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

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ActorScript™ extension of C#®, Java®, Objective C®, C++, JavaScript®, and SystemVerilog using iAdaptive™ concurrency for antiCloud™ privacy and security:ⁱ One computer is no computer in IoT

Carl Hewitt

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

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

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

ActorScript is differentiated from previous programming languages by the following:

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

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

Java and JavaScript are registered trademarks of Oracle, Inc.

Objective C is a registered trademark of Apple, Inc.

ⁱⁱ with no single point of failure

- Safety, security and readability
 - Programs are *extension invariant*, i.e., extending a program does not change the meaning of the program that is extended.
 - Applications cannot directly harm each other.
 - Variable races are eliminated while allowing flexible concurrency.
 - Lexical singleness of purpose. Each syntactic token is used for exactly one purpose.
- Performanceⁱ
 - Imposes no overhead on implementation of Actor systems in the sense that ActorScript programs are as efficient as the same implementation in machine code. For example, message passing has essentially same overhead as procedure calls and looping.
 - Execution dynamically adjusted for system load and capacity (e.g. cores)
 - Locality because execution is not bound by a sequential global memory model
 - Inherent concurrency because execution is not limited by being restricted to communicating *sequential* processes
 - Minimize latency along critical paths

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

Message passing using types is the foundation of system communication:

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

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

ⁱ Performance can be tricky as illustrated by the following:

- "Those who would forever give up correctness for a little temporary performance deserve neither correctness nor performance." [Philips 2013]
- "The key to performance is elegance, not battalions of special cases" [Jon Bentley and Doug McIlroy]
- "If you want to achieve performance, start with comprehensible." [Philips 2013]
- Those who would forever give up performance for a feature that slows everything down deserve neither the feature nor performance.

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

Introduction

ActorScript is based on the Actor mathematical model of computation that treats "*Actors*" as the universal conceptual primitive of digital computation [Hewitt, Bishop, and Steiger 1973; Hewitt 1977; Hewitt 2010a]. Actors have been used as a framework for a theoretical understanding of concurrency, and as the theoretical basis for several practical implementations of concurrent systems.

ActorScript

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

This paper makes use of the following typographical conventions that arise from underlying namespaces for types, messages, language constructs, syntax categories, *etc.*¹

- type identifiers
 - blue for types in general (e.g., **Account**)
 - green for the special case of implementation types (e.g., **SimpleAccount**)
- program variables (e.g., **aBalance**)
- message names (e.g., **withdraw**)
- reserved words² for language constructs (e.g., **Actor**)
- logical variables (e.g., *x*)
- comments in programs (e.g. `/* this is a comment */`)

There is a diagram of the syntax categories of ActorScript in an appendix of this paper in addition to an appendix with an index of symbols and names along with an explanation of the notation used to express the syntax of ActorScript.³

Actors

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

The Actor model is a mathematical theory that treats "*Actors*" as the universal conceptual primitive of digital computation. The model has been used both as a framework for a theoretical understanding of concurrency, and as the theoretical basis for several practical implementations of concurrent systems. Unlike previous models of computation, the Actor model was inspired by

¹ The choice of typography in terms of font and color has no semantic significance. The typography in this paper was chosen for pedagogical motivations and is in no way fundamental. Also, only the abstract syntax of ActorScript is fundamental as opposed to the surface syntax with its many symbols, e.g., **→**, *etc.*

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

An Actor is a computational entity that, in response to a message it receives, can concurrently:

- send messages to addresses of Actors that it has
- create new Actors
- designate how to handle the next message it receives.

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

The Actor model can be used as a framework for modeling, understanding, and reasoning about, a wide range of concurrent systems. For example:

- Electronic mail (e-mail) can be modeled as an Actor system. Mail accounts are modeled as Actors and email addresses as Actor addresses.
- Web Services can be modeled with endpoints modeled as Actor addresses.
- Object-oriented programming objects with locks (e.g. as in Java and C#) can be modeled as Actors.

Actor technology will see significant application for coordinating all kinds of digital information for individuals, groups, and organizations so their information usefully links together. Information coordination needs to make use of the following information system principles:

- **Persistence.** *Information is collected and indexed.*
- **Concurrency:** *Work proceeds interactively and concurrently, overlapping in time.*
- **Quasi-commutativity:** *Information can be used regardless of whether it initiates new work or becomes relevant to ongoing work.*
- **Sponsorship:** *Sponsors provide resources for computation, i.e., processing, storage, and communications.*
- **Pluralism:** *Information is heterogeneous, overlapping and often inconsistent. There is no central arbiter of truth.*
- **Provenance:** *The provenance of information is carefully tracked and recorded.*

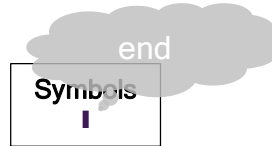
The Actor Model is designed to provide a foundation for inconsistency robust information coordination.

Notation

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

Expressions

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



Expressions evaluate to Actors. For example, $1+3$ █ⁱⁱⁱ is equivalent^{iv} to 4 █.

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

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

Types

Types are Actors. Type names are shown as follows:

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

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

ⁱ sometimes called "names"

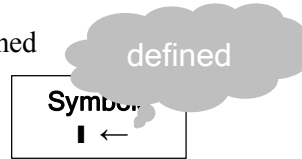
ⁱⁱ Furthermore, all special symbols have ASCII equivalents for input with a keyboard. An IDE can convert ASCII for a symbol equivalent into the symbol. See table in an appendix to this article.

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

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

Identifier Definitions, *i.e.*, \leftarrow

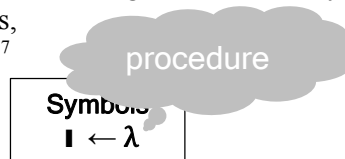
An identifier definition has an identifier to be defined followed by " \leftarrow " followed by the definition. For example, $x \leftarrow 3$ defines the identifier x to be the Actor 3.



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

Procedure Definitions, *i.e.*, \rightarrow

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 " λ ", followed by a procedure name, a list of formal arguments, return type, " \rightarrow " and body of the procedure.⁷ For example the procedure can be defined as follows:ⁱ



λ Double \equiv [v :Integer]:Integer \rightarrow v+v

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

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 "⁹ followed by a message with arguments delimited by "[" and "]". For example, Double. \cdot [2+1] means send Double the message [3]. Thus Double. \cdot [2+1] is equivalent to 6.

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

ⁱ Anonymous procedures are also allowed as in the following:

λ [v :Integer]:Integer \rightarrow v+v

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`.

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

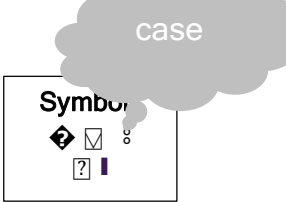
Cases, i.e., `⋄`, `⋄`, `⋄` `?`

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 "`?`".¹¹ A case consists of

- a pattern followed by ":" and an expression to compute the value for the case. *All of the patterns before an **else** case must be disjoint; i.e., it must not be possible for more than one to match.*
- optionally (at the end of the cases) *one or more* of the following cases: "**else**" followed by an optional pattern, ":", and an expression to compute the value for the case. An **else** case applies *only* if none of the patterns in the preceding 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: **12**.

ⁱ "`⋄`" is fancy typography for "`?`"

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

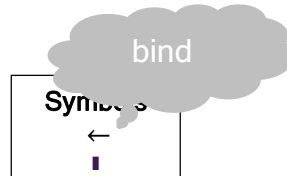
ⁱⁱⁱ As is standard, ActorScript uses the token "`///`" to begin a one-line comment.

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

Binding locals, i.e., Let ← .

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, "←", and an expression for the Actor to be matched. For example, aProcedure.["G", "F", "F"] is equivalent to the following:

```
Let x ← "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 ← "F".           // x is "F"  
  Let y ← aProcedure.["G", x, x].  
    // y is aProcedure.["G", "F", "F"]  
    anotherProcedure.[x, y]
```

The above is equivalent to

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

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

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

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

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

- [1, v[2, 3], 4] 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]

The formal syntax of list expressions is in the following end note: **15**.

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

- [[x, 2], vy] 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

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

λ Reverse<aType> \equiv
 $[aList:[aType^*]]:[aType^*] \rightarrow$
 aList \diamond
 $[] \circ [] \boxtimes$
 $[first, \forall rest] \circ [\forall rest, first] \text{ ? } \blacksquare^{16}$

Symbols

$\rightarrow \diamond \circ \leftarrow \lambda \forall$
 $\text{ ? } \blacksquare$

spread

The formal syntax of patterns is in the following end note: 17.

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

λ AlternateElements<aType> \equiv
 $[aList:[aType^*]]:[aType^*] \rightarrow$
 aList \diamond
 $[] \circ [] \boxtimes$
 $[anElement] \circ [anElement] \boxtimes$
 $[firstElement, secondElement] \circ [firstElement] \boxtimes$
 else \circ
 $[firstElement, secondElement, \forall remainingElements] \circ$
 $[firstElement, \forall AlternateElements.[remainingElements]] \text{ ? } \blacksquare^{18}$

Symbols

$\diamond \circ \boxtimes \forall$
 $\langle \rangle$
 $\text{ ? } \blacksquare$

spread

Consequently,

- AlternateElements<Integer>.[[]] \blacksquare is equivalent to $[]):[Integer^*] \blacksquare$
- AlternateElements<Integer>.[[3]] \blacksquare is equivalent to $[3]:[Integer^*] \blacksquare$
- AlternateElements<Integer>.[[3, 4]] \blacksquare is equivalent to $[3]:[Integer^*] \blacksquare$
- AlternateElements<Integer>.[[3, 4, 5]] \blacksquare is equivalent to $[3, 6]:[Integer^*] \blacksquare$

General Message-passing interfaces

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

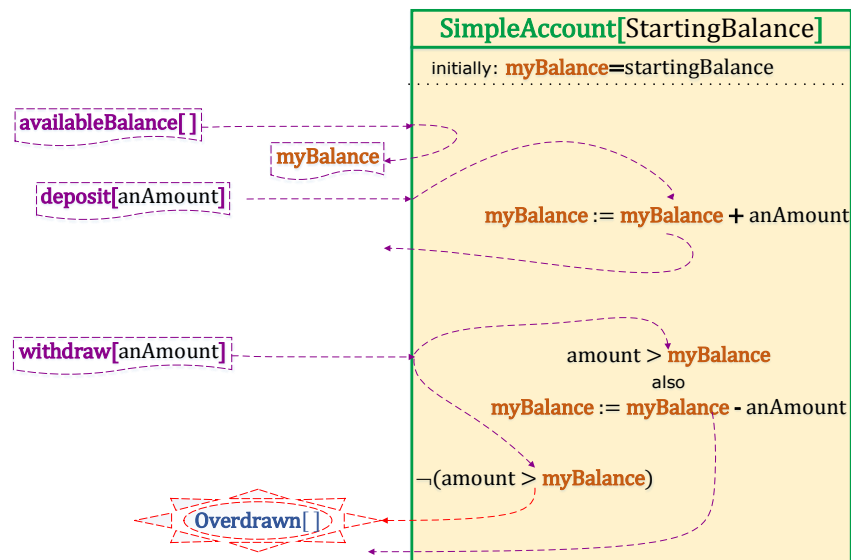
```
Interface Account with availableBalance[ ]→Euro,
                        deposit[Euro]→Void,
                        withdraw[Euro]→Void;
```

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

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

Message handlers in an Actor execute mutually exclusively while in a region of mutual exclusion which is called "cheese." In this paper assignable variables are colored orange, which by itself has no semantic significance, i.e., printing this article in black and white does not change any meaning. The use of assignments is strictly controlled in order to achieve better structured programs.¹⁹

Below is a diagram for the implementation SimpleAccount of Account:



Variable races are impossible in ActorScript

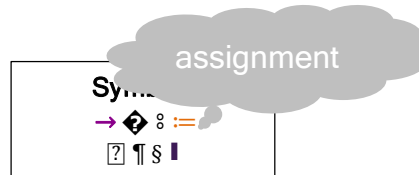
An Actor can be created using "Actor" optionally followed by the following:

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

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

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

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



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

myBalance := startingBalance.

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

implements **Account** using

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

deposit[anAmount:**Euro**]:**Void** →

Void // return **Void**

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

// the *next* message is processed with

// **myBalance** reflecting the deposit

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

(amount > **myBalance**) ⚡

True : Throw **Overdrawn**[] ☑

False : **Void** // return **Void**

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

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

As a result of the above definition,

Implementation SimpleAccount extends **Account**¶

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

ⁱ variable declarations separated by commas

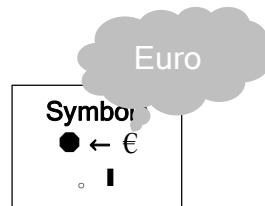
Antecedents, Preparations, and Necessary Concurrency, *i.e.*, $\textcircled{\bullet}$

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.availableBalance[ ]
```

The above expression returns €3.



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

Quasi-commutativity can be used to tame indeterminacy while at the same time facilitating implementations that run exponentially faster than those in the parallel lambda calculus.¹

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

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

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

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

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

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

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

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

As a result of the above definition:

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

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

```
Let anAccountSupervisor ← AccountSupervisor.[[€3]].  
  Let anAccount ← anAccountSupervisor.[[account]],  
    aRevoker ← anAccountSupervisor.[[revoker]].  
  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 exception29  
    // myBalance remains €1  
  anAccountSupervisor.withdrawFee[[€4]] ●  
    // €4 is withdrawn even though withdrawableIsRevoked  
    // myBalance is negative €3  
  anAccount.availableBalance[[ ]]
```

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

Type Extension

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

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

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

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

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

As a result of the above definition:

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

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

For example,

- "The" is equivalent to the following:
`Let Leaf[aString] ← Leaf["The"]. aString`
- `Leaf["The"].[hash]` is equivalent to `Hash.["The"]`.

For example,

`((Leaf["The"]):Tree).[hash]` is equivalent to `Hash.["The"]`.

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

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

As a result of the above definition:

Implementation structure Fork[Tree, Tree] extends Tree

For example, `Hash.[Hash.["The"], Hash.["boy"]]` is equivalent to the following:

`(Fork[Leaf["The"], Leaf["boy"]]).[hash]`

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

- `((Leaf["The"]):Tree)↓?Fork` is equivalent to **False**.
- `((Leaf["The"]):Tree)↓?Leaf` is equivalent to **True**.

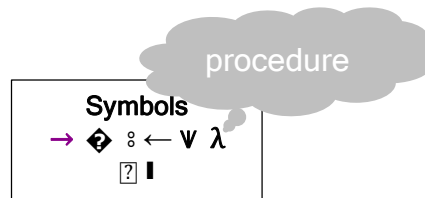
Conversion from of a type to an extension of the type is done using an expression of the extension can followed by "↓" and the type. For example,

- `((Leaf["The"]):Tree)↓Leaf` is equivalent to `Leaf.["The"]`.
- `((Leaf["The"]):Tree)↓Fork` throws an exception.

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

`λ Fringe ≡`

```
[aTree:Tree]:[String*] →
  aTree
  ↓↓Leaf[aString] : [aString]
  ↓↓Fork[left, right] :
    [VFringe.[left],
     VFringe.[right]]
```



For example, `[["The", "boy"]:String*]` is equivalent to the following:
`Fringe.[Fork[Leaf["The"], Leaf["boy"]]]`³²

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

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

Casting is as allowed only as follows:

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

Swiss cheese

Swiss cheese [Hewitt and Atkinson 1977, 1979; Atkinson 1980]³³ is a generalization of mutual exclusion with the following goals:

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

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

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

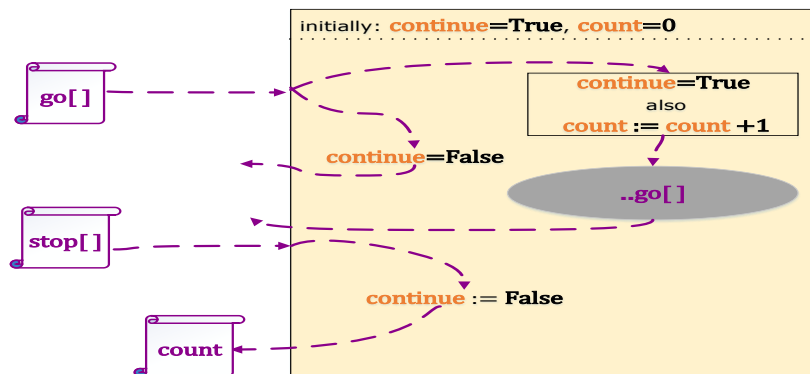
- **count** initially **0**
- **continue** initially **True**

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

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

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

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



λ CreateUnbounded \equiv

```

[ ]:Integer  $\rightarrow$ 
  Let aCounter  $\leftarrow$  Counter.[ ]. // 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 Counter:

Actor Counter[]

```

count := 0, // the variable count is initially 0
continue := True.
stop[ ]:Integer  $\rightarrow$  count // return count
  afterward continue := False!
  // continue is updated to False for the next message received
go[ ]:Void  $\rightarrow$ 
  continue  $\Leftarrow$ 
    True  $\circ$  Prep count := count+1  $\bullet$ . // increment count
    hole ..go[ ]  $\boxtimes$  // send go[ ] to this counter
    False  $\circ$  Void  $\boxtimes$ ! // if continue is False, return Void

```

Symbols	
\rightarrow	\Leftarrow
\circ	\boxtimes
\bullet	\boxtimes
\boxtimes	\boxtimes

As a result of the above definition

Implementation Counter has go[] \rightarrow Void,
 stop[] \rightarrow Integer!

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

Coordinating Activities

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

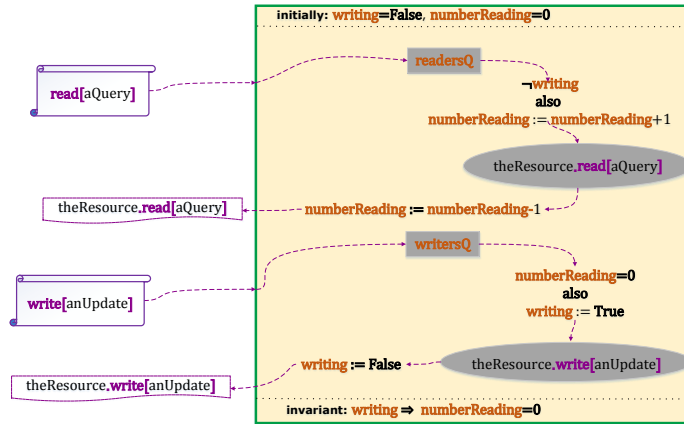
Below are two implementations of readers/writer guardians for a shared resource that implement different policies:³⁵

1. *ReadingPriority*: The policy is to permit maximum concurrency among readers without starving writers.³⁶
 - a. When no writer is waiting, all readers start as they are received.
 - b. When a writer has been received, no more readers can start.
 - c. When a writer completes, all waiting readers start even if there are writers waiting.
2. *WritingPriority*: The policy is that readers get the most recent information available without starving writers.³⁷
 - a. When no writer is waiting, all readers start as they are received.
 - b. When a writer has been received, no more readers can start.
 - c. When a writer completes, just one waiting reader is permitted to complete if there are waiting writers.

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

Interface ReadersWriter with `read[Query]→ QueryAnswer,`
`write[Update]→ Void`

Cheese diagram for **ReadersWriter** implementations:



Note:

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

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

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

ⁱ A variable is orange in the diagram

ⁱⁱ Of course, other external Actors can change.

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

Actor **ReadingPriority**[theResource:ReadersWriter]
 invariants **numberReading** ≥ 0 , **writing** \Leftrightarrow **numberReading** = 0.
 queues **readersQ**, **writersQ**. // **readersQ** and **writersQ** are initially empty
writing := False,
numberReading := 0.
 implements **ReadersWriter** using
read[aQuery:Query]:QueryAnswer \rightarrow

Symbols

\rightarrow \diamond \circ \square \wedge \vee \neg
 $?$ \uparrow $\$$ \mathbb{I}

Prep (**writing** \vee \neg IsEmpty **writersQ**) \diamond
 True \circ **Enqueue** **readersQ** // release cheese while in **readersQ**
 backout (\neg **writing** \wedge **numberReading** = 0 \wedge IsEmpty **readersQ**) \diamond
 True \circ Void **permit** **writersQ** \square
 False \circ Void $?$
 Void \square
 False \circ Void $?$.

Preconditions \neg **writing**. // commentary for error checking
 Prep **numberReading** ++ // increment **numberReading**
permit **readersQ**
 hole theResource.**read**[aQuery] // release cheese while reading
 afterward
 (IsEmpty **writersQ**) \diamond
 True \circ **Permit** **readersQ** also **numberReading** -- \square ³⁹
 False \circ
numberReading = 1 \diamond
 True \circ **Permit** **writersQ** also **numberReading** -- \square
 False \circ **numberReading** -- $?$ $?$ \uparrow

write[anUpdate:Update]:Void \rightarrow
 Prep (**numberReading** > 0 \vee \neg IsEmpty **readersQ** \vee **writing** \vee \neg IsEmpty **writersQ**) \diamond
 True \circ **Enqueue** **writersQ** // release cheese while in **writersQ**
 backout (IsEmpty **writersQ** \wedge \neg **writing**) \diamond
 True \circ Void **permit** **readersQ** \square
 False \circ Void $?$
 Void \square
 False \circ Void $?$.

Preconditions **numberReading** = 0, \neg **writing**. // commentary for error checking
 Prep **writing** := True. // record that writing is happening
 hole theResource.**write**[anUpdate] // release cheese while writing
 afterward (IsEmpty **readersQ**) \diamond
 True \circ **Permit** **writersQ** also **writing** := False \square
 False \circ **Permit** **readersQ** also **writing** := False $?$ $\$$ \mathbb{I}

Illustration of writing-priority:

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

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

queues **readersQ**, **writersQ**.

writing := False,

numberReading := 0.

implements **ReadersWriter** using

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

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

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

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

True \diamond : Void **permit writersQ** \square

False \diamond : Void \square

Void \square

False \diamond : Void \square .

Preconditions \neg **writing**. // commentary for error checking

Prep **numberReading**++.

permit IsEmpty writersQ \diamond

True \diamond : **readersQ** \square

False \diamond : Void \square

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

(IsEmpty **writersQ**) \diamond

True \diamond : **Permit readersQ also numberReading--** \square

False \diamond :

numberReading=1 \diamond

True \diamond : **Permit writersQ also numberReading--** \square

False \diamond : **numberReading--** \square \square \uparrow

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

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

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

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

True \diamond : Void **permit readersQ** \square

False \diamond : Void \square

Void \square

False \diamond : Void \square .

Preconditions **numberReading**=0, \neg **writing**.

// commentary for error checking

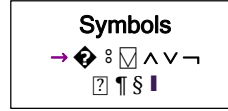
Prep **writing** := True.

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

(IsEmpty **readersQ**) \diamond

True \diamond : **Permit writersQ also writing := False** \square

False \diamond : **Permit readersQ also writing := False** \square \square \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.

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

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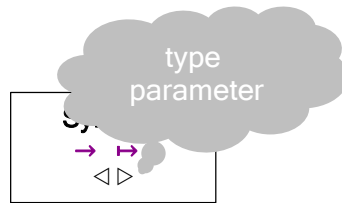
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Appendix 1. Extreme ActorScript

Parameterized Types, *i.e.*, \langle , \rangle

Parameterized Types are specialized using other types delimited by " \langle " and " \rangle ":



```
Actor Double<aType≡Arithmetic>  
  [x:aType]:aType → aType[x+x]§!  
  // addition for aType that is Arithmetic
```

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

```
Interface Graph<Graph, Edge, Vertex>  
  with [[vertices]] ↦ [Vertex*]!
```

```
Interface Edge<Graph, Edge, Vertex>  
  with [[graph]] ↦ Graph,  
       [[source]] ↦ Vertex,  
       [[target]] ↦ Vertex!
```

```
Interface Vertex<Graph, Edge, Vertex>  
  with [[graph]] ↦ Graph,  
       [[incoming]] ↦ [Edge*],  
       [[outgoing]] ↦ [Edge*]!
```

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

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

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

The formal syntax of parameterized types is in the following end note: 40 .

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

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

A discriminate can be constructed using the discrimination followed by "[", an expression for the discriminant and "]",

A discriminate can be projected as follows:

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

For example, consider the following definition:

Discrimination IntegerOrString between Integer, String|

Consequently,

- $(\text{IntegerOrString}[3])\downarrow\text{Integer}|$ is equivalent to $3|$.
- $(\text{IntegerOrString}["a"])\downarrow\text{Integer}|$ throws an exception because **String** is not the same as the discriminant **Integer**.
- $(\text{IntegerOrString}[3])\downarrow?\text{Integer}|$ is equivalent to **True|**.
- The *pattern* $x\downarrow\text{String}$ matches $\text{IntegerOrString}["a"]$ and binds x to "a".

- The expression below is equivalent to $2|$:

$\text{IntegerOrString}[3] \diamond y\downarrow\text{Integer} \circledast y-1 \square$
 $x\downarrow\text{String} \circledast x \square |$

The formal syntax of type discrimination is in following end note: **41**.

Structures

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

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

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

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

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

For example,

- The expression `Let xi ← 3. Terminal<Integer>[x]!` is equivalent to `Terminal<Integer>[3]!`
- The pattern `Terminal<Integer>[x]` matches `Terminal<Integer>[3]` and binds `x` to 3.

The structure `TrieFork` can be defined as follows:

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

ⁱ `x` is of type `Integer`

For example,

- The expression

Let $x \leftarrow 3$.

TrieFork[**Terminal**[x], **Terminal**[$x+1$]]⁴²

is equivalent to the following:

TrieFork[**Trie**[**Terminal**[5], **Trie**[**Terminal**[6]]]

- The pattern **TrieFork**<**Integer**>[x , y] matches

TrieFork[**Trie**[**Terminal**[5], **Trie**[**Terminal**[6]]]

and binds x to **Terminal**[5] and y to **Terminal**[6].

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

```

λ TrieFringe<aType> ≡
  [aTrie:Trie<aType>]:[aType*] →
  aTrie ↖
  Terminal<aType>[x] ⋮ [x] ▢
  TrieFork<aType>[left, right] ⋮
  [∀TrieFringe.[left], ∀TrieFringe<aType>.[right]] ?43

```

procedure

Symbols

→ ↖ ⋮ ← ∀ λ

? ▢

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

```

λ TrieSameFringe?<aType> ≡
  [left:Trie<aType>, right:Trie<aType>]:Boolean →
  // test if two Tries have the same fringe
  TrieFringe<aType>.[left] = TrieFringe<aType>.[right]44

```

The formal syntax of structures is in the following end note: 45

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

Nullable

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

In an expression,

- "**Nullable**" followed by an Expression is a non-null nullable.
- "**Null**" followed by a type is the nullable that is the null of that type.
- "⊙" followed by an expression for a nullable is the Actor in the nullable or throws an exception if and only if the nullable is null.

For example,

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

In a pattern,

- "⊙" followed by a pattern matches a nullable if and only if it is non-null and the pattern matches the Actor in the nullable.
- "**Null**" followed by a type only matches the null of the type.

For example,

- The pattern ⊙x matches **Nullable** 3, binding x to 3

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

Processing Exceptions, *i.e.*, Try catch 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  
  Exception[aString] : aString
```

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: 47.

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 ≥ 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 λ [y:Float]:Boolean → y < 1
```

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

Multiple implementations of a type

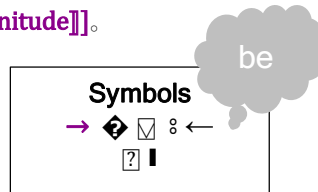
The interface type **Complex** is defined as follows:

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

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

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

```
  [[real]]:Float → myReal!
  [[imaginary]]:Float → myImaginary!
  [[magnitude]]:Float →
    SquareRoot.[myReal*myReal + myImaginary*myImaginary]!
  [[angle]]:Degrees →
    Let theta ← Arcsine.[myImaginary/.[[[magnitude]]].
    myReal>0 ◆
    True ∃ theta!
    False ∃
      myImaginary >0 ◆
      True ∃ 180°-theta!
      False ∃ 180°+theta ? ?!
```



Consequently,

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

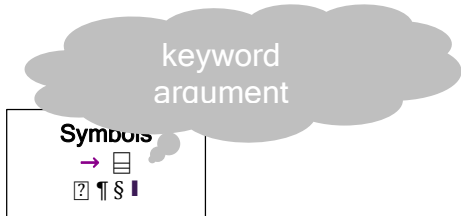
For example, cartesianans can be used in the following procedure definitions:⁵⁰

```
λ Times<Complex> ≡ [u:Complex, v:Complex]:Complex →
  Cartesian[u.[[[real]]]*v.[[[real]]] - u.[[[imaginary]]]*v.[[[imaginary]]],
  u.[[[imaginary]]]*v.[[[real]]] + u.[[[real]]]*v.[[[imaginary]]]!
```

```
λ Equivalent<Complex> ≡ [u:Complex, v:Complex]:Boolean →
  u.[[[real]]] = v.[[[real]]] ∧ u.[[[imaginary]]] = v.[[[imaginary]]]!
```

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

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



```
Structure Polar[angle⊞ _:Degrees default 0°,
// angle of type Degrees is a named argument of Polar with
// default 0°
magnitude⊞ _:Length default 1]
implements Complex using
[[real]:Float → magnitude*Sine.[angle]¶
[[imaginary]:Float → magnitude*Cosine.[angle]§¶
```

Consequently,

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

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

```
λ Times<Polar>≡
[Polar[angle⊞ anAngle, magnitude⊞ aMagnitude],
Polar[angle⊞ anotherAngle, magnitude⊞ anotherMagnitude]]
:Complex →
Polar[angle⊞ anAngle+anotherAngle,
magnitude⊞ aMagnitude*anotherMagnitude]¶52
```

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

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

A set is unordered with duplicates removed.

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

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

A set is unordered with duplicates allowed.

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

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 making use of the following:

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

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

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

```
{Number*} has average[] |>> Float
```

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

The program is as follows:⁵⁶

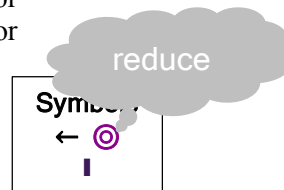
```

λ AgeWithAverageOfNumberOfContactsSortedByAge =
  [records:{ContactRecord*}:Sorted<Age> →
    records.filter [[aRecord:ContactRecord]
      ..> aRecord.[citizenship] ⚡
          "US" : True ☑
          else : False ?]
    .collect [[aRecord:ContactRecord]
      ..> [aRecord.[yearsOld],
          aRecord.[numberOfContacts]]]
    .reduceRange
      [[aSetOfNumberOfContacts:{Integer*}]
      ..> aSetOfNumberOfContacts.average[ ]]
    .sort[LessThanOrEqual<Age>]!
  
```

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

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 "reduce" a future by returning an Actor computed by the future or throwing an exception. For example, the following expression is equivalent to `Factorial.[9999]!`



```

Let aFuturei ← Future Factorial.[9999]。
☉aFuture! // do not proceed until Factorial.[9999] has
           // been reducedii
  
```

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

```

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

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.

Note that the following are all equivalent:

- \textcircled{F} Future (4+Factorial.[9999]) $\mathbf{!}$
- 4+ \textcircled{F} Future Factorial.[9999] $\mathbf{!}$
- 4+ \textcircled{F} Factorial.[9999] $\mathbf{!}$
- \textcircled{F} (4+Factorial.[9999]) $\mathbf{!}$

Also \textcircled{F} Factorial.[9999]+ \textcircled{F} Fibonacci.[9000] $\mathbf{!}$ is equivalent to the following:

```
Let n ←  $\textcircled{F}$ Factorial.[9999],
    m ←  $\textcircled{F}$ Fibonacci.[9000].
n+m $\mathbf{!}$  // return Factorial.[9999]+Fibonacci.[9000]
```

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

```
Let aFuture ← Future Factorial.[9999].
readCharacter.[ ]  $\diamond$ 
  'x'  $\textcircled{!}$  1 $\square$  // readCharacter.[ ] returned 'x'
  else  $\textcircled{!}$  1+  $\textcircled{aFuture}$   $\textcircled{?}$  $\mathbf{!}$ 
  // 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>⁵⁹ concurrently with its being created:

```
 $\lambda$  Size  $\equiv$  [aFutureList:FutureList<String>]:Integer  $\rightarrow$ 
aFutureList  $\diamond$ 
  []  $\textcircled{!}$  0 $\square$ 
  [first,  $\forall$ rest]  $\textcircled{!}$  first.[length] + Size.[ $\textcircled{rest}$ ]  $\textcircled{?}$  $\mathbf{!}$ 60
  // reducing a FutureList reduces only the head
```

Below is the definition of a procedure that postpones computation of a **FutureList** that is the "fringe" of a Trie.ⁱ

```
 $\lambda$  TrieFringe<aType>  $\equiv$  [aTrie:Trie<aType>]:FutureList<aType>  $\rightarrow$ 
aTrie  $\diamond$ 
Terminal<aType>[x]  $\textcircled{!}$  [x] $\square$ 
ForkTrie<aType>[left, right]  $\textcircled{!}$ 
  [ $\forall$ TrieFringe.[left],  $\forall$ Postpone61 TrieFringe<aType>.[right]]  $\textcircled{?}$  $\mathbf{!}$ 62
```

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

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

```

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

```

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

```

λ FutureListOfReducedElements<aType> ≡
  [aListOfFutures:[Future<aType>*]:FutureList<aType> →
    aListOfFutures ↯
    [] : []
    [aFirst, VaRest] :
      [⊙aFirst,
        VFuture FutureListOfReducedElements<aType>.[⊙aRest]] ]63

```

The formal syntax of futures is in the following end note: 64.

Language extension, i.e., ()

The following is an illustration of language extension that illustrates postponed execution:⁶⁵

```

Actor ("Postpone" anExpression:Expression<aType>)
  :Postpone<aType>

implements Expression<Future<aType>> using
  eval[e:Environment]:Future<aType> →
    Future Actor implements aType using
      aMessage → // aMessage received
      Let postponed ← anExpression.eval[e].
        postponed.aMessage
        // return result of sending aMessage to postponed
        become postponed$
        // become the Actor postponed for
        // the next message receivedi

```

The formal syntax of language extension is in the following end note: 66.

ⁱ this is allowed because postponed is of type aType

In-line Recursion (e.g., looping), i.e. $\lambda [\leftarrow , \leftarrow] \triangleq$

Inline recursion (often called looping) is accomplished using an initial invocation with identifiers initialized using " \leftarrow " followed by " \triangleq " 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 \leftarrow 9, accumulation \leftarrow 1] \triangleq
 n=1 \diamond True ε accumulation \boxtimes
 False ε Factorial_.[n-1, n* accumulation] \boxtimes ⁱⁱ

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

The following expression returns a list of ten times successively calling the parameterless procedure Pⁱⁱⁱ (of type $[\] \rightarrow$ Integer):

FirstTenSequentially_.[n \leftarrow 10] \triangleq
 n=1 \diamond True ε [P_.[$\]$] \boxtimes
 False ε Let x \leftarrow P_.[$\]$ \bullet .
 [x, \forall FirstTenSequentially_.[n-1]] \boxtimes ⁶⁷

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

OneOfTen_.[n \leftarrow 10] \triangleq
 n=1 \diamond True ε P_.[$\]$ \boxtimes
 False ε \oplus P_.[$\]$ either \oplus OneOfTen_.[n-1] \boxtimes ⁶⁸

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

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

ⁱⁱ equivalent to the following:

Factorial_.[n:Integer \leftarrow 9, accumulation:Integer \leftarrow 1]:Integer \triangleq
 n=1 \diamond True ε accumulation \boxtimes
 False ε Factorial_.[n-1, n* accumulation] \boxtimes ⁱⁱ

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

^{iv} The procedure P may be indeterminate, *i.e.*, return different results on different calls.

Strings

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

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

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

For example:

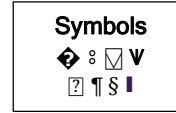
- `"x, "2", vy"` is a pattern that matches `"1234"` and binds `x` to `"1"` and `y` to `"34"`.
- `"1", "2", vOy"` is a pattern that only matches `"1234"` if `y` is `"34"`.
- `"vx, vy"` is an illegal pattern because it can match ambiguously.

As an example of the use of spread, the following procedure reverses a string:⁷⁰

```

λ Reverse ≡ [aString:String]:String →
  aString ↻
  " " : " " ↻
  "first, vrest" : "vrest, first" ↻

```



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

General Messaging, *i.e.*, . and ◎

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

For example, if anExpression is of type Expression<Integer> then,

```
anExpression.eval[anEnvironment]!
```

is equivalent to the following:

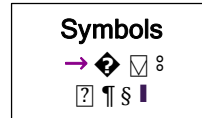
```

Let aMessage ← eval◎Expression<Integer>[anEnvironment]。
  anExpression.aMessage!

```

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

Atomic Operations, i.e. Atomic compare update updated notUpdated
 For example, the following example implements a lockable that spins to lock:⁷³



```

Actor SpinLock[ ]
  locked := False. // initially unlocked
  implements Lockablei using
  lock[ ]:Void →
    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.
      // commentary for error checking:
      // locked must have contents True
      Void □ // if updated return Void
      notUpdated ∃ Attempt.[ ] ? † // if not updated, try again
  unLock[ ]:Void →
    Preconditions locked =True. // commentary for error checking:
    // locked must have contents True
    Void afterward locked := False § † // reset locked to False
  
```

The formal syntax of atomic operations is in the following end note: 74.

ⁱ Interface **Lockable** with **lock[]** → **Void**,
unLock[] → **Void** †

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

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

For example,

```
Enumeration DayName of Monday, Tuesday, Wednesday, Thursday,  
Friday, Saturday, Sunday┆
```

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

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

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

UsingNamespace DayName┆

```
λ 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: 76.

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"].[]┆
```

ⁱ aRectangle is of type **Object** JavaScript

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

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

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

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

Java types can be 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`.

The following notation is used for XML:⁷⁷

```
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">`

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

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

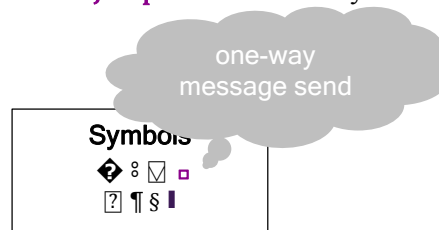
One-way messaging, e.g., Θ , and \square

One-way messaging is often used in hardware implementations.

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

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

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



```

Actor ArithmeticLogicUnit<aType>[]
  implements ALU<aType> using
    jumpGreater[x:aType, y:aType,
      firstGreaterAddress:Address, elseAddress:Address]: $\Theta$   $\rightarrow$ 
      InstructionUnit $\square$ Execute[(x>y)  $\diamond$ 
        True  $\diamond$  firstGreaterAddress $\square$ 
        False  $\diamond$  elseAddress  $\square$ ]  $\uparrow$ 
    addJumpPositive[x:aType, y:aType, sumLocation:Location<aType>,
      positiveAddress:Address, elseAddress:Address]: $\Theta$   $\rightarrow$ 
      Let z  $\leftarrow$  (x+y).
      sumLocation  $\diamond$ 
      aVariableLocation:VariableLocation<aType>i  $\diamond$ 
      Prep VariableLocation.store[z]  $\bullet$ .
      // continue after acknowledgement of store
      (z > 0)  $\diamond$  True  $\diamond$  InstructionUnit $\square$ execute[positiveAddress]  $\square$ 
      False  $\diamond$  InstructionUnit $\square$ execute[elseAddress]  $\square$   $\square$ 
      aTemporaryLocation:TemporaryLocation<aType>ii  $\diamond$ 
      Prep aTemporaryLocation $\square$ write[z].
      // continue concurrently with processing write
      (z > 0)  $\diamond$  True  $\diamond$  InstructionUnit $\square$ execute[positiveAddress]  $\square$ 
      False  $\diamond$  InstructionUnit $\square$ execute[elseAddress]  $\square$   $\square$   $\square$ 

```

ⁱ VariableLocation<aType> has store[aType] \rightarrow Void \mathbf{I}

ⁱⁱ TemporaryLocation<aType> has write[aType] \rightarrow Θ \mathbf{I}

The formal syntactic definition of one-way named-message and receiving is in the following end note: 78

Using multiple other implementations , *i.e.*, ☐

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

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

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

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

```
Actor Boy[aMagnitude:Meter, aLength:Year]
  uses Male[aMagnitude], Human[aLength]。
  // uses implementations Male and Human79
  [[magnitude]:Meter → (☐Male).[[length]]█
  // using this Actor with Male interface
  [[length]:Year → (☐Human).[[magnitude]]$█
  // using this Actor with Human interface
```

For example,

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

Inconsistency Robust Logic Programs

Logic Programs⁸⁰ 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:

$\vdash_t \text{Human}[\text{Socrates}] \blacksquare$

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

$\Vdash_t \text{Mortal}[\text{Socrates}] \blacksquare$

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 $t' \leftarrow \text{Extension}_\bullet[t]$.

$\vdash_{t'} \psi,$

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

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

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

ⁱ See appendix on Inconsistency Robust Natural Deduction.

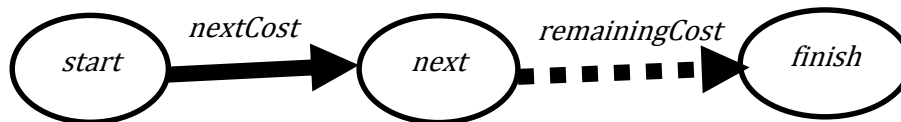
Aggregation using Ground-Complete Predicates

Logic Programs in ActorScript are a further development of Planner. For example, suppose there is a ground-complete predicate⁸¹ `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
```

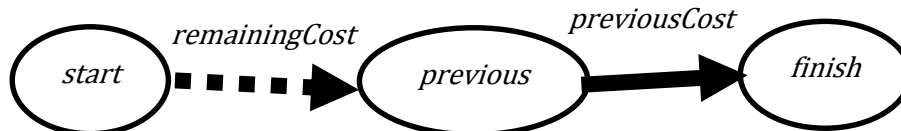
The following goal-driven Logic Program works forward from `start` to find the cost to `finish`:⁸²

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



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

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



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

Appendix 2: Meta-circular definition of ActorScript

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

The message `eval`

John McCarthy is justly famous for Lisp. One of the more remarkable aspects of Lisp was the definition of its interpreter (called Eval) in Lisp itself. The exact meaning of Eval defined in terms of itself has been somewhat mysterious since, on the face of it, the definition is circular.⁸³

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

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

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

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

```
Actor BasicExpression<aType> [ ]
    perform[e:Environment, c:CheeseQ] ->
        Try Let anActor ← [ Expression<aType>.eval[e] ]
            Prep c.release[ ].
            anActor
        cleanup c.release[ ]
```

ⁱ Interface `Construct`

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

```

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

The interface **Type**

The implementation **PrimitiveType** is defined as follows:

Implementation **PrimitiveType** partially implements **Type** with

```

extension?[Type] |..> Boolean,
has?[MethodSignature] |..> Boolean,
sendOneWay[aType⊃Type, Message] → ⊖,
sendRequest[aType⊃Type having aMessage→returnType,
             aMessage] → returnType,
encrypt[aType⊃Type] → Encrypted,
decrypt[Encrypted having decrypt[Encrypted] → aType] → aType,
return[Customer<aReturnType>, aReturnType] → Void,
throw[Customer, Exception] → Void!i
  
```

Implementation **Encrypted** has

```

// Encrypted is a primitive implementation type
decrypt[Type having decrypt[Encrypted] → aType] → aType!
// ∀[t: Type, x:t] → t.encrypt[x].decrypt[t] = x
  
```

CommunicationType is a restriction of **Type** that can be used only for communication:

Interface **CommunicationType** restricts **Type** using

```

sendOneWay[aType⊃Type, Message] → ⊖,
sendRequest[aType⊃Type having aMessage→returnType,
             aMessage] → returnType,
return[Customer<aReturnType>, aReturnType] → Void,
throw[Customer, Exception] → Void!
  
```

ⁱ For example, **recipientType** could be **DepositOnlyAccount** and **aMessage** could be **Message**<**DepositOnlyAccount**, **deposit**[**Euro**] → Void> where

```

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

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

Interface **SendingType** restricts **CommunicationType** using

```
sendOneWay[Type having aMessage→Θ,  
aMessage] → Θ,  
sendRequest[Type having aMessage→returnType,  
aMessage] → returnType
```

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

Type Discrimination

Interface **DiscriminationType** extends **Type** with

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

```
Actor (anExpression:Expression<aType>  
"↑" castExpression:Type<aDiscriminationType>)  
:DiscriminationUp<aType, aDiscriminationType>  
  
uses BasicExpression<aType>[]  
partially implements Expression<aType> using  
eval[e:Environment]:aType →  
castExpression.eval[e].up[anExpression.eval[e]]
```

```

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

```

```

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

```

```

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

```

```

Actor
("↓↓" aStructurePattern: Pattern <aStructureType>)
    : DiscriminationPatternDownDown <aStructureType,
                                     aDiscriminationType>

uses BasicPattern <aStructureType> [ ]
partially implements Pattern <aStructureType> using
    match [anActor: DiscriminationStructureInstance <aType,
                                                         aDiscriminationType>,
            e: Environment]: Nullable <Environment> →
    structurePattern.match [aDiscriminationStructureInstanceType
                            .down [anActor],
                            e] |

```

```

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

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

```

```

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

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

```

Type restriction

```
Interface RestrictionType<aType>  
  extends Type with up[aType] → RestrictionType<aType> |
```

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

```
Actor ("Interface" aRestrictionType  
  "restricts" typeExpression: Type <aType>  
  "with" signatureExpressions: Signatures "I"): Definition  
Actor implements Definition using  
eval[e: Environment]: Environment →  
  Let signatures ← signatureExpressions.eval[e].  
  Preconditions typeExpression.eval[e].has?[signatures].  
  e.bind[aRestrictionType,  
    type ⊔ RestrictionType<aType>,  
    to ⊔  
  Actor implements RestrictionType<aType> using  
    up[anInstance: aType]: aRestrictionType →  
      RestrictionInstance[anInstance] |
```

```
Structure RestrictionInstance[anInstance: aType] uses BasicType [ ]  
partially reimplements  
  RestrictionType<aType> having  
    (aMessage → aReturnType) ∈ signatures) > using  
sendRequest[aRecipient: aRestrictionType,  
  aMessage: aMessage]: aReturnType →  
  aRecipient ◆  
  ↓↓ RestrictionInstance[anInstance] :  
    sendRequest[anInstance, aMessage] ☒  
  else : Throw CastException [ ] ? |  
sendOneWay[aRecipient: aRestrictionType,  
  aMessage: aMessage]: ⊖ →  
  aRecipient ◆  
  ↓↓ RestrictionInstance[anInstance] :  
    sendOneWay[anInstance, aMessage] ☒  
  else : Throw CastException [ ] ? |
```


Type extension

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

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

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

```
Actor  
(("↑↑" aPattern: Pattern <aStructureExtensionType>> )  
  : StructureExtensionPatternUpUP <anExtensionType, aBaseType>  
uses BasicPattern <aStructureExtensionType> [ ]  
partially implements Pattern <aStructureExtensionType> using  
  match[anActor: StructureExtensionInstance <anExtensionType,  
    aBaseType>,  
    e: Environment]: aType →  
  aPattern.match[aStructureExtensionType.up[anActor], e]!
```

```

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

```

```

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

```

```

Actor
("↓↓" aStructurePattern: Pattern <aStructureExtensionType>)
      : ExtensionPatternDownDown <aBaseType, aStructureExtensionType>
uses BasicPattern <aStructureExtensionType> [ ]
partially implements Pattern <aStructureExtensionType> using
  match[anActor: ExtensionStructureInstance <aType,
    aStructureExtensionType>,
    e: Environment]: Nullable <Environment> →
  aStructurePattern..match[aStructureExtensionType..down[anActor],
    e]

```

```

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

```

```

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

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

```

Nullable, e.g., \odot

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

Implementation **Nullable** \langle aType \rangle has
reduce[] \rightarrow aType!

```
Actor ("Nullable" anExpression: Expression <aType>)
                                     : Nullable <aType>
uses BasicExpression <Nullable <aType>> [ ]
partially implements Expression <Nullable <aType>> using
eval[e: Environment]: Nullable <aType>  $\rightarrow$ 
  Let anActor  $\leftarrow$  anExpression.eval[e]  $\bullet$ .
  Actor implements Nullable <aType> using
    reduce [ ]: aType  $\rightarrow$  anActor!
```

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

```
Actor (Null aType: Type <aType>): NullPattern <aType>
implements Pattern <Nullable <aType>> using
  match[anActor: Nullable <aType>, e: Environment]
    : Nullable <Environment>  $\rightarrow$ 
  anActor  $\Leftrightarrow$ 
    Null aType.eval[e]  $\ni$  Nullable e  $\boxtimes$ 
    else  $\ni$  Null Environment [ ]!
```

```
Actor (" $\odot$ " anExpression: Expression <Nullable <aType>>)
                                     : NullableReduction <aType>
uses BasicExpression <aType> [ ]
partially implements Expression <aType> using
eval[e: Environment]: aType  $\rightarrow$ 
  ((anExpression.eval[e])  $\downarrow$  Nullable <aType>).reduce [ ]!
```

Future, e.g., \odot , and \oplus

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

Implementation **Future** $\langle aType \rangle$ has
reduce $[] \rightarrow aType$!

```
Actor ("Future" anExpression: Expression <aType>))
                                     :Future <aType>
uses BasicExpression<Future<aType>>[ ]
partially implements Expression<Future<aType>> using
eval[e:Environment]:Future<aType> →
  Let aFuture ←
    Future Try anExpression.eval[e]
    catch ⚡
      anException :
        Actor
          implements Future<aType> using
            reduce[ ]:aType →
              Throw anException$?.
  Actor implements Future<aType> using
    reduce[ ]:aType →  $\odot$ aFuture $!
```

```
Actor (" $\odot$ " anExpression: Expression <Future<aType>>))
                                     :FutureReduction <aType>
uses BasicExpression<aType>[ ]
partially implements Expression<aType> using
eval[e:Environment]:aType →
  anExpression.eval[e].reduce[ ]$!
```

```
Actor (" $\oplus$ " anExpression: Expression <aType>))
                                     :Mandatory <aType>
uses BasicExpression<aType>[ ]
implements Expression<aType> using
eval[e:Environment]:aType →
   $\odot$ Future anExpression.eval[e] $!
```

The message **match**

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

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

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

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

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

Message sending, e.g.,

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

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

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

List Expressions and Patterns

```

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

```

```

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

```

```

Actor ("[" first:Pattern<aType> ","
      "∨" rest:Pattern<[aType*> "]" ):Pattern <[aType*>
implements Pattern<[aType*> using
match[anActor:aType, e:Environment]:Nullable<Environment> →
anActor ◆
[first, ∨rest]:[aType*] §
first.match[first, e] ◆
Null Environment § Null Environment ☑
⊙aNewEnvironment §
rest.match[restValue, aNewEnvironment] ?☑
else § Null Environment ?§I

```


Exceptions

```

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

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

```

```

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

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

```

Continuations using perform

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

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

```

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

```

Atomic compare and update

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

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

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

Cases

```

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

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

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

```

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

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

```

Holes in the cheese

```
Actor (anExpression: Expression <aType>
      "afterward" someAssignments: Assignments " ")
      : Afterward <aType>

implements Continuation <aType> using
perform[e: Environment, c: CheeseQ]: aType →
  Let anActor ← anExpression.eval[e] ●
  Prep someAssignments.carryOut[e, c] ●
  c.release[] ●
  anActor$!
```

```
Actor (aVariable: Variable <aType>
      "!=" anExpression: Expression <aType>): Assignment

implements Assignment using
carryOut[e: Environment]: Void →
  e.assign[aVariable, to ⊔ anEpression.eval[e]]$!
```

```
Actor ("Hole" anExpression: Expression <aType>): Hole <aType>

implements Continuation <aType> using
perform[e: Environment, c: CheeseQ]: aType →
  Let frozenEnvironment ← e.freeze[] ●
  // create frozen environment so that subsequent assignments
  // subsequent assignments do not affect evaluating anExpression
  Prep c.release[] ●
  anExpression.eval[frozenEnvironment]$!
```

```

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

```

```

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

```

```

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

```

```

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

```

```

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

```

```

Actor ("Enqueue" anExpression: QueueExpression "●"
      aContinuation: Continuation <aType>): Enqueue <aType>
implements Continuation <aType> using
perform[e: Environment, c: CheeseQ]: aType →
  Let anInternalQ ← anExpression.eval[e].
  Prep anInternalQ.enqueueAndLeave[ ] ●.
  aContinuation.perform[e, c] §1

```


A Simple Implementation of Actor

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

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

```
Actor Initialized<aType>
[anInterface:aType,
 handlers:[Handler*],
 e:Environment,
 c:CheeseQ]:aType →
  Actor implements anInterface using
  receivedMessage:Type →
    // receivedMessage received for anInterface
    Prep c.acquire[ ] ●。
    Let aReturned ←
      Try Select.[receivedMessage, handlers, e, c]
      cleanup c.release[ ] ●。
    // release cheese and rethrow exception
    Prep c.release[ ] ●。
    aReturned$!
```

Actor Select

```
[receivedMessage:Message,  
 handlers:[Handler*],  
 e:Environment,  
 c:Queue]:aType →  
 handlers ↕  
 [] : Throw MessageRejected[]  
 [(aMessageDeclaration:MessageDeclaration <aType>  
   ":" ReturnDeclaration <aType> "→"  
   body:Continuation <aType>)  
   :ContinuationHandler <aType>]  
  
 vrestHandlers] :  
 aMessageDeclaration.match[receivedMessage, e] ↕  
   Null Environment :  
     Select.[receivedMessage, restHandlers, e, c] ↕  
       // process next handler  
     @newEnvironment :  
       Execute <aType>.[body, newEnvironment, c] [??] |
```

An implementation of cheese that never holds a lock

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

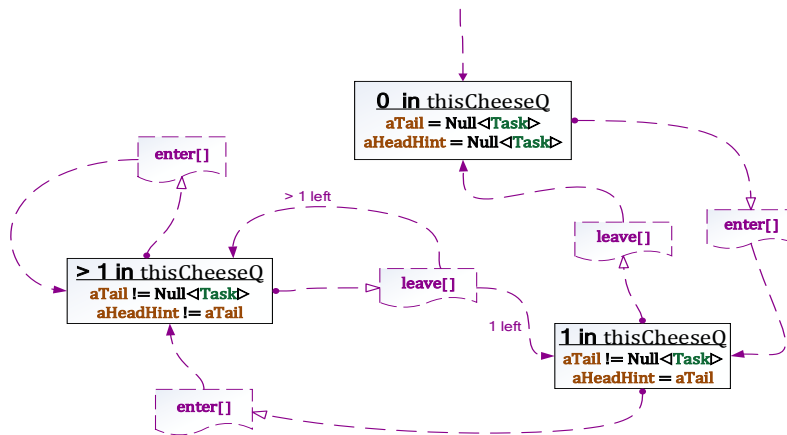
```

Actor CheeseQ[ ]
  invariants aTail=Null Activity ⇒ previousToTail=Null Activity。
  aHeadHint := Null Activity,           // aHeadHint:Nullable<Activity>84
  aTail := Null Activity。              // aTail:Nullable<Activity>85
  acquire[ ]:Void nonexclusive in myActivity →86
    Preconditions myActivity.#[previous]= Null Activity,
                  myActivity.#[nextHint]= Null Activity。
                                     // commentary for error checking
    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 : Void ☑ // successfully entered cheese
                  else : Suspend [?] ☑ // current activity is suspended
        notUpdated : attempt.[ ] [?] ! // make another attempt
  release[ ]:Void nonexclusive in myActivity →
                                     // release message received running myActivity
  Preconditions aTail≠Null Activity。87 // 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]
                 afterward aHeadHint := ahead.#[nextHint] [?] $
  internal SubCheeseQ using // internal interface
  [head]:Activity nonexclusive →
  Preconditions aTail≠Null Activity。 // commentary for error checking
  findHead.[backIterator:Activity] ←
    aHeadHint ◆
    Null Activity : @aTail ☑
    @anActivity : anActivity [?]:Activity ≜
  backIterator.#[previous] ◆
  Null Activity : // backIterator is head of this cheese queue
  Prep aHeadHint := Nullable backIterator ●。
    backIterator ☑
  @previousBackIterator :
    // 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:



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

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

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

Implementation Activity has

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

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

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

```

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

```

where

```

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

```

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

Symbol	IDE ASCII ⁱ	Read as	Category	Matching Delimiters	Unicode (hex)
⏏	;;	end	top level terminator		25AE
:	:	of specified type	infix		
⌈	[:]	this Actor with interface (aspect)	prefix		2360
⊙	\o ⁸⁸	reduce (nullables, futures)	prefix		29BE
↓	\v/	down	infix		2193
↓?	\v/?	down query	infix		
↓↓	\v/\v/	match downed	prefix		
↑	(^)	up	infix		2191
⊙	(.)	qualified by	infix		22A1
λ	/\	procedure	prefix	λ and →	03BB
≡	===	defined as	infix		2261
▪	.	is sent	infix		
▪▪	..	send to this Actor	prefix		2025
Ⓟ	\p ⁸⁹	necessarily concurrent	prefix		29B7
↪	->	message type returns type ⁹⁰	infix		21A6
↪	\>	cacheable ↪			
→	-->	message received ⁹¹		¶	2192
←	<--	be ⁹²	infix		2190
⊙	?	cases	separator	?	FFFD
⊙	[∨]	alternative case	separator	⊙ and ?	29B6
⊙	[?]	end cases	terminator	⊙ and catch⊙	2370
¶	\p ⁹³	another message handler	separator for handlers	→	00B6
§	\s	end handlers	terminator	implements and extension	00A7
⋮	(:)	case	separator for case		2982
●	_/	before	separator	Let binding, preparation, and Enqueue	2BC3
▼	\∨	variable dependency	separator	preparation	25BC
◦	\.	end	terminator	preparations, Preconditions, extends, and ⋮	FF61
≡	=/\=	to be	infix		225C


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

$\text{:}=\text{}$	$\text{:}=\text{}$	is assigned	infix		2254
O	$\backslash\text{O}^{\text{94}}$	matches value of ⁹⁵	prefix		2315
=	=	same as?	infix		
\neq	$\text{!}=\text{}$	Different from?	infix		2260
[]	$\text{[}=\text{]}$	keyword or field	infix		2338
$\text{:}[\text{[]}]$	$\text{:}[\text{=}]\text{}$	assignable field	infix		
< 	< 	begin type parameters	left delimiter	> (Unicode hex: 0077)	0076
\ /	\ /	spread ⁹⁶	prefix		2A5B
$\text{\{}$	$\text{\{}$	begin set	left delimiter	$\text{\}}$	
[[begin list	left delimiter	 	
$\text{\{ }$	$\text{\{ }$	begin multi-set	left delimiter	$\text{\} }$	2983
[]	[formatted message	left delimiter]	27E6
""	\ "	Left string structure	left delimiter	""	201C
((begin grouping	left delimiter)	
((begin syntax	left delimiter)	2985
(-)	(-)	nothing ⁹⁷	expression		229D
\.	\.	one-way send	infix		219E
 	 	join	infix		2294
[<=]	[<=]	constrained by	infix		2291
[>=]	[>=]	extends	infix		2292
=>	=>	logical implication	infix		21E8
<=>	<=>	logical equivalence	infix		21D4
\^	\^	logical conjunction	infix		00D9
\vee	\vee	logical disjunction	infix		00DA
\neg	- 	logical negation	prefix		00D8
\vdash	 -	assert	prefix and infix		22A2
\Vdash	 -	goal	prefix and infix		22A9
//	//	begin 1-line comment	prefix	EndOfLine	
/*	/*	begin comment	prefix	*/	

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End Notes

¹ Quotation by the author from late 1960s.

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

³ The delimiters `(` and `)` are used to delimit program syntax with the character `"` and the character `"` to delimit tokens. For example, `(3 "+" 4)` is an expression that can be evaluated to 7. A special font is used for syntactic categories.

For example,

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

Also,

```
(Numerical "-" Numerical):Numerical |
("-" Numerical):Numerical |
(Numerical "*" Numerical):Numerical |
(Numerical "/" Numerical):Numerical |
("Remainder" Numerical "/" Numerical):remainder:Numerical |
("QuotientRemainder" Numerical "/" Numerical)
:[Numerical, Numerical] |
("True" ⊔ "False"):Expression <Boolean> |
(Expression <Boolean> "∧" Expression <Boolean>)
:Expression <Boolean> |
(Expression "∨" Expression):Expression <Boolean> |
("¬" Expression <Boolean>):Expression <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 ≡ Word ≡ Expression |
```

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

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

⁵ `(Type ← Expression <Type>):Definition |`

```
(messageType:Type ("↳" ⊔ "↳") returnType:Type):Type |
```

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

```
( ⊔ MoreTypes):Types |
```

```
(Type ⊔ (Type ", " MoreTypes)):MoreTypes |
```

⁶ $((Identifier \langle aType \rangle \leftarrow Expressions \langle aType \rangle): Definition \mid$
 $((Expression \langle aType \rangle (\sqcup \text{"."})))$
 $\sqcup (Expression (\text{","} \sqcup \text{"\bullet"})) MoreExpressions \langle aType \rangle))$
 $: Expressions \langle aType \rangle \mid$
 $((Expression \langle aType \rangle \text{"."}))$
 $\sqcup (Expression (\text{","} \sqcup \text{"\bullet"})) MoreExpressions \langle aType \rangle))$
 $: MoreExpressions \langle aType \rangle \mid$

⁷ Generalization of the notation of [Church 1932].

⁸ $((\lambda (\sqcup ProcedureName \text{"="}))$
 $[" ArgumentDeclarations "]" (:" Type \langle returnType \rangle) \rightarrow$
 $Expression \langle returnType \rangle): Definition \mid$
 $ProcedureName \sqsubseteq Expression \mid$
 $(\sqcup MoreDeclarations): ArgumentDeclarations \mid$
 $(SimpleDeclaration (\sqcup (\text{","} MoreKeywordDeclarations)))$
 $\sqcup (SimpleDeclaration \text{","} MoreDeclarations))$
 $: MoreDeclarations \mid$
 $// Comma is used to separate declarations.$
 $((Identifier (\sqcup \text{"default"} Expression)): SimpleDeclaration \mid$
 $(KeywordArgumentDeclaration$
 $\sqcup (KeywordDeclaration \text{","} MoreKeywordDeclarations))$
 $: MoreKeywordDeclarations \mid$
 $(Keyword \text{"\equiv"} SimpleDeclaration)): KeywordDeclaration \mid$
 $Keyword \sqsubseteq Word \mid$

⁹ The symbol \bullet is fancy typography for an ordinary period when it is used to denote message sending.

¹⁰ $((Recipient: Expression \text{"\bullet"} [" Arguments "]"): ProcedureSend \mid$
 $ProcedureSend \sqsubseteq Expression \mid$
 $// Recipient is sent a message with Arguments$
 $(\sqcup MoreArguments): Arguments \mid$
 $((Expression (\sqcup (\text{","} MoreKeywordArguments))))$
 $\sqcup (Expression \text{","} MoreArguments)): MoreArguments \mid$
 $(KeywordArgument$
 $\sqcup (KeywordArgument$
 $\text{","} MoreKeywordArguments)): MoreKeywordArguments \mid$
 $(Keyword \text{"\equiv"} Expression): KeywordArgument \mid$

$(Identifier \langle Procedure \rangle$
 $[" ArgumentDeclarations "]" ":" returnType: Type \langle aType \rangle \rightarrow$
 $Expressions \langle aType \rangle \text{"\bullet"}): Definition \langle Procedure \rangle \mid$

¹¹ ? solves the infamous "dangling else" problem [Abrahams 1966].

```

12 (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> |
13 ("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 |
14 (recipient:Expression
    "." MessageName "[" Arguments " ]"):NamedMessageSend |
NamedMessageSend ⊆ Expression |
// Recipient is sent message MessageName with Arguments
MessageName ⊆ Word |
("Interface" Identifier> "with"
    MessageHandlerSignatures " | "):InterfaceDefinition |
InterfaceDefinition ⊆ Definition |

```

```

(⊔ MoreMessageHandlerSignatures))
    :MessageHandlerSignatures!
(MessageHandlerSignature
  (⊔ MoreMessageHandlerSignatures))
    :MoreMessageHandlerSignatures!
(MessageName [" ArgumentTypes "] (">"⊔|>")
  returnType:Type):MessageHandlerSignature !
MessageHandlerSignature ⊆Expression !
15 ("[" ComponentExpressions<aType> "]" )
    :Expression<[aType*]>!
    // An ordered list with elements ComponentExpressions
(⊔ MoreComponentExpressions<aType> )
    :ComponentExpressions<aType>!
(((⊔ "v") Expression<aType> )
  ⊔ ((⊔ "v") Expression<aType>
    ", " MoreComponentExpressions<aType> )))
    :MoreComponentExpressions<aType>!
([" TypeExpressions<aType> "]" ):TypeExpression<aType>!
(⊔ MoreTypeExpressions<aType> ):TypeExpressions<aType>!
(TypeExpression<aType>
  ⊔ (TypeExpression<aType> ", " MoreTypeExpressions<aType> ))
    :MoreTypeExpressions<aType>!
16 Equivalent to the following:
λ Reverse<aType> ≡
[aList:[aType*] ]:[aType*] →
aList ↔
[ ]:[aType*] ⊗ [ ]:[aType*] ⊗
[first, vrest]:[aType*] ⊗ [vrest, first]:[aType*] ⊗ !
17 ("_"):UnderscorePattern !
UnderscorePattern ⊆Pattern !
Identifier ⊆Pattern !
(Pattern "thatIs" Expression ):ThatIs !
ThatIs ⊆Pattern !
("∘" Expression<aType> ):Pattern<aType>!
([" ComponentPatterns<aType> "]" ):Pattern<[aType*]>!
    // A pattern that matches a list whose elements match
    // ComponentPatterns
(⊔ MoreComponentPatterns<aType> )
    :ComponentPatterns<aType>!

```

```

((Pattern <aType>
  ⌊ ("V" Pattern <aType>)
  ⌊ (Pattern <aType> "," MoreComponentPatterns <aType>))
    :MoreComponentPatterns <aType>

```

¹⁸ Equivalent to the following:

```

λ AlternateElements<aType> ≡ [aList:[aType*]],[aType*] →
aList ⋄
  []:[aType*] ⋄ []:[aType*] ⋄
  [anElement]:[aType*] ⋄ [anElement]:[aType*] ⋄
  [firstElement, secondElement]:[aType*] ⋄
  [firstElement]:[aType*] ⋄
  else ⋄
  [firstElement, secondElement, VremainingElements]:[aType*] ⋄
  [firstElement,
    VAlternateElements,[remainingElements]],[aType*] ⋄

```

¹⁹ Dijkstra[1968] famously blamed the use of the goto as a cause and symptom of poorly structure programs. However, assignments are the source of much more serious problems.

²⁰ Continuations in ActorScript are related to continuations introduced in [Reynolds 1972] in that they represent a continuation of a computation. The difference is that a continuation of Reynolds is a procedure that has as an argument the result of the preceding computation. Consequently, a continuation of Reynolds is closer to a customer in the Actor Model of computation.

```

21 ("Actor" ConstructorDeclaration ActorBody):Expression
  // The above expression creates an Actor with
  // declarations for variables and message handlers
  ( ⌊ ("uses" ConstructorList) ))
  ( ⌊ "management" Expression <Management> )
  NamedDeclaration
  MessageHandlers
  InterfaceImplementations):ActorBody
(Identifier" <" ParametersDeclarations ">"
  ( ⌊ ("[" ArgumentDeclarations "]" ) ))
    :ConstructorDeclaration
(Constructor ( ⌊ ". " )
  ( ⌊ (Constructor " , " MoreConstructors " . " ) ):ConstructorList
(Constructor
  ⌊ (Constructor " , " MoreConstructors ) ):MoreConstructors
(ActorQueues NamesDeclarations):NamedDeclaration
( ⌊ (MoreNameDeclarations " . " ) ):NamesDeclarations

```

```

(NameDeclaration
  ⊔ (NameDeclaration
    ", " MoreNamesDeclarations)):MoreNameDeclarations ⊐
(Identifier
  "←" Expression<aType>):IdentifierDeclaration ⊐
IdentifierDeclaration ⊆ NameDeclaration ⊐
(Variable
  "!=" Expression<aType> InstanceVariableQualifications)
  :VariableDeclaration ⊐
VariableDeclaration ⊆ NameDeclaration ⊐
Variable ⊆ Word ⊐
InstanceVariableQualifications ⊆ InstanceQualifications ⊐
( ⊔ InstanceVariableQualification
  ⊔ ( InstanceVariableQualification
    InstanceVariableQualifications)
    :InstanceVariableQualifications ⊐
"nonpersistent" ⊆ InstanceVariableQualification ⊐
  // A nonpersistent variable must be Nullable,
  // and can be nulled out before a message is received
("queues" 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 "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> ⊐
22 ("Prep" MoreAntecedents".
  Continuation <aType>"."):Preparation <aType> ⊐
(Antecedent ⊔ ( Antecedent ("," ⊔ "●") MoreAntecedents))
                                     :MoreAntecedents ⊐

Expression ⊆ Antecedent ⊐
StructureAssignment ⊆ Antecedent ⊐
ArrayAssignment ⊆ Antecedent ⊐

```

²³ For example, consider the following:

```

Actor NeedTwo[]
  queues waiting.
  hasOne := False.
  go[]:Void → hasOne ⇨ True ∃ Void permit waiting ☐
                False ∃ Prep hasOne := True ●.
                enqueue waiting ●
                Void ☐§!

```

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

```

Let aNeedTwo ← NeedTwo.[]
  Prep @aNeedTwo.go[] ●.
  aNeedTwo.go[]!

```

However following expression might never return because of optional concurrency:

```

Let aNeedTwo ← NeedTwo.[]
  Prep aNeedTwo.go[] ●.
  aNeedTwo.go[]!

```

²⁴ ("@" anExpression:Expression <aType>
 ((⊔ ("sponsor" Expression <Sponsor>I)):Expression <aType>I
 // Execute anExpression in parallel and respond with the outcome.
 // In every case, anExpression must complete before execution leaves
 // the lexical scope in which it appears.

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

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

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

²⁸ equivalent to the following:

```

myBalance ◦ SimpleAccount :=
  myBalance ◦ SimpleAccount - anAmount

```

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

³⁰ ("Enqueue" QueueExpression "●"
 Continuation <aType>):Continuation <aType>I
 /*
 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> "s"
  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" "s" ExpressionsContinuation<aType>)
  ⊔ ("else" Pattern<patternType> "s"
    ExpressionsContinuation<patternType, aType>))
  :ContinuationElseCase<patternType, aType>|
(((Continuation ( ⊔ "。"))
  ⊔ (Expression ("," ⊔ "●") MoreExpressionsContinuation))
  :ExpressionsContinuation |
(((Continuation"。")
  ⊔ (Expression"," MoreExpressionsContinuation))
  : MoreExpressionsContinuation |

```

³¹ Equivalent to the following:

```
λ Fringe ≡ [aTree:Tree]:[String*] →
  aTree ◊
  Leaf[aString] § [aString]:[String*] ◻
  Fork[left, right] §
  [∀Fringe.[left], ∀Fringe.[right]]:[String*] ? ◻
```

³² Equivalent to the following:

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

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

```
34 (".." Message <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 */
```

³⁵ ReadersWriterConstraintMonitor defined below monitors a resource and throws an exception if it detects that ReadersWriter constraint is violated, e.g., for a resource r using the above scheduler:

```
ReadingPriority[ReadersWriterConstraintMonitor[r]].
Actor ReadersWriterConstraintMonitor[theResource:ReadersWriter]
  writing := False,
  numberReading := 0.
implements ReadersWriter using
  read[aQuery:Query]:QueryAnswer
  Preconditions ¬writing. // commentary for error checking
  Prep numberReading++ ●.
  hole theResource.read[aQuery]
  afterward numberReading-- ◻
  write[anUpdate:Update]:Void →
  Preconditions numberReading=0, ¬writing.
  Prep writing := True ●.
  hole theResource.write[anUpdate]
  afterward writing := False ● § ◻
```

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

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

³⁸ ("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 release the
 cheese.
 5. If no exception is generated by the activity while in the queue,
 then when allowed to continue, re-acquire the cheese to
 perform Continuation. */
 Cases can be continuations:
 (test:Expression <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 release the
       cheese and return the value of Expression. */
  VariableAssignments:Afterward |
  ("Permit" aQueue:Expression <FIFO>
    ( ( ( "also" VariableAssignments ))):Afterward |
```

The following can be used temporarily release 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. */
```

³⁹ -- is postfix decrement

```

40 ((Identifier<Type>
    "<" ParametersDeclarations">"
    Expressions ):ParameterizedDefinition |
ParameterizedDefinition ⊆ Definition |
// Parameterize definition with ParametersDeclarations |
( ⊔ MoreParameterDeclarations ):ParametersDeclarations |
(ParameterDeclaration
    ⊔ (ParameterDeclaration
        "," MoreParameterDeclarations)))
    :MoreParameterDeclarations |
(Identifier<Type> ( ⊔ Qualifier )):ParameterDeclaration |
( ⊔ ("extends" Type )):TypeQualifier |
(Identifier<Type> "<" Parameters">"):TypeExpression |
(Identifier<Type>
    ⊔ ( ⊔ (Identifier<Type> "," Parameters ))) :Parameters |
41 ("Discrimination" Identifier<Type>
    MoreTypeDiscriminations "!" ):Definition |
(Identifier<Type>
    ⊔ (Identifier<Type> "," MoreTypeDiscriminations))
    :MoreTypeDiscriminations |
(Expression <DiscriminationType> "↓" Type <aType>)
    :Expression <aType> |
// Discriminate to have the type Type <aType> if possible.
// Otherwise, an exception is thrown.
(Expression <aDiscriminationType> "↓?" Type <aType>)
    :Expression <Boolean> |
// If Expression discriminates to have the type Type <aType>,
// then True, else False.
(Pattern <DiscriminationType> "↓" 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
42 Equivalent to the following:
Let x ← 3.
TrieFork <Integer> [Terminal <Integer> [x] ↑Trie <Integer>,
Terminal <Integer> [x+1] ↑Trie <Integer> ] |

```

⁴³ Equivalent to the following:

```
λ TrieFringe<aType> ≡ [aTrie:Trie<aType>]:[aType*] →
  aTrie ↯
  ↯Terminal<aType>[x] ⋈ [x]:[aType*] ↯
  ↯TrieFork<aType>[left, right] ⋈
  [∀TrieFringe.[left],
   ∀TrieFringe<aType>.[right]]:[aType*] ? !
```

⁴⁴ Equivalent to the following:

```
λ TrieSameFringe?<aType> ≡
  [left:Trie<aType>, right:Trie<aType>]:Boolean →
  TrieFringe.[left] = TrieFringe.[right] !
```

⁴⁵ (*Identifier*<aType> "[" Arguments"]"):Expression<aType> !

(*Identifier*<aType> "[" Patterns"]"):Pattern<aType> !

⁴⁶ ("Nullable" Expression<aType>):Expression<Nullable<aType>> !

("⊙" Expression<Nullable<aType>>):Expression<aType> !

// reduce Expression if not null.

// Otherwise, an exception is thrown.

("⊙" Pattern<aType>):Pattern<Nullable<aType>> !

// If matching Actor is a non-null nullable

// then Pattern must match the Actor in the nullable.

⁴⁷ ("Try" anExpression:Expression<aType>

"catch↯" ExpressionCases<Exception, aType> "?")

:Expression<aType> !

/*

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

("Try" anExpression:Expression<aType>

"catch↯" ContinuationCases<Exception, aType> "?")

:Continuation<aType> !

/*

- If anExpression throws an exception that matches the pattern of a case, then the response of *TryContinuation* is the response computed by the expression of the case.
- If aContinuation doesn't throw an exception, then then the response of *TryExpression* is the response computed by anExpression. */

```

("Try" anExpression:Expression <aType>
  "cleanup" cleanup:Expression <aType>):Expression <aType> |
/*
  • If anExpression throws an exception, then the value of
    TryExpression is the value computed by cleanup.
  • If anExpression doesn't throw an exception, then then the
    value of TryExpression is the value computed by
    anExpression. */
48 ("Preconditions" test:Expressions <Boolean> " "
  Expressions <aType>):Expression <aType> |
  // Each of expressions in test must evaluate to True or
  // an exception is thrown
("Preconditions" Expressions <Boolean> " "
  ExpressionsContinuation <aType>):Continuation <aType> |
  // Each of expressions in Expressions must evaluate to True or
  // an exception is thrown
(value:Expression <aType>
  "postcondition" pre:Expression <[aType]→Boolean>
  :Expression <aType> |
  // The expression pre must evaluate to True when sent value
  // or an exception is thrown
49 ° is a reserved postfix operator for degrees of angle
50 Using parameterized procedures like the ones below can improve the
  simplicity and effectiveness of types by comparison with other approaches
51 Equivalent to the following:
  λ Times ≡ [u:Complex, v:Complex]:Complex →
    Cartesian[u.[real]*v.[real] - u.[imaginary]*v.[imaginary],
      u.[imaginary]*v.[real]
      + u.[real]*v.[imaginary]]↑Complex |
52 Equivalent to the following:
  λ Times ≡ [Polar[angle□ anAngle, magnitude□ aMagnitude],
    Polar[angle□ anotherAngle,
      magnitude□ anotherMagnitude]]:Complex →
    Polar[angle□ anAngle+anotherAngle,
      magnitude□ aMagnitude*aMagnitude]↑Complex |
53 ("Structure" Identifier <Type> "[" FieldDeclarations "]"
  ( ⊔ ("uses" ConstructorList ))
  NamedDeclaration
  MessageHandlers
  MoreInterfaceImplementations):Definition |
  // Structure definition with StructureImplementation
  (anExpression:Expression <anotherType> "↓" Type <aType>)
  :Expression <aType> |

```

```

(anExpression:Expression<anotherType>>
  "↓?" Type<aType>):Expression<Boolean>┆
  // If anExpression is an extension of aType, then True else False
(aPattern:Pattern<anotherType>>
  "↓" Type<anotherType>):Pattern<aType>┆
  // Matching Actor must be an extension of aType which
  // matches aPattern
("↓↓" Type<Extension<anotherType>>):Pattern<aType>>┆
  // Matching Actor must be an extension of aType
(┆ MoreFieldDeclarations):FieldDeclarations┆
((SimpleFieldDeclaration
  (┆ (" MoreNamedFieldDeclarations)))
  ┆ (SimpleFieldDeclaration
    ", MoreFieldDeclarations)):MoreFieldDeclarations┆
((Identifier
  (┆ "default" Expression)):SimpleFieldDeclaration┆
(NamedFieldDeclaration
  ┆ (NamedFieldDeclaration
    ", MoreNamedFieldDeclarations))
    :MoreNamedFieldDeclarations┆
(FieldName
  ("┆" ┆":┆") SimpleFieldDeclaration))
    :NamedFieldDeclaration┆
FieldName┆QualifiedName┆
  // ":┆" is used for assignable fields.
((┆ Identifier) ActorBody):StructureImplementation┆
(Expression "[" FieldName "]" ):FieldSelector┆
  // FieldName of Expression which must be a structure
FieldSelector┆Expression┆
(StructureName "[" FieldExpressions "]" ):StructureExpression┆
StructureExpression┆Expression┆
(┆ MoreFieldExpressions):FieldExpressions┆
((SimpleFieldExpression(┆ (" MoreNamedFieldExpressions)))
  ┆ (SimpleFieldExpression
    ", MoreFieldExpressions)):MoreFieldExpressions┆
(NamedFieldExpression
  ┆ ( NamedFieldExpression
    ", MoreNamedFieldExpressions))
    :MoreNamedFieldExpressions┆
(FieldName
  ("┆" ┆":┆") SimpleFieldExpression))
    :NamedFieldExpression┆

```

```

(StructureName "[" FieldPatterns "]" ):StructurePattern |
StructurePattern ⊆ Pattern |
( ⊔ MoreFieldPatterns ):FieldPatterns |
(((SimpleFieldPattern( ⊔ ("," MoreNamedFieldPatterns))))
 ⊔ ( SimpleFieldPattern "," MoreFieldPatterns))
:MoreFieldPatterns |

(NamedFieldPattern
 ⊔ ( NamedFieldPattern
    "," MoreNamedFieldPatterns))
:MoreNamedFieldPatterns |

(FieldName ("⊔" ⊔ ":"⊔) SimpleFieldExpression))
:NamedFieldPattern |

```

⁵⁴ ("{" ComponentExpressions "}"):Expression<{aType*}> |
// A set of Actors without duplicates

("{" ComponentPatterns "}"):Pattern<{aType*}> |

⁵⁵ ("{" ComponentExpressions "}"):Expression<{aType*}> |
// A multiset of the Actors with possible duplicates

("{" ComponentPatterns "}"):Pattern<{aType*}> |

⁵⁶ Optimization of this program is facilitated because:

- The records are cacheable because their type is {ContactRecord*}
- All of the operators are cacheable
- The operators are annotated as cacheable using "|.>"

⁵⁷ ("Map" "{" ComponentExpressions "}"):Expression<Map> |

⁵⁸ It is possible to define a procedure that will produce a "bottomless" future.

For example, Actor f []:Future<aType> → Future f.[] |

⁵⁹ An Actor 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>>.

⁶⁰ Equivalent to the following:

λ Size ≡ [aFutureList:FutureList<String>]:Integer →

aFutureList ⇔

[]:FutureList<String> ⋮ 0

[first, vrest]:FutureList<String> ⋮

first.[length]+Size.[rest][] |

⁶¹ (Postpone Expression<aType>):Expression<Future<aType>> |

// postpone execution of the expression until the value is needed.

⁶² Equivalent to the following:

```
λ TrieFringe<aType> ≡ [aTrie:Trie<aType>]:FutureList<aType> →
  aTrie ◊
  ↓↓Terminal<aType>[x] ∶ [x]:[aType*] ◻
  ↓↓ForkTrie<aType>[left, right] ∶
    [vTrieFringe.[left]],
    vPostpone TrieFringe<aType>.[right]:[aType*] ? ◻
```

⁶³ Equivalent to the following:

```
λ FutureListOfReducedElements<aType> ≡
  [aListOfFutures:[Future<aType>*]:FutureList<aType> →
  aListOfFutures ◊
  []:[Future<aType>*] ∶ []:FutureList<aType> ◻
  [aFirst, vRest]:[Future<aType>*] ∶
  [⊙aFirst,
  vFuture FutureListOfReducedElements<aType>.[⊙aRest]]
  :FutureList<aType> ? ◻
```

⁶⁴ ("Future" aValue: Expression<aType>

```
(( ⊔ ("sponsor" Expression<Sponsor>))))
:Expression<Future<aType>> ◻
// A future for aValue.
```

```
("⊙" Expression Future<aType>>):Expression<aType> ◻
// Reduce a future
```

⁶⁵ A **Postpone** expression does not begin execution of Expression₁ until a request is received as in the following example:

```
λ IntegersBeginningWith ≡ [n:Integer]:<FutureList<Integer>> →
  [n, vPostpone IntegersBeginningWith.[n+1]] ◻
```

Note: A **Postpone** expression can limit performance by preventing concurrency

```
66 ("(" MoreGrammers ")"):Grammar ◻
("(" Grammar "⊔" Grammar ")"):Grammar ◻
(ReservedWord ( ⊔ StartsWithIdentifier )):StartsWithReserved ◻
StartsWithReserved ⊆ MoreGrammers ◻
(Identifier ( ⊔ StartsWithReserved )):StartsWithIdentifier ◻
StartsWithIdentifier ⊆ MoreGrammers ◻
("\ "" 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 ◻
```

⁶⁷ Equivalent to the following:

```
FirstTenSequentially.n ← 10:Integer* ≜  
  n=1 ⇨ True ∶ P.[ ]:Integer* ✓  
  False ∶ Let x ← P.[ ] ●.  
    [x, ∀FirstTenSequentially.n-1]:Integer* ? |
```

⁶⁸ Equivalent to the following:

```
OneOfTen.n:Integer ← 10:Integer ≜  
  n=1 ⇨ True ∶ P.[ ] ✓  
  False ∶ ⊕P.[ ] either ⊕OneOfTen.n-1 ? |
```

⁶⁹ (LoopName:Identifier " " [" Initializers " "
 (⊔ (":" Return Type:aType))
 " ≜" Expression <aType>):Expressions <aType> |
 (⊔ MoreInitializers):Initializers |
 (Initializer ⊔ (Initializer " " MoreInitializers))
 :MoreInitializers |
 (Identifier " ←" Expression):Initializer |

⁷⁰ The implementation below requires careful optimization.

```
71 (" " ComponentExpressions " "):Expression <String> |  
  (" " ComponentPatterns " "):Pattern <String> |
```

```
72 (recipient:Expression <recipientType>  
  " " message:MessageExpression <recipientType>):Expression |  
  // Send recipient the message
```

⁷³ The implementation below can be highly inefficient.

```
74 ("Atomic" aLocation:Expression <anotherType>  
  "compare" comparison:Expression <anotherType>  
  "update" update:Expression <anotherType> " ⇨"  
  "updated" " ∶"  
    compareIdentical:ExpressionsContinuation <aType> " ✓"  
  "notUpdated" " ∶"  
    compareNotIdentical:ExpressionsContinuation <aType> " ?")  
    :Continuation <aType> |
```

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

```
75 (Identifier "" Qualifier):QualifiedName |  
  QualifiedName ⊆ Expression |  
  Identifier ⊆ QualifiedName |  
  (Identifier ⊔ (Identifier "" Qualifier)):Qualifier |
```

⁷⁶ ("Enumeration" Identifier<IdentifierType>
 MoreEnumerationNames"."):Definition I
 (EnumerationName
 ⊔ (EnumerationName
 "," MoreEnumerationNames)):MoreEnumerationNames I
 EnumerationName ⊆ Word I

⁷⁷ Declarations provide version number, encoding, schemas, etc.

⁷⁸ (recipient:Expression
 "□" MessageName "[" Arguments "]):Expression <Void> I
 /* recipient is sent one-way message with MessageName and
 Arguments. Note that Expression <⊖> cannot be used to
 produce a value. */
 (MessageName "[" ArgumentDeclarations "]" ":" "⊖"
 (⊔ ("sponsor" Identifier<IdentifierType>)))
 "→" ExpressionsContinuation <⊖>):MessageHandler I
 /* one-way message handler implementation with
 ArgumentDeclarations that has a one-way continuation
 that returns nothing */
 ("⊖" (⊔ ("permit" aQueue:Expression))
 (⊔ ("afterward" Afterward))):Continuation <⊖> I

⁷⁹ note the absence of "□" in the **implementation** subexpressions

⁸⁰ [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.

⁸¹ 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].

⁸² Execution can proceed differently depending on how sets fit into computer storage units.

⁸³ /* Consider a dialect of Lisp which has a simple conditional expression of the following form:

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

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

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

```
Define (Eval expression environment)
    // Eval of expression using environment defined to be
    (if (Numberp expression)           // if expression is a number then
        expression                     // return expression else
        (if ((Equal (First expression) (Quote if))
            // if First of expression is "if" then
            (if (Eval (First (Rest expression) environment)
                // if Eval of First of Rest of expression is True then
                (Eval (First (Rest (Rest expression)) environment)
                    // return Eval of First of Rest of Rest of expression else
                    (Eval (First (Rest (Rest (Rest expression)) environment))
                        // return Eval of First of Rest of Rest of Rest of expression
                    ...)))
```

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

⁸⁴ If non-null points to head with current holder of cheese

⁸⁵ If non-null, pointer to backwards list ending with head that holds cheese

⁸⁶ // **acquire** message received running myActivity

⁸⁷ /* this cheese queue is not empty because myActivity is at the head of the queue */

⁸⁸ Not to be confused with \0 which is the null character or with \o which is \circ .

⁸⁹ Not to be confused with \p which is ¶

⁹⁰ Used in type specifications for interfaces.

⁹¹ Used in message handlers.

⁹² Used to bind identifiers in **Let**.

⁹³ Not to be confused with \P which is Ⓟ

⁹⁴ Not to be confused with \0 which is the null character or with \O which is Ⓞ.

⁹⁵ Used in patterns.

⁹⁶ Used in structures.

⁹⁷ Used in one-way message passing.