\leq$  pivotIndex  $\leq$  right.
     $\square$  QuickSort.[anArray, left, pivotIndex - 1],
      // Recursively sort elements smaller than the pivot
     $\square$  QuickSort.[anArray, pivotIndex + 1, right]  $\square$ 
      // Concurrently recursively sort elements at
      // least as big as pivot
  False : Void  $\square$  I

```



```

Partition.[anArray:Array<Number>, left:Integer, right:Integer,
  pivotIndex:Integer]:Integer  $\equiv$ 
  Preconditions anArray.lower[ ]  $\leq$  left  $\leq$  pivotIndex  $\leq$  right  $\leq$  anArray.upper[ ].
  Let pivot  $\leftarrow$  anArray[pivotIndex]  $\bullet$ .
  Prep anArray.swap[pivotIndex, right]  $\bullet$ .67
  Let finalStoreIndex  $\leftarrow$ 
    Move.[iterationIndex:Integer  $\leftarrow$  left,
      storeIndex:Integer  $\leftarrow$  left]:Integer  $\triangleq$ 
    Preconditions left  $\leq$  storeIndex  $\leq$  iterationIndex  $\leq$  right.
    iterationIndex < right  $\Leftarrow$ 
      True :
        anArray[iterationIndex]  $\leq$  pivotValue  $\Leftarrow$ 
          True :
            Prep anArray.swap[iterationIndex, storeIndex]  $\bullet$ .
            Move.[iterationIndex + 1, storeIndex + 1]  $\square$ 
          False : Move.[iterationIndex + 1, storeIndex]  $\square$   $\square$ 
        False : storeIndex  $\square$   $\bullet$ .
    Prep anArray.swap[finalStoreIndex, right]  $\bullet$ . // Move to its final place
  finalStoreIndex I

```

For example, consider:

```

Let anArray  $\leftarrow$  Array.[3, 2, 1].
Prep QuickSort.[anArray, 0, 2]  $\bullet$ .
anArray I

```

The above returns **Array**[1, 2, 3] **I**.

Inconsistency Robust Logic Programs

Logic Programs⁶⁸ 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 $\vdash_t \text{Mortal}[x] \rightarrow (\vdash_t \text{Human}[\$x] \rightarrow \vdash_t \text{Mortal}[x]) \mathbf{!}$

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

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

SubArguments

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

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

Let $t' \leftarrow \text{extension} \cdot [t] \circ$

$\vdash_{t'} psi,$

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

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.

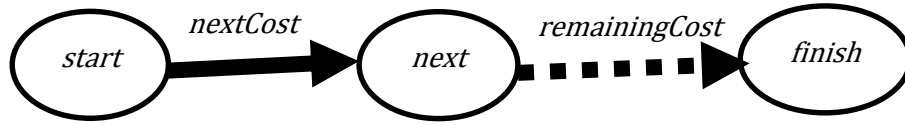
Aggregation using Ground-Complete Predicates

Logic Programs in ActorScript are a further development of Planner. For example, suppose there is a ground-complete predicate⁶⁹ `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
```

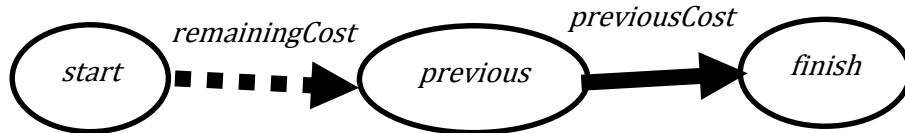
The following goal-driven Logic Program works forward from *start* to find the cost to *finish*:⁷⁰

```
When  $\vdash$  Path[start, finish, aCost]  $\rightarrow$ 
     $\vdash$  aCost=Minimum {nextCost + remainingCost
        |  $\vdash$  Link[start, next≠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≠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.⁷¹

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

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

Interface Expression<aType> with
eval[Environment]→ aType■

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

((anIdentifier:Identifier<aType>):Expression<aType> ≡
eval[anEnvironment]→ anEnvironment.**lookup**[anIdentifier]■

The interface **Type**

The interface **Type** is defined as follows:

Interface Type with
extensionFrom?[Type] |..> Boolean
has?[MethodSignature] |..> Boolean■

((anotherType:Type<anotherType> “⊇” aType:Type<aType>)
:Expression<Boolean> ≡
eval[anEnvironment]→
(anotherType.**eval**[anEnvironment])
.extensionFrom?[aType.**eval**[anEnvironment]]■

```

((anotherType:Type<anotherType> “has” aSignature:Signature)
                                     :Expression<Boolean> ≡
eval[anEnvironment]→
  (anotherType.eval[anEnvironment])
    .has?[aSignature.eval[anEnvironment]]!

```

Meta expressions

Meta followed by an Actor is an Actor of type **MetaType** where

Interface **MetaType** with

```

of?[Type] |..> Boolean,
ofExtensionFom?[Type] |..> Boolean!

```

```

(“Meta” anExpression:Expression<aType>)
                                     :Expression<MetaType> ≡
eval[anEnvironment]→
  Actor implements MetaType using
    of?[anotherType] ..>
      aType = anotherType,
    ofExtensionFom?[anotherType] ..>
      aType ≡ anotherType!

```

```

((anExpression:Expression<anotherType> “:?” aType:Type<aType>)
                                     :Expression<Boolean> ≡
eval[anEnvironment]→
  (Meta anExpression.eval[anEnvironment])
    .of?[aType.eval[anEnvironment]]!

```

```

((anExpression:Expression<anotherType> “:≡?” aType:Type<aType>)
                                     :Expression<Boolean> ≡
eval[anEnvironment]→
  (Meta anExpression.eval[anEnvironment])
    .ofExtensionFrom?[aType.eval[anEnvironment]]!

```


Future, ↓, and □

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

Interface **Future**<aType> with **resolve[]** → aType

```

(“Future” anExpression: Expression <aType>)
    : Expression <Future<aType>> ≡
Actor implements Expression<Future<aType>> using
    eval[anEnvironment] →
        Let aFuture: Future<aType> ←
            Future Try anExpression. eval[anEnvironment]
            catch
                anException :
                    Actor
                    implements Future<aType>
                    resolve[ ] → Throw anException.
Actor implements Future<aType> using
    resolve[ ] → ↓aFuture §

```

```

(“↓” anExpression: Expression <Future<aType>>)
    : Expression <aType> ≡
Actor implements Expression<aType> using
    eval[anEnvironment] →
        anExpression. eval[anEnvironment]. resolve[ ] §

```

```

(“□” anExpression: Expression <aType>)
    : Expression <aType> ≡
Actor implements Expression<aType> using
    eval[anEnvironment] →
        ↓Future anExpression. eval[anEnvironment] §

```

The message **match**

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

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

```
((anIdentifier: Identifier <aType>)): Pattern <aType> ≡
  match[anActor: aType, anEnvironment] →
    anEnvironment. bind[anIdentifier, to { anActor } ] !
```

```
(("_"): UniversalPattern <aType> ≡
  match[anActor: aType, anEnvironment] → anEnvironment !
```

```
(("$ $" anExpression: Expression <Type>))
                                     : ValuePattern <aType> ≡
  match[anActor, anEnvironment] →
    (anActor = anExpression. eval[anEnvironment]) ?
    True : Nullable anEnvironment
    False : Null <Environment> ? !
```

```
((aPattern: Pattern <aType>
  ":" anExpression: Type <aType>))
                                     : TypedPattern <anotherType> ≡
  match[anActor, anEnvironment] →
    (anActor : { ? anExpression. eval[anEnvironment] }) ?
    True : aPattern. match[anActor, anEnvironment]
    False : Null <Environment> ? !
```

```
(("⊃" anExpression: Type <aType>): TypedPattern <anotherType> ≡
  match[anActor, anEnvironment] →
    (anActor : { ? anExpression. eval[anEnvironment] }) ?
    True : Nullable anEnvironment
    False : Null <Environment> ? !
```

Message sending, e.g., `.`

```
(procedure:Expression <argumentsType→returnType>
  " " "[" arguments:Arguments <argumentsType> "]"
  ":" returnType)
  :ProcedureSend <argumentsType, returnType> ≡
eval[anEnvironment]→
(procedure.eval[anEnvironment])
  .[V(expressions.eval[anEnvironment])]$!
```

```
(recipient:Expression <recipient> " "
  name:MessageName "[" Varguments
    :Arguments <argumentsType> "]"
    :NamedMessageSend <expressionType> ≡
eval[anEnvironment]→
Let aRecipient ← recipient.eval[anEnvironment].
  aRecipient
    .Message[QualifiedName[name recipientType],
      [Varguments.eval[anEnvironment]]]$!
```

```
(recipient:Expression <recipientType>
  " " aMessage:Message <Message <recipientType>>)
  :UnnamedMessageSend <expressionType> ≡
eval[anEnvironment]→
(recipient.eval[anEnvironment])
  .(aMessage.eval[anEnvironment])$!
```

List Expressions and Patterns

```
("[" firstExpression:Expression <aType>
  " " secondExpression:Expression <aType> "]"
  :ListExpression <aType> ≡
eval[anEnvironment]→
Let first ← firstExpression.eval[anEnvironment],
  second ← secondExpression.eval[anEnvironment].
  [first, second]$!
```

```

(("[" firstExpression:Expression<aType>
  "," "V" restExpression:Expression<aType> "]" )
  :ListExpression<aType> ≡

eval[anEnvironment]→
  Let first ← firstExpression.eval[anEnvironment],
    rest ← restExpression.eval[anEnvironment]。
  [first, Vrest]$!

```

```

(("[" firstPattern:Pattern<aType>
  "," "V" restPattern:ListPattern<aType> "]" )
  :ListPattern<aType> ≡

match[anActor:aType, anEnvironment]→
  anActor ⚡
  [first, Vrest] :
    firstPattern.match[first, anEnvironment] ⚡
    ⊗⊗Null Environment :
      Null <Environment>,
      aNewEnvironment⊗Environment :
        restPattern.match[restValue, aNewEnvironment] ?$!
  else : Null <Environment> ?$!

```

Exceptions

```

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

eval[anEnvironment]→
  Try anExpression.eval[anEnvironment] catch⚡
    anException:Exception : CasesEval.[anException,
      exceptions,
      anEnvironment] ?$!

```

Try ... catch⚡

```

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

eval[anEnvironment]→
  Try anExpression.eval[anEnvironment] catch⚡
    _ : Prep aCleanup.eval[anEnvironment] ●。
  Rethrow?$!

```

Continuations using **perform**

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

Interface **Continuation** $\langle aType \rangle$ **with**
perform [**Environment**, **CheeseQ**] \mapsto **aType** **|**
Discrimination **Construct** $\langle aType \rangle$ **between**
Continuation $\langle aType \rangle$, **Expression** $\langle aType \rangle$ **|**

Execute. [**aConstruct**:**Construct** $\langle aType \rangle$,
 anEnvironment:**Environment**,
 aCheeseQ:**CheeseQ**]:**aType** \equiv
 aConstruct \blacklozenge **aContinuation** \ominus **Continuation** $\langle aType \rangle$ $:$
 aContinuation.**perform**[**anEnvironment**,
 aCheeseQ] \boxtimes
 anExpression \ominus **Expression** $\langle aType \rangle$ $:$
 anExpression.**eval**[**anEnvironment**] \boxtimes **|**

Atomic compare and update

```

(("Atomic" location: Expression <Location <anotherType>,
  "compare" comparison: Expression <anotherType>
  "update" update: Expression <anotherType> "⚡"
  "updated" "⌘"
    compareIdentical: ContinuationList <aType> "☑"
  "notUpdated" "⌘"
    compareNotIdentical: ContinuationList <aType>)
  :Atomic <aType> ≡

perform[anEnvironment, aCheeseQ] →
  (location. eval[anEnvironment])
  .compareAndConditionallyUpdate[comparison. eval[anEnvironment],
    update. eval[anEnvironment]] ⚡
  True ⌘ compareIdentical. perform[anEnvironment, aCheeseQ] ☑
  False ⌘
    compareNotIdentical. perform[anEnvironment, aCheeseQ] ?!

Actor SimpleLocation <anotherType>. [initialContents]
  contents := initialContents.
  implements Location <anotherType> using
    compareAndConditionallyUpdate[comparison, update] →
      (contents = comparison) ⚡
      True ⌘ True afterward contents := update ☑
      False ⌘ False ?!

```

Cases

```

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

eval[anEnvironment] →
  CasesEval.[anExpression.eval[anEnvironment],
    cases,
    anEnvironment] $!

CasesEval.[anActor: anotherType,
  cases: [<ExpressionCase <anotherType, aType> *],
  anEnvironment: Environment]: aType ≡

cases ⚡
  [] : Throw NoApplicableCase[ ],
  [first, vrest] :
    first ⚡ ((aPattern: Pattern <anotherType> "⚡"
      anExpression: Expression <aType>)
        : ExpressionCase <aType> :
      aPattern.match[anActor, anEnvironment] ⚡
      ⊗ ⊗ Null Environment :
        CasesEval.[anActor, rest, anEnvironment] ☐
        newEnvironment ⊗ Environment :
          anExpression.eval[newEnvironment] ? ☐
      ("else" elsePattern: Pattern <anotherType> "⚡"
        elseExpression: Expression <aType>)
        : ExpressionElseCase <aType> :
      elsePattern.match[anActor, anEnvironment] ⚡
      ⊗ ⊗ Null Environment :
        Throw ElsePatternMustMatch[ ] ☐
        newEnvironment ⊗ Environment :
          elseExpression.eval[newEnvironment] ? ☐
      ("else" "⚡"
        elseExpression: Expression <aType>)
        : ExpressionElseCase <aType> :
      elseExpression.eval[anEnvironment] ☐
    else : Throw NoApplicableCase[ ] ? ? !

```

```

((anExpression: Expression <anotherType> "⚡"
  cases: ContinuationCases <anotherType, aType> "?")
  : CasesContinuation <aType> ≡
  perform[anEnvironment, aCheeseQ] →
    CasesPerform. [anExpression. eval[anEnvironment], cases,
      anEnvironment, aCheeseQ] $!
CasesPerform. [anActor: anotherType,
  cases: [ContinuationCase <aType> *],
  anEnvironment: Environment,
  aCheeseQ: CheeseQ]: aType ≡
cases ⚡
[] : Throw NoApplicableCase[ ],
[first, ∀rest] :
  first ⚡ ((aPattern: Pattern <anotherType> "⚡"
    aContinuation: Continuation <aType>))
    : ContinuationCase <aType> :
    aPattern. match[anActor, anEnvironment] ⚡
    ⊗ ⊗ Null Environment :
    CasesPerform. [anActor,
      rest,
      anEnvironment,
      aCheeseQ] ⊗
    newEnvironment ⊗ Environment :
    aContinuation. perform[newEnvironment,
      aCheeseQ] ⊗ ⊗
  ("else"
    elsePattern: Pattern
    <anotherType> "⚡"
    elseContinuation: Continuation <aType>))
    : ContinuationElseCase <aType> :
    elsePattern. match[anActor, anEnvironment] ⚡
    ⊗ ⊗ Null Environment :
    Throw ElsePatternMustMatch[ ] ⊗
    newEnvironment ⊗ Environment :
    elseContinuation. eval[newEnvironment] ⊗ ⊗
  ("else" "⚡"
    elseContinuation: Continuation <aType>))
    : ContinuationElseCase <aType> :
    elseContinuation. perform[anEnvironment, aCheeseQ] ⊗
  else : Throw NoApplicableCase[ ] ⊗ ⊗ !

```


Holes in the cheese

```
((anExpression: Expression <aType>
  "afterward" someAssignments: Assignments "。")
  : Continuation <aType> ≡
  perform[anEnvironment, aCheeseQ] →
  Let anActor ← anExpression.eval[anEnvironment] ●。
  Prep someAssignments.carryOut[anEnvironment, aCheeseQ] ●
  aCheeseQ.leave[ ] ●。
  anActor$!
```

```
((aVariable: Variable <aType>
  "!=" anExpression: Expression <aType>): Assignment ≡
  carryOut[anEnvironment] →
  anEnvironment.assign[aVariable,
    to ≡ anExpression.eval[anEnvironment]]$!
```

```
((“Hole” anExpression: Expression <aType>): Hole <aType> ≡
  perform[anEnvironment, aCheeseQ] →
  Let frozenEnvironment ← anEnvironment.freeze[ ] ●。
  // create frozen environment so that subsequent assignments
  // subsequent assignments do not affect evaluating anExpression
  Prep aCheeseQ.leave[ ] ●。
  anExpression.eval[frozenEnvironment]$!
```

```
((“Prep” aPreparation: Preparation “。 ”
  anExpression: Expression <aType>): Continuation <aType> ≡
  perform[anEnvironment, aCheeseQ] →
  Let frozenEnvironment ← anEnvironment.freeze[ ] ●。
  // create frozen environment so that
  // preparation does not affect evaluating anExpression
  Prep aPreparation.carryOut[anEnvironment, aCheeseQ] ●
  aCheeseQ.leave[ ] ●。
  anExpression.eval[frozenEnvironment]$!
```

```

(("Hole" anExpression: Expression <anotherType>
  "afterward" anAfterward: AfterwardContinuation <aType> "?" )
  : Continuation <aType> ≡
perform[anEnvironment, aCheeseQ] →
  Let frozenEnvironment ← anEnvironment.freeze[ ] ●.
  Prep aCheeseQ.leave[ ] ●.
  Try Let anActor ← anExpression.eval[frozenEnvironment] ●.
    Prep aCheeseQ.enter[ ] ●
    anAfterward
      .perform[anEnvironment, aCheeseQ] ●
    aCheeseQ.leave[ ].
  anActor
catch ⚡
  anException :
    Prep aCheeseQ.enter[ ] ●
    anAfterward
      .perform[anEnvironment, aCheeseQ] ●
    aCheeseQ.leave[ ].
  throw anException afterward ?$!

```

```

(("Hole" anExpression: Expression <anotherType>
  "returned"
    returnedCases: ContinuationCases <anotherType, aType> "?"
  "threw"
    threwCases: ContinuationCases <anotherType, aType> "?")
    : Continuation <anotherType, aType> ≡
perform[anEnvironment, aCheeseQ] →
  Let frozenEnvironment ← anEnvironment.freeze[ ] ●。
  Prep aCheeseQ.leave[ ] ●。
  Try Let anActor ← anExpression.eval[frozenEnvironment] ●。
    Prep aCheeseQ.enter[ ] ●。
    CasesPerform..[anActor,
      returnedCases,
      anEnvironment,
      aCheeseQ]
  catch anException: ApplicationException :
    Prep aCheeseQ.enter[ ] ●。
    CasesPerform..[anException,
      threwCases,
      anEnvironment,
      aCheeseQ] ? $!

```

```

(("Enqueue" anExpression: QueueExpression "●")
    : Enqueue <aType> ≡
perform[anEnvironment, aCheeseQ] →
  Let anInternalQ ← anExpression.eval[anEnvironment]。
  anInternalQ.enqueueAndLeave[ ] $!

```

```

(("Enqueue" anExpression: QueueExpression "●"
  aContinuation: Continuation <aType>): Enqueue <aType> ≡
perform[anEnvironment, aCheeseQ] →
  Let anInternalQ ← anExpression.eval[anEnvironment]。
  Prep anInternalQ.enqueueAndLeave[ ] ●。
  aContinuation.perform[anEnvironment, aCheeseQ] $!

```

Type Discrimination, *i.e.*, Discrimination, \ominus and \odot

```

(("Discrimination" aDiscrimination "between"
  typeExpressions: Expressions <Type> "I"): Definition ≡
  Actor implements Definition using
  eval[anEnvironment] →
  Let types: List <Type> ←
    typeExpressions. eval[anEnvironment].
  Let aDiscrimination[aType: Type] ≡
    aType ∈ types ⇐
    True : DiscriminationInstance. [x, aType] ✓
    False : Throw NotADiscriminant[aType] ?
  DiscriminationInstance. [x: aType, aType: Type] ≡
  Actor implements aDiscrimination using
  discriminate[anotherType] →
    anotherType ⇐
    aType : x ✓
    else :
      Throw WrongDiscriminant[anotherType] ?,
  (discrimination: Expression <aDiscrimination>
    "⊖" discriminant: Expression <Type>))
    : Expression <discriminant> ≡
  Actor implements Expression <discriminant> using
  eval[anEnvironment] →
    (discrimination. eval[anEnvironment])
    .discriminate[discrimination
      .eval[anEnvironment]],
  (aPattern: Pattern <aType>
    "⊙" discriminant: Expression <Type>)))
    : Pattern <aDiscrimination> ≡
  Actor implements Pattern <aDiscrimination> using
  match[anActor: aType, anEnvironment] →
    aPattern. match[anActor
      ⊙(discriminant
        .eval[anEnvironment]),
      anEnvironment].

VoidI

```

A Simple Implementation of Actor

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

```

(("Actor" declarations: ActorDeclarations
  "implements" Identifier<aType>
  "using" handlers: Handlers<anInterface> "$"): Actor<aType> ≡
Actor implements Expression<anInterface> using
  eval[anEnvironment] →
    Initialized.[anInterface.eval[anEnvironment],
      handlers,
      declarations.initialize[anEnvironment],
      SimpleCheeseQ.[ ]]$!

```

```

Initialized.[anInterface:aType,
  handlers: List<Handler<aType>>,
  anEnvironment: Environment,
  cheeseQ: CheeseQ]: aType ≡
Actor implements anInterface using
  receivedMessage: Message<aType> →
    // receivedMessage received for anInterface
    Prep aCheeseQ.enter[ ] ●.
    Let aReturned ← Try Select.[receivedMessage,
      handlers,
      anEnvironment,
      aCheeseQ]
      cleanup aCheeseQ.leave[ ] ●.
    // leave cheese and rethrow exception
    Prep aCheeseQ.leave[ ] ●.
    aReturned$!

```

```

Select. [receivedMessage: Message<aType>,
        handlers: List<Handler<aType>>,
        anEnvironment: Environment,
        aCheeseQ: CheeseQ]: aType ≡
handlers ⚡
[ ] : Throw NotApplicable[ ] ☑
[(aMessageDeclaration: MessageDeclaration<aType> "→"
  body: Continuation<aType>))
  : ContinuationHandler<aType>] ☑
vrestHandlers] :
aMessageDeclaration. match [receivedMessage,
                             anEnvironment] ⚡
  ⊗ ⊗ Null Environment : Select. [receivedMessage,
                                   restHandlers,
                                   anEnvironment,
                                   aCheeseQ] ☑
                                   // process next handler
  newEnvironment ⊗ Environment :
    Execute. [body, newEnvironment, aCheeseQ] [?] ? !
    // execute body with extension of anEnvironment

```

An implementation of cheese that never holds a lock

The following is an implementation of cheese that does not hold a lock.⁷²

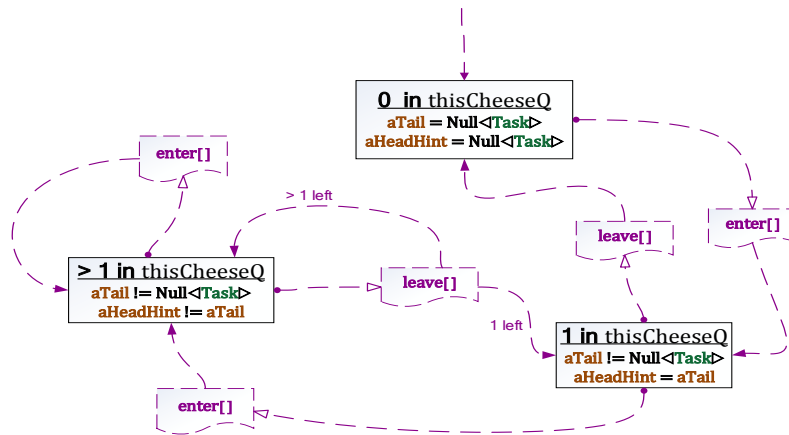
```

Actor SimpleCheeseQ[ ]
  invariants aTail=Null <Activity> ⇒ previousToTail=Null <Activity>.
  aHeadHint := Null <Activity>, // aHeadHint:Nullable<Activity>73
  aTail := Null <Activity>. // aTail:Nullable<Activity>74
  implements CheeseQ75 using nonexclusive
  enter[ ] in myActivity →76
    Preconditions myActivity[previous]=Null <Activity>,
      myActivity[nextHint]=Null <Activity>.77
    attempt.[ ]:Void ≜
      Prep myActivity[previous] := aTail ●. // set provisional tail of queue
      Atomic aTail compare aTail update myActivity ◆
      updated : // inserted myActivity in cheese queue with previous
        myActivity[previous]=Null <Activity> ◆
        True : Void □ // successfully entered cheese
        False : Suspend [ ] □ // current activity is suspended
      notUpdated : attempt.[ ] [ ] □ // make another attempt
  leave[ ] in myActivity → // leave message received running myActivity
  Preconditions aTail != Null <Activity>.78 // commentary for error checking
  Let ahead ← [ ] SubCheeseQ.head[ ] ●.
  Preconditions ahead=myActivity // commentary for error checking
  Atomic aTail compare ahead update Null <Activity> ◆
  updated : // last activity has left this cheese queue
  Void afterward aHeadHint := Null <Activity> □
  notUpdated : // another activity is in this cheese queue
  MakeRunnable ahead[nextHint] ⊗ Activity
  afterward aHeadHint := ahead[nextHint] [ ] §
  also implements internal SubCheeseQ79 using nonexclusive
  head[ ] → Preconditions aTail != Null <Activity>.
  findHead.[ ] backIterator:Activity ←
    aHeadHint = Null <Activity> ◆
    True : aTail ⊗ Activity □
    False : aHeadHint ⊗ Activity [ ] :Activity ≜
  backIterator[previous] ◆
  ⊗ ⊗ Null Activity : // backIterator is head of this cheese queue
  Prep aHeadHint := Nullable backIterator ●.
  backIterator □
  previousBackIterator ⊗ Activity :
    // backIterator is not the head of this cheese queue
  Prep 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:




```

Actor SimpleInternalQ. [aCheeseQ: CheeseQ]
  aHead := Null <Activity>, // aHead: Nullable<Activity>
  aTail := Null <Activity>.
implements InternalQ80 using nonexclusive
  enqueueAndLeave[] in myActivity →
    // enqueueAndLeave message received in myActivity
    Prep [[: SubInternalQ.remove[myActivity]] ●
      aCheeseQ.leave[] ●. // myActivity is the head of aCheeseQ
    Suspend¶
    // myActivity is suspended and when resumed returns Void ¶
  enqueueAndDequeue[anInternalQ] in myActivity →
    Preconditions → anInternalQ.empty?[] . // commentary for error checking
    Prep [[: SubInternalQ.add[myActivity]] ●
      ■.dequeue[] ●.
    Suspend¶
  dequeue[] in myActivity → Preconditions → ■.empty?[] .
    Prep aCheeseQ.leave[] ●. // myActivity is the head of aCheeseQ
    MakeRunnable [[: SubInternalQ.remove[]] ¶
      // make runnable the removed activity
  empty?[] → aTail = Null <Activity> §
also implements internal SubInternalQ81 using nonexclusive
  add[anActivity] →
    aTail ◆
    ⊙ ⊙ Null Activity :
      Void afterward aHead := Nullable anActivity,
        aTail := Nullable anActivity ▢
    theTail ⊙ Activity : Void afterward theTail[rest] := anActivity [?] ¶
  remove[] → Preconditions → ■.empty?[] . // commentary for error checking
  Let theFirst ← aHead ⊙ Activity ●.
  aTail = aHead ◆
  True : theFirst afterward aHead := Null <Activity>,
    aTail := Null <Activity> ▢
  False : theFirst afterward aHead := (aHead ⊙ Activity)[rest] [?] § ¶

```

Appendix 3. ActorScript Symbols with Readings. IDE ASCII, and Unicode code points

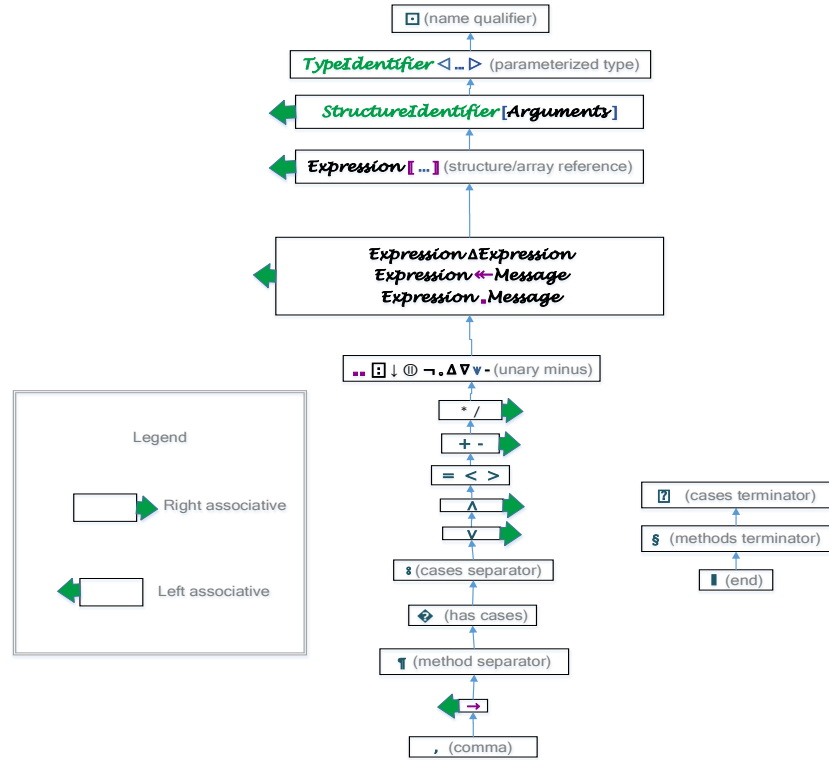
Symbol	IDE ASCII ⁱ	Read as	Category	Matching Delimiters	Unicode (hex)
␣	;;	end	top level terminator		25AE
:	:	of specified type	infix		
:?	:?	of tested type	infix		
:≡?	:>=?	of extension from type	infix		
⌈⌋	[:]	cast	infix		2360
⌈⌋⌈⌋	[:] [:]	this Actor with interface (aspect)	prefix		
⊗	(<)	injection	infix		29C0
⊗	(>)	expression/ pattern projection	infix		29C1
↓	\ /	resolve	prefix		2139
⌈⌋	[.]	qualified by	infix		22A1
▪	.	is sent	infix		
▪▪	..	delegate to this Actor	prefix		
□	| _ |	necessarily concurrent	prefix		29B7
↪	| - >	message type returns type ⁸²	infix		21A6
↪	| . . >	cacheable message type returns type			
→	-- >	message received ⁸³		¶	2192
←	< --	be ⁸⁴	infix		2190
⬢	?	cases	separator	?	FFFD
⬢	[\ /]	alternative case	separator	⬢ and ?	29B6
⬢	[?]	end cases	terminator	⬢ and catch⬢	2370
¶	\p	another message handler	separator for handlers	→	00B6
§	\s	end handlers	terminator	implements	00A7
⋮	(:)	case	separator for case		2982
●	_ /	before	separator	Let binding, preparation, Enqueue,	00C4

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

◦	(.)	end	terminator	preparations, Preconditions, and :	FF61
≡	=== ⁸⁵	defined as	infix		2261
<u>△</u>	=/\=	to be	infix		225C
:=	:=	is assigned	infix		2254
\$\$	\$\$	matches value of ⁸⁶	prefix		
=	=	same as?	infix		
<u>□</u>	[=]	keyword or field	infix		2338
: <u>□</u>	:[=]	assignable field	infix		
◁	<	begin type parameters	left delimiter	▷ (Unicode hex: 0077)	0076
∨	\|/	spread ⁸⁷	prefix		2A5B
{	{	begin set	left delimiter	}	
[	[	begin list	left delimiter]	
{|	{|	begin multi-set	left delimiter	}|	2983
[[	[[	array reference	left delimiter	]] (Unicode hex: 27E7)	27E6
(	(	begin grouping	left delimiter)	
(|	(|	begin syntax	left delimiter	) (Unicode hex: 2986)	2985
⊖	(-)	nothing ⁸⁸	expression		229D
←	<<-	one-way send	infix		219E
→	->>	one-way receive	infix	¶	21A0
⌋	⌋|	join	infix		2294
⊆	[<=]	constrained by	infix		2291
⊇	[>=]	extends	infix		2292
⇒	==>	logical implication	infix		21E8
⇔	<=>	logical equivalence	infix		21D4
^	^	logical conjunction	infix		00D9
∨	∨	logical disjunction	infix		00DA
¬	-|	logical negation	prefix		00D8
⊢	|-	assert	prefix and infix		22A2
⊨	||-	goal	prefix and infix		22A9
//	//	begin 1-line comment	prefix	EndOfLine	
/*	/*	begin comment	prefix	*/	

Appendix 4. Grammar Precedence

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



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

- (t[p]).m[x]
- (x ⋄ p1 § y1 ⋄) ⋄ p2 § y2 ⋄

Index

- , 19
- ⬅, 8, 60, 72
- ⬅ ... [?], 59
- ⬅, 73, 78
- ⬅. *See* ⬅
- ⬅, 37, 46, 49, 66, 73
- !=, 66
- , 12, 29, 72, 73
- \$\$, 70, 73
- ⌈, 36, 73
- ⌈, 73, *See* Expressions
- „, 58
- /*, 73
- //, 73
- ;, 54, 72
- ?: 72
- :⌈, 73
- [, 6, 9, 40, 41, 55, 73
- _ 54
- {, 73
- |••>, 72
- ++, 19
- ⊖, 48, 73
- , 42, 43, 45, 72, *See* Qualifiers
- ⊖, 72
- =, 33, 34, 44, 47, 66, 73
- ⊖, 29, 66, 68, 72
- , 6, 42, 55, 72
- , 16, 33, 34, 68, 72
- ▼, 35, 36, 39, 40, 41, 55, 56, 73
- ⇒, 11, 49, 61, 66, 68, 72
- △, 40, 41, 44, 50, 66, 72
- ≡, 6, 72, *See* ActorScript definitions
- ⊖, 14, 73
- ⊖, 51
- ⊖, 73
- ↳, 71, 73
- ↳, 71, 73
- ⊖, 34, 73
- ⊖, 72
- ⊖⊖, 13, 66, 68, 72
- ⊖, 8, 62, 63, 72
- , 12, 16, 50, 53, 72
- ⊖, 5, 72, *See* Expressions
- , 11, 19, 20, 72
- , 48, 73
- ↳, 9, 72
- ⇒, 73
- ↓, 38, 39, 53, 72
- ←, 40, 72, *See* Binding locals
- ↩, 48, 73
- ↔, 73
- §, 10, 72
- ¶, 10, 72
- §, 8, 58, 72
- ⌋, 36
- Actor**, 10, 11, 16, 19, 64
 - dequeue**, 68
 - enqueueAndDequeue**, 68
 - enqueueAndLeave**, 68
 - Future**, 38
 - InternalQ**, 68
 - Swiss cheese, 14
- Actor Model
 - Message passing, 1
 - types, 1
- ActorScript
 - ASCII, 72
 - cases, 8
 - definitions, 6
 - Expressions, 5
 - general messaging, 42
 - Grammar Precedence, 74
 - Integrated Development
 - Environment, 5
 - resolve future, 38
 - Symbols, 72
 - Types, 5
 - Unicode, 72
 - patterns, 7
 - variables, 10, 18
 - XML, 47
- afterward**, 11, 16, 44, 68
- Agha, G., 21
- Arrays, 49
- Athas, W., 21
- Atkinson, R., 21
- Atomic**, 44, 66
- Atomic ... compare ... update ... updated ... notUpdated ...**, 57
- Attardi, G., 21
- backout**, 19, 20
- Baker, H., 21
- Barber, G., 21
- Beard, P., 21
- become**, 43
- Bishop, P., 21
- Boden, N., 21
- Briot, J., 21
- Cartesian**, 33
- catch** ⬅, 31, 58
- cheese, 18

- hole, 16, 19, 20
- CheeseQ**, 66
- cleanup**, 31
- Clinger, W., 21
- Complex**, 33, 34
- Continuation**, 57
- Customer**, 48, 49
- Dahl, O., 1
- Dally, W., 21
- de Jong, P., 21
- Dedecker, J., 21
- default**, 34
- Discrimination**, 29
- either**, 41
- Enqueue**, 19, 20, 63
- Enumeration**, 45
- eval**, 51
- exception, 31
- extends**, 13
- Fork**, 31, 39
- FriAM, 21
- Function** (JavaScript), 46
- Future**, 38, 39, 40, 53
- FutureList**, 40
- Garst, B., 21, 67
- Greif, I., 21
- Hole**, 16, 61
- Hole ... after**, 61
- Hole ... returned ... threw**, 62
- Import**, 46
- in**, 66, 68
- Interface**, 9, 51
- JavaScript, 46
- JSON**, 46
- Kahn, K., 21
- Leaf**, 30, 39
- Let**, 9, 12, 16, 30, 33, 38, 42, 43, 46, 49, 50, 70
- Let**, 38
- Let ... ●**, 50, 66, 68
- Lieberman, H., 21
- List**, 35, 39
- Lists**, 35
- Logic Program
 - Backward chaining, 69
 - forward chaining, 69
 - subarguments, 70
- MakeRunnable**, 66, 68
- Manning, C., 21
- Map**, 37
- Mason, I., 21
- match**, 54
- Message**, 42, 43
- Meta**, 52
- MetaType**, 52
- Miller, M. S., 21
- Montalvo, F. S., 21
- Montanari, U., 21
- Morningstar, C., 21
- mustMatch**, 54
- Nassi, I., 21
- nonexclusive**, 66, 68
- Null**, 30
- Nullable**, 30, 54, 66, 68
- Nygaard, K., 1
- of?**, 52
- Object**, 46
- Object** (JavaScript), 46
- One-way messaging, 48
- parameterized
 - type, 29
- perform**, 57
- permit**, 19, 20
- Polar**, 34
- postcondition**, 32
- Postpone**, 39, 43
- Precondition**, 20, 32
- Prep**, 12
- Prep ... ●**, 66
- Qualifiers, 45
- queues**, 19, 20
- Reinhardt, T., 21
- return**, 48, 49
- Schumacher, D., 21
- Seitz, C., 21
- Set**, 37
- Simi, M., 21
- Smith, S., 21
- Steiger, R., 21
- String**, 37, 41
- Structure**, 30, 31, 37
- suchThat**, 7
- Suspend**, 66, 68
- swap** message. *See* Arrays
- Swiss cheese, 14
- Talcott, C., 21
- Thati, P., 21
- thatIs**, 8, 19
- Theriault, D., 21
- This** (JavaScript), 46
- throw**, 48, 49
- Throw**, 11, 31
- Tokoro, M., 21
- Tree**, 30, 39
- Try**, 31
- Try ... catch** ♦, 56

Try ... cleanup, 56
type
 paramaterized, 29
Type, 51
UsingNamespace, 45
Varela, C., 21
variable
 Actor, 18
 ActorScript, 10
Void, 10, 11
When, 71
Woelk, D., 21
XML, 47
Yonezawa, A., 21

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 \sqsubseteq Expression`

Also,

`((Numerical "-" Numerical):Numerical)`
`("-" Numerical):Numerical`
`((Numerical "*" Numerical):Numerical)`
`((Numerical "/" Numerical):Numerical)`
`((Remainder Numerical "/" Numerical):remainder:Numerical)`
`((QuotientRemainder Numerical "/" Numerical)
:[Numerical, Numerical])`
`(("True" \sqcup "False"):Expression \triangleleft Boolean)`
`((Expression \triangleleft Boolean \wedge Expression \triangleleft Boolean)
:Expression \triangleleft Boolean)`
`((Expression \vee Expression):Expression \triangleleft Boolean)`
`(("¬" Expression \triangleleft Boolean):Expression \triangleleft Boolean)`
`(("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 \sqsubseteq *Word* \sqsubseteq *Expression* **|**

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

((*Expression* \sqcup *Definition* \sqcup *Judgment*))) "**|**":*Top* **|**

- ⁵ *Type* \sqsubseteq *Expression* \langle *Type* \rangle **|**

((*aType*:*Type* (("**→**" \sqcup "**|..>**") *anotherType*:*Type*)): *Type* **|**

(("[" *Types* "]")): *Type* **|**

((\sqcup *MoreTypes*)): *Types* **|**

((*Type* \sqcup ((*Type* "**,**" *MoreTypes*))): *MoreTypes* **|**

- ⁶ ((*Identifier* \langle *aType* \rangle "**=**" *Expressions* \langle *aType* \rangle): *Definition* \langle *Identifier* \rangle **|**

(((*Expression* \langle *aType* \rangle ((\sqcup "**o**.")))

\sqcup ((*Expression* ("**,**" \sqcup "**●**") *MoreExpressions* \langle *aType* \rangle)))

: *Expressions* \langle *aType* \rangle **|**

(((*Expression* \langle *aType* \rangle "**o**."))

\sqcup ((*Expression* ("**,**" \sqcup "**●**") *MoreExpressions* \langle *aType* \rangle)))

: *MoreExpressions* \langle *aType* \rangle **|**

- ⁷ *ProcedureName* "**.**"

"[" *ArgumentDeclarations* "]" (("**:**" *Type* \langle *aType* \rangle) "**=**"

Expression \langle *aType* \rangle): *Definition* **|**

ProcedureName \sqsubseteq *Expression* **|**

((\sqcup *MoreDeclarations*): *ArgumentDeclarations* **|**

((*SimpleDeclaration* ((\sqcup ("**,**" *MoreKeywordDeclarations*)))

\sqcup ((*SimpleDeclaration* "**,**" *MoreDeclarations*)))

: *MoreDeclarations* **|**

// Comma is used to separate declarations.

((*Identifier*

\sqcup ((*Identifier* "**:**" *Expression* \langle *Type* \rangle)))

((\sqcup "**default**" *Expression*)): *SimpleDeclaration* **|**

((*KeywordArgumentDeclaration*

\sqcup ((*KeywordDeclaration* "**,**" *MoreKeywordDeclarations*)))

: *MoreKeywordDeclarations* **|**

((*Keyword* "**≡**" *SimpleDeclaration*)): *KeywordDeclaration* **|**

Keyword \sqsubseteq *Word* **|**

- ⁸ The symbol **.** is fancy typography for an ordinary period when it is used to denote message sending.

- ⁹ ((*Recipient*:*Expression* "**.**" "[" *Arguments* "]"): *ProcedureSend* **|**

ProcedureSend \sqsubseteq *Expression* **|**

// *Recipient* is sent a message with *Arguments*

((\sqcup *MoreArguments*): *Arguments* **|**

```

((Expression ( ⊔ (" MoreKeywordArguments )))
  ⊔ (Expression "," MoreArguments )):MoreArguments |
(KeywordArgument
  ⊔ (KeywordArgument
    "," MoreKeywordArguments )):MoreKeywordArguments |
(Keyword "⊔" Expression ):KeywordArgument |
(Identifier<Procedure> "⊔" "[" ArgumentDeclarations "]"
  ( ⊔ (":" returnType:Type <aType> )))
  "≡" Expressions <aType> "I"):Definition <Procedure> |
10 [?] takes care of the infamous "dangling else" problem [Abrahams 1966].
11 (test:Expression<patternType> "⊔"
  ExpressionCases <patternType, aType> "[?"]):Expression <aType> |
(ExpressionCase <patternType, aType>
  ⊔ MoreExpressionCases <patternType, aType>))
  :ExpressionCases <patternType, aType> |
(ExpressionCase <patternType, aType> ⊔
  (ExpressionCase <patternType, aType>
    "⊔" MoreExpressionCases <patternType, aType> ))
  ⊔ ExpressionElseCases <patternType, aType> ))
  :MoreExpressionCases <patternType, aType> |
( ⊔ ExpressionElseCase <patternType, aType>
  ⊔ (ExpressionElseCase <patternType, aType>
    "⊔" MoreExpressionElseCases <patternType, aType> )))
  :ExpressionElseCases <patternType, aType> |
(ExpressionElseCase <patternType, aType>
  ⊔ (ExpressionElseCase <patternType, aType>
    "⊔" MoreExpressionElseCases <patternType, aType> )))
  :MoreExpressionElseCases <patternType, aType> |
(("else" ":" Expressions <aType> ))
  ⊔ ("else" Pattern <patternType> ":" Expressions <aType> )))
  :ExpressionElseCase <patternType, aType> |
// The else case is executed only if the patterns before
// the else case do not match the value of test.
(Pattern <patternType> ":" Expressions <aType> ))
  :ExpressionCase <aType> |
12 ("Let" MoreLetBindings "⊔"
  result:Expressions <aType> ):Expression <aType> |
// Bindings are independent of each other
(LetBinding ⊔ (LetBinding "," MoreBindings ))
  :MoreLetBindings |

```

```

(LetBinding
  ( (LetBinding ("," ( " " "●")) MoreDependentLetBindings ))
  :MoreDependentLetBindings )
  // Each binding before a "●" is completed before its successors
  (Pattern "←" Expression):LetBinding )
13 (recipient:Expression
  " " MessageName "[" Arguments "]"):NamedMessageSend )
NamedMessageSend ⊆ Expression )
  // Recipient is sent message MessageName with Arguments
  MessageName ⊆ Word )
("Interface" Identifier<Type>
  ( ( ("extends" Identifier<anotherType>)) "with"
    MessageHandlerSignatures " ") :InterfaceDefinition )
InterfaceDefinition ⊆ Definition )
( ( MoreMessageHandlerSignatures ))
  :MessageHandlerSignatures )
(MessageHandlerSignature
  ( ( MoreMessageHandlerSignatures ))
  :MoreMessageHandlerSignatures )
(MessageName "[" ArgumentTypes "]" ( "→" ( " " "→" ))
  returnType:TypeExpression):MessageHandlerSignature )
MessageHandlerSignature ⊆ Expression )
14 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.
15 Continuations in ActorScript are related to continuations introduced in
[Reynolds 1972] in that they represent a continuation of a computation. The
difference is that a continuation of Reynolds is a procedure that takes as an
argument the result of the preceding computation. Consequently, a
continuation of Reynolds is closer to a customer in the Actor Model of
computation.

```

¹⁶ (**"Actor"** ConstructorDeclaration ActorBody):Expression **!**
 // The above expression creates an Actor with
 // declarations for variables and message handlers
 ((**⊔** ("extends" ConstructorList))))
 ((**⊔** "management" Expression <[aType]→Manager>))
 NamedDeclaration
 MessageHandlers
 InterfaceImplementations):ActorBody **!**
 (Identifier "[" ArgumentDeclarations "]")
 :ConstructorDeclaration **!**
 (Constructor (**⊔** " "))
⊔ (Constructor "," MoreConstructors " ")):ConstructurList **!**
 (Constructor
⊔ (Constructor "," MoreConstructors)):MoreConstructors **!**
 (ActorQueues NamesDeclarations):NamedDeclaration **!**
 ((**⊔** (MoreNameDeclarations " ")):NamesDeclarations **!**
 (NameDeclaration
⊔ (NameDeclaration
 "," MoreNamesDeclarations)):MoreNameDeclarations **!**
 (Identifier
 ((**⊔** (":" Type <aType>)))
 "←" Expression<aType>):IdentifierDeclaration **!**
 IdentifierDeclaration **⊆** NameDeclaration **!**
 (Variable (**⊔** (":" Type <aType>)))
 "!=" Expression<aType> InstanceVariableAQualifications))
 :VariableDeclaration **!**
 VariableDeclaration **⊆** NameDeclaration **!**
 Variable **⊆** Word **!**
 InstanceIVariableQualifications **⊆** InstanceQualifications **!**
 ((**⊔** InstanceVariableQualification
⊔ (InstanceVariableQualification
 InstanceIVariableQualifications))
 :InstanceIVariableQualifications **!**
 "nonpersistent" **⊆** InstanceVariableQualification **!**
 // A nonpersistent variable must be of type Nullable<aType>,
 // and can be nulled out before a message is received
 ("queues" QueueNames " "):ActorQueues **!**
 (QueueName **⊔** (QueueName "," QueueNames)):QueueNames **!**
 QueueName **⊆** Word **!**
 QueueName **⊆** Expression <Queue> **!**
 ("Void"):Expression **!**

```

((InterfaceImplementation
  ( ⊔ MoreInterfaceImplementations)))
                                     :InterfaceImplementations ⊐
("also" InterfaceImplementation
  ( ⊔ MoreInterfaceImplementations)))
                                     :MoreInterfaceImplementations ⊐
(( ⊔ "partially")
  ("implements" ⊔ "reimplements")
    ( ⊔ "exportable") Type <aType> "using"
      (MessageHandlers "§") ⊔ UniversalMessageHandler)
                                     :InterfaceImplementation <aType> ⊐
(MessagePattern
  ( ⊔ (":" Type)))
  ( ⊔ ("sponsor" Identifier <Sponsor>)))
  "→" ExpressionsContinuation <aType>
                                     :UniversalMessageHandler <aType> ⊐
( ⊔ MoreMessageHandlers):MessageHandlers ⊐
(MessageHandler
  ⊔ (MessageHandler "¶" MoreMessageHandlers)))
                                     :MoreMessageHandlers ⊐

  // The message handler separator is ¶.
(MessageName "[ ArgumentDeclarations "]"
  ( ⊔ ( ":" returnType:Type <aType>))
  ( ⊔ ("sponsor" Identifier <Sponsor>)))
  "→" ExpressionsContinuation <aType>):MessageHandler ⊐
  // For a message with MessageName with arguments,
  // the response is Continuation
(Expression <aType>
  "afterward" VariableAssignments):Continuation <aType> ⊐
  // Return Expression and afterward perform
  // MoreVariableAssignments
(VariableAssignment
  ⊔ (VariableAssignment
    "," MoreVariableAssignments "."))
                                     :VariableAssignments ⊐
(VariableAssignment
  ⊔ (VariableAssignment
    "," MoreVariableAssignments)))
                                     :MoreVariableAssignments ⊐
(Variable "==" Expression <aType>):VariableAssignment <aType> ⊐

```

¹⁷ (“**Prep**” *MoreAntecedents* “.”)
Continuation <**aType**> “.”):*Preparation* <**aType**> **I**
 ((*Antecedent* \sqcup (*Antecedent* (“,” \sqcup “●”) *MoreAntecedents*)))
 :*MoreAntecedents* **I**

Expression \sqsubseteq *Antecedent* **I**
StructureAssignment \sqsubseteq *Antecedent* **I**
ArrayAssignment \sqsubseteq *Antecedent* **I**

¹⁸ For example, consider the following:

```
Actor SimpleNeedTwo.[ ]
  queues waiting.
  hasOne := False.
  implements NeedTwo using
    [ ] → hasOne  $\diamond$  True : Void permit waiting  $\boxtimes$ 
      False : Prep hasOne := True ●.
      enqueue waiting ●
      Void  $\boxtimes$  I
```

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

```
Let aNeedTwo ← SimpleNeedTwo.[ ].
```

```
  Prep  $\square$  aNeedTwo.[ ] ●.
```

```
  aNeedTwo.[ ] I
```

However following expression might never return because of optional concurrency:

```
Let aNeedTwo ← SimpleNeedTwo.[ ].
```

```
  Prep aNeedTwo.[ ] ●.
```

```
  aNeedTwo.[ ] I
```

¹⁹ (“ \square ” *anExpression*:*Expression* <**aType**>
 ((\sqcup (“**sponsor**” *Expression* <**Sponsor**> **I**)):*Expression* <**aType**> **I**
 // Execute *anExpression* concurrently and respond with the outcome.
 // In every case, *anExpression* must complete before execution leaves
 // the lexical scope in which it appears.

²⁰ The ability to extend implementation is important because it helps to avoid code duplication.

²¹ cf. [Crahen 2002, Amborn 2004, Miller, et. al. 2011]

²² note the absence of “.” in the **implementation** subexpression

²³ equivalent to the following:

```
myBalance  $\square$  SimpleAccount := myBalance  $\square$  SimpleAccount – anAmount
```

²⁴ ignoring exceptions in this way is *not* a good practice

²⁵ (“Enqueue” QueueExpression “●”
Continuation <aType>))) : Continuation <aType> |
/*
1. Enqueue activity in QueueExpression
2. Leave the cheese
3. When the cheese is re-entered perform Continuation. */
(“Prep” Preparation “.”
“enqueue” QueueExpression “●”
Continuation <aType>)) : Continuation <aType> |
/*
1. Perform Preparation
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 <patternType, aType> “?”))
: Continuation <aType> |
(ContinuationCase <patternType, aType>
⊔ (ContinuationCase <patternType, aType>
“⊔” MoreContinuationCases <patternType, aType>))
ContinuationElseCases))
: ContinuationCases <patternType, aType> |
(ContinuationCase <patternType, aType>
⊔ (ContinuationCase <patternType, aType>
“⊔” MoreContinuationCases <patternType, aType>))
: MoreContinuationCases <patternType, aType> |
(Pattern <patternType> “:”
ExpressionsContinuation <patternType, aType>))
: ContinuationCase <patternType, aType> |
(⊔
MoreContinuationElseCases <patternType, aType>))
: ContinuationElseCases <patternType, aType> |
(ContinuationElseCase <patternType, aType>
⊔ (ContinuationElseCase <patternType, aType>
“⊔” MoreContinuationElseCases <patternType, aType>))
: MoreContinuationElseCases <patternType, aType> |
(“else” “:” ExpressionsContinuation <aType>))
⊔ (“else” Pattern <patternType> “:”
ExpressionsContinuation <patternType, aType>))
: ContinuationElseCase <patternType, aType> |
((Continuation (⊔ “.”))
⊔ (Expression (“,” ⊔ “●”) MoreExpressionsContinuation))
: ExpressionsContinuation |

```

(((Continuation“.”)
  ⊔ ((Expression“,”MoreExpressionsContinuation))
    : MoreExpressionsContinuation ⊥

```

²⁶ Swiss cheese was called “serializers” in the literature.

```

27((“■” Message<aType>):Expression<aType>⊥
  // Delegate message to this Actor.
  (“Prep” Preparation“.”
    “hole” Expression<aType>):Continuation<aType>⊥
    /*
      1. Carry out Preparation
      2. Leave the cheese
      3. The result is the result of evaluating Expression */

```

²⁸ ReadersWriterConstraintMonitor defined below monitors a resource and throws an exception if it detects that ReadersWriter constraint is violated, e.g., for a resource r using the above scheduler:

```

      ReadingPriority[ReadersWriterConstraintMonitor[r]].
Actor ReadersWriterConstraintMonitor.[theResource:ReadersWriter]
  writing := False,
  numberReading:(Integer thatIs ≥0) := 0,
  implements ReadersWriter using
    read[query]→
    Preconditions ¬writing. // commentary for error checking
    Prep numberReading++●.
    hole theResource.read[query]
    afterward numberReading--⊥
  write[update]→
    Preconditions numberReading=0, ¬writing.
    Prep writing := True●.
    hole theResource.write[update]
    afterward writing := False●§⊥

```

²⁹ A downside of this policy is that readers may not get the most recent information.

³⁰ A downside of this policy is that writing and reading may be delayed because of lack of concurrency among readers.

³¹ (“Prep” Preparation.
“enqueue” QueueExpression
(⊔ “backout” Expressions)
Continuation <aType>))) : Continuation <aType> |
/*
1. Perform Preparation
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 Expressions, and leave the
cheese.
5. If no exception is generated by the activity while in the queue,
then when allowed to continue, re-enter the cheese to perform
Continuation. */
Cases can be continuations:
(test:Expression <patternType> “?”
ContinuationCases <patternType, aType> “?”)
: Continuation <aType> |
(ContinuationCase <patternType, aType>
⊔ MoreContinuationCases <patternType, aType>)
: ContinuationCases <patternType, aType> |
(ContinuationCase <patternType, aType> ⊔
(ContinuationCase <patternType, aType>
“⊔” MoreContinuationCases <patternType, aType>)
⊔ ContinuationElseCases <patternType, aType>)
: MoreContinuationCases <patternType, aType> |
(⊔ ContinuationElseCase <patternType, aType>
⊔ (ContinuationElseCase <patternType, aType>
“⊔” MoreContinuationElseCases <patternType, aType>))
: ContinuationElseCases <patternType, aType> |
(ContinuationElseCase <patternType, aType>
⊔ (ContinuationElseCase <patternType, aType>
“⊔” MoreContinuationElseCases <patternType, aType>))
: MoreContinuationElseCases <patternType, aType> |
(("else" ":" ContinuationList <aType>))
⊔ ("else" Pattern <patternType>
":" ExpressionsContinuation <aType>))
: ContinuationElseCase <patternType, aType> |
// The else case is executed only if the patterns before
// the else case do not match the value of test.
(Pattern <patternType> ":" ExpressionsContinuation <aType>))
: ContinuationCase <patternType, aType> |

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

```
((Expression <aType>
  ( ( ( "permit" aQueue:Expression )))
  ( ( ( "afterward" Afterward ))))):Continuation <aType> |
  /* If there are activities in aQueue, then the one of them gets the
     cheese next and also perform Afterward, then leave the cheese
     and return the value of Expression. */
VariableAssignments:Afterward |
(("Permit" aQueue:Expression ( ( ( "also" VariableAssignments )))
                               :Afterward |
```

The following can be used temporarily leave the cheese:

```
("Hole" Expression <aType>):Continuation <aType> |
/*
  1. Leave the cheese
  2. The response is the result of evaluating Expression */
("Prep" Preparation ".")
hole Expression <aType>
( ( ( "afterward" Afterward ))):Continuation <aType> |
/*
  1. Carry out Preparation
  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 */
("Prep" Preparation ".")
hole Expression <anotherType>
( ( ( "returned"
      normal:ContinuationCases <anotherType, aType> "?" )))
( ( ( "threw"
      exceptional:ContinuationCases <anotherType, aType>
                                     "?" )))
                               :Continuation <aType> |

/*
  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. */
```

³² -- is postfix decrement

```

33 Preconditions present for error checking
34 // commentary for error checking
35 ((Identifier<Type>
    "<" ParametersDeclarations ">"
    "≡" Expressions):ParameterizedDefinition |
    ParameterizedDefinition ≡ Definition |
    // Parameterize definition with ParametersDeclarations |
    ( ⊔ MoreParameterDeclarations):ParametersDeclarations |
    (ParameterDeclaration
        ⊔ (ParameterDeclaration
            "," MoreParameterDeclarations)))
    :MoreParameterDeclarations |
    (Identifier<Type> ( ⊔ Qualifier)):ParameterDeclaration |
    ( ⊔ ("extends" Identifier<Type> )):TypeQualifier |
    (Identifier<Type> "<" Parameters ">"):TypeExpression |
    (Identifier<Type>
        ⊔ ( ⊔ (Identifier<Type> "," Parameters)):Parameters |
36 ("Discrimination" Identifier<Type>
    MoreTypeDescriminations "!" ):Definition |
    (Identifier<Type>
        ⊔ (Identifier<Type> "," MoreTypeDescriminations)))
    :MoreTypeDescriminations |
    (Expression <aDiscriminationType> "⊗" Type <aType>))
    :Expression <aType> |
    // Discriminate to have the type Type <aType> if possible.
    // Otherwise, an exception is thrown.
    (Pattern <aDiscriminationType> "⊗" Type <aType>))
    :Pattern <aType> |
    // If matching Actor is a discrimination that can be discriminated
    // then Pattern must match the discriminate.
    ("⊗⊗" Type <aType>):Pattern <aType> |
    // Matching Actor must be discrimination that can be
    // discriminated as aType
37 (Identifier<aType> "[" Arguments ""]):Expression <aType> |
    (Identifier<aType> "[" Patterns ""]):Pattern <aType> |
38 ("Structure" Identifier<Type> "[" FieldDeclarations "]"
    ( ⊔ ("extends" ConstructorList)))
    NamedDeclaration
    MessageHandlers
    MoreInterfaceImplementations):Definition |
    // Structure definition with StructureImplementation
    ( ⊔ MoreFieldDeclarations):FieldDeclarations |

```

```

((SimpleFieldDeclaration
    ( ⊔ ("," MoreNamedFieldDeclarations)))
 ⊔ (SimpleFieldDeclaration
    "," MoreFieldDeclarations)):MoreFieldDeclarations ⊥
((Identifier
    ⊔ (Identifier ":" TypeExpression))
    ( ⊔ "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
    ("⊔" ⊔ ":"⊔) SimpleFieldExprpression))
        :NamedFieldExpression ⊥
(StructureName "[" FieldPatterns "]" ):StructurePattern ⊥
StructurePattern ⊆ Pattern ⊥
( ⊔ MoreFieldPatterns):FieldPatterns ⊥
((SimpleFieldPattern( ⊔ ("," MoreNamedFieldPatterns)))
    ⊔ ( SimpleFieldPattern "," MoreFieldPatterns))
        :MoreFieldPatterns ⊥
(NamedFieldPattern
    ⊔ ( NamedFieldPattern
        "," MoreNamedFieldPatterns))
        :MoreNamedFieldPatterns ⊥

```

```

    (FieldName ("[" " " ":"]) SimpleFieldExpression))
                                                    :NamedFieldPattern I
39 ("Try" anExpression:Expression <aType>
    "catch" ExpressionCases <Exception, aType> "[?]")
                                                    :Expression <aType> I
/*
    • If anExpression throws an exception that matches the pattern
      of a case, then the value of TryExpression is the value
      computed by ExpressionCases
    • If anExpression doesn't throw an exception, then then the
      value of TryExpression is the value computed by
      anExpression. */
("Try" anExpression:Expression <aType>
    "catch" ContinuationCases <Exception, aType> "[?]")
                                                    :Continuation <aType> I
/*
    • If anExpression throws an exception that matches the pattern of
      a case, then the response of TryContinuation is the
      response computed by the expression of the case.
    • If aContinuation doesn't throw an exception, then then the
      response of TryExpression is the response computed by
      anExpression. */
("Try" anExpression:Expression <aType>
    "cleanup" cleanup:Expression <aType>):Expression <aType> I
*/
    • If anExpression throws an exception, then the value of
      TryExpression is the value computed by cleanup.
    • If anExpression doesn't throw an exception, then then the
      value of TryExpression is the value computed by
      anExpression. */
40 ("Preconditions" test:Expressions Expressions):Expression I
    // Each of expressions in test must evaluate to True or
    // an exception is thrown
    ("Preconditions" Expressions ExpressionsContinuation)
                                                    :Continuation I
    // Each of expressions in Expressions must evaluate to True or
    // an exception is thrown
    (value:Expression <aType>
    "postcondition" pre:Expression <[aType]→Boolean>))
                                                    :Expression <aType> I
    // The expression pre must evaluate to True when sent value
    // or an exception is thrown
41 ° is a reserved postfix operator for degrees of angle
42 i.e., i*i=-1 where i is the imaginary number Cartesian[0, 1]

```

```

43 ("[" ComponentExpressions "]" ):Expression <List> |
    // An ordered list with elements ComponentExpressions
    ( [ MoreComponentExpressions ] :ComponentExpressions |
      ((( [ "V" ) Expression )
        [ ( [ "V" ) Expression
            "," MoreComponentExpressions ] ]
          :MoreComponentExpressions |
        ("[" TypeExpressions "]" ):TypeExpression |
        ( [ MoreTypeExpressions ] :TypeExpressions |
        (TypeExpression [ (TypeExpression "," MoreTypeExpressions ) ]
          :MoreTypeExpressions |
44 ("_"):UnderscorePattern |
    UnderscorePattern ⊆ Pattern |
    Identifier ⊆ Pattern |
    (Pattern "suchThat" Expression ):SuchThat |
    SuchThat ⊆ Pattern |
    (Pattern "thatIs" Expression ):ThatIs |
    ThatIs ⊆ Pattern |
    ("$$" Expression <Type> ):Pattern <Type> |
    ("[" ComponentPatterns "]" ):Pattern <List> |
    // A pattern that matches a list whose elements match
    // ComponentPatterns
    ( [ MoreComponentPatterns ] :ComponentPatterns |
    (Pattern
      [ ( "V" Pattern )
      [ (Pattern "," MoreComponentPatterns ) ] ]
        :MoreComponentPatterns |
45 ("{" ComponentExpressions "}"):Expression <Set> |
    // A set of Actors without duplicates
    ("{" ComponentPatterns "}"):Pattern <Set> |
46 ("{" ComponentExpressions "}"):Expression <Multiset> |
    // A multiset of the Actors with possible duplicates
    ("{" ComponentPatterns "}"):Pattern <Multiset> |
47 Optimization of this program is facilitated because:
    • The records are cacheable because their type is Set<ContactRecord>
    • All of the operators are cacheable
    • The operators are annotated as cacheable using "[..>"
48 ("Map" "{" ComponentExpressions "}"):Expression <Map> |
49 It is possible to define a procedure that will produce a "bottomless" future.
    For example, f.[ ]:Future<aType> ≡ Future f.[ ] |
50 (Postpone Expression <aType> |):Expression <Future<aType>> |
    // postpone execution of the expression until the value is needed.

```

⁵¹ (**"Future"** aValue:Expression<aType>
 ((**⊔** (**"sponsor"** Expression<Sponsor>))))
 :Expression<Future<aType>>|
 // A future for aValue.
 (**"↓"** ExpressionFuture<aType>>):Expression<aType>>|
 // Resolve a future

⁵² (LoopName:Identifier **"."** **"["** Initializers **"]"**
 ((**⊔** (**":"** Return Type:aType))
"⊔" Expression<aType>):Expressions<aType>|
 ((**⊔** MoreInitializers):Initializers|
 (Initializer **⊔** (Initializer **"."** MoreInitializers))
 :MoreInitializers|
 (Identifier (**⊔** (**":"** TypeExpression))) **"←"** Expression):Initializer|

⁵³ The implementation below requires careful optimization.

⁵⁴ (**"String"** **"["** ComponentExpressionns **"]"**):Expression<String>|
 (**"String"** **"["** ComponentPatterns **"]"**):Pattern<String>|

⁵⁵ (recipient:Expression<recipientType>
"." message:MessageExpression<recipientType>):Expression|
 // Send recipient the message

⁵⁶ /* A **Postpone** expression does not begin execution of Expression₁ until a
 request is received. Illustration:
 IntegersBeginningWith.**[n:Integer]:<FutureList<Integer> ≡**
[n, vPostpone IntegersBeginningWith.[n+1]]****|
 Note: A **Postpone** expression can limit performance by preventing
 concurrency */

⁵⁷ (**"("** MoreGrammars **)"**):Grammar|
 (**"("** Grammar **"⊔"** Grammar **)"**):Grammar|
 (ReservedWord (**⊔** StartsWithIdentifier)):StartsWithReserved|
 StartsWithReserved **⊔** MoreGrammars|
 (Identifier (**⊔** StartsWithReserved)):StartsWithIdentifier|
 StartsWithIdentifier **⊔** 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<Grammar> **"⊔"** Identifier<Grammar> **"|"**):Judgment|

⁵⁸ The implementation below can be highly inefficient.

⁶⁸ [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.

⁶⁹ 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].

⁷⁰ Execution can proceed differently depending on how sets fit into computer storage units.

⁷¹ /* Consider a dialect of Lisp which has a simple conditional expression of the following form:

(("(" "if" test:Expression then:Expression else:Expression)"))

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

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

```
(Eval expression environment) ≡
    // 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! */

⁷² The implementation **CheeseQ** uses activities to implement its queue where for type **Activity** the following holds:

```
Structure Activity[previous:≡ Nullable<Activity>,
    // if null then head of queue else,
    // pointer to backwards list to head
    nextHint:≡ Nullable<Activity>]
    // if non-null then pointer to next
    // activity to get cheese after this one
```

⁷³ If non-null points to head with current holder of cheese

⁷⁴ If non-null, pointer to backwards list ending with head that holds cheese

⁷⁵ Interface **CheeseQ** with **enter[] ↦ Void**,
leave[] ↦ Void

⁷⁶ // **enter** message received running myActivity

⁷⁷ // commentary for error checking

⁷⁸ `/* this cheese queue is not empty because myActivity is at the head of
the queue */`

⁷⁹ `Interface SubCheeseQ with head[] ↪ Activity`

⁸⁰ `Interface InternalQ with enqueueAndLeave[] ↪ Void,
enqueueAndDequeue[InternalQ] ↪ Activity,
dequeue[] ↪ Activity,
empty?[] ↪ Boolean`

⁸¹ `Interface SubInternalQ with add[Activity] ↪ Void,
remove[] ↪ Activity`

⁸² Used in type specifications for interfaces.

⁸³ Used in message handlers.

⁸⁴ Used to bind identifiers in **Let**.

⁸⁵ Three equal signs because two equal signs have a meaning in Java

⁸⁶ Used in patterns.

⁸⁷ Used in structures.

⁸⁸ Used in one-way message passing.