An abstract behavioral model of distributed concurrent objects (1)

Einar Broch Johnsen

Dept. of Informatics, University of Oslo
Email: einarj@ifi.uio.no

COST Action IC0701 Winter School
on Verification of Object-Oriented Programs

Viinistu, Estonia, Jan 27 2009

Creol at a glance

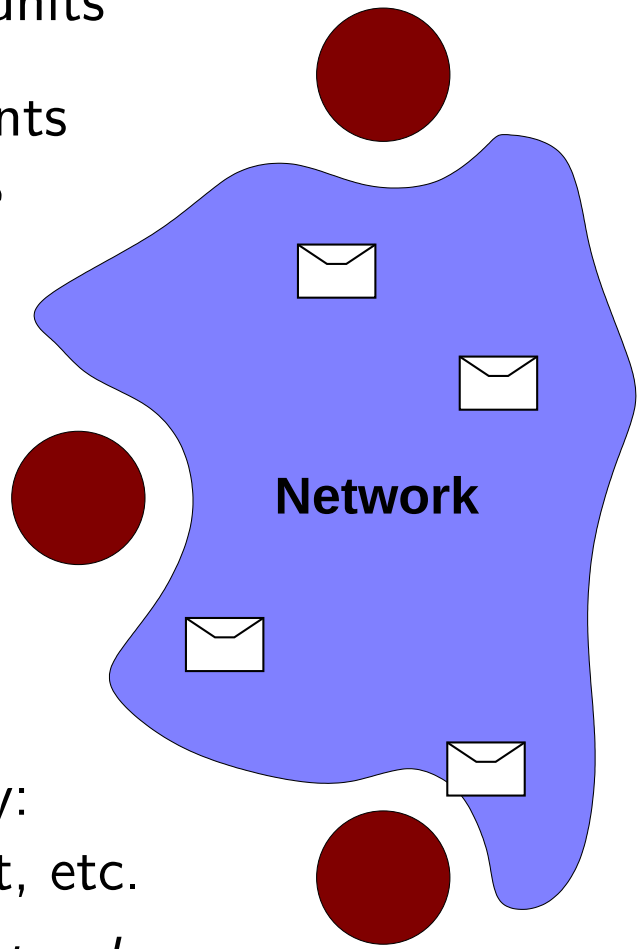
- An executable OO modelling language
- Formally defined semantics in rewriting logic
- Targets open distributed systems
- Abstracts from the particular properties of the (object) scheduling and of the (network) environment
- The language design should support verification

Talk Overview

- Distributed concurrent objects in Creol
- Semantics and execution platform
- Reasoning about Creol models
- Runtime evolution of Creol models

Open Distributed Systems

- Consider systems of communicating software units
- **Distribution**: geographically spread components
  - Networks may be *asynchronous* and *unstable*
  - Component availability may vary over time
- **Evolution**: systems change at runtime
  - New requirements / bug fixes
  - Changing environments
  - Mars Rovers reprogrammed 11 times since landing on Mars!
- ODS *dominate* critical infrastructure in society: bank systems, air traffic control, e-government, etc.
- ODS: *complex*, *error prone*, and *poorly understood*



Objects, Concurrency, Distribution

Goal:
Formal object-oriented framework to model and reason about ODS

Design issues

- **Interacting software units**: objects exchanging method calls
- **Concurrency**: threads, race conditions, scheduling, ...
- **Distribution**: data sharing and synchronization between objects
- **Openess**: Software units provided by other parties, upgrades, ...

High-Level Executable Modeling

Specification level	Specification formalism examples
Design–oriented	UML/OCL, State diagrams
Abstract behavioral	Creol
Implementation–oriented	SPEC#, Java+JML
Implementation	Java, ...

Levels of abstraction in (models of) object–oriented software systems

- OO: the dominant paradigm today
- Model between a design and an implementation language
- Abstraction: Nondeterministic behavior
  - Abstracts from specific network solutions and protocols
  - Abstracts from specific scheduling policies in objects
- Abstraction: Local computation uses ADTs (no rep. objects)
- Executable semantics, directly supports simulation / testing
- Abstract behavioral specifications will be further developed in Hats!

Shared Variables and Concurrency (1)

$\langle$**thread 1** : $x := x + 2\rangle$

$\langle$**thread 2** : $x := x - 3\rangle$

- $x = 5$

What are the possible values for x after execution?

- $x = 4$
- $x = 2$
- $x = 7$

To control the outcomes of the execution, we need a **locking discipline**!

Concurrency in the OO setting

Qualified name space: Threads operate on the object state

$\langle$**thread 1** : $o.x := o.x + 2\rangle$

$\langle$**thread 2** : $o.x := o.x - 3\rangle$

- $o.x = 5$

Methods: Threads correspond to method activations

```
class C
begin
  var x : T := 5
  op m1() == x := x + 2
  op m2() == x := x - 3
end
```

- $o.x = 5$

- May have a **dynamic number** of method activations!
- To regain control, we need a locking discipline again!

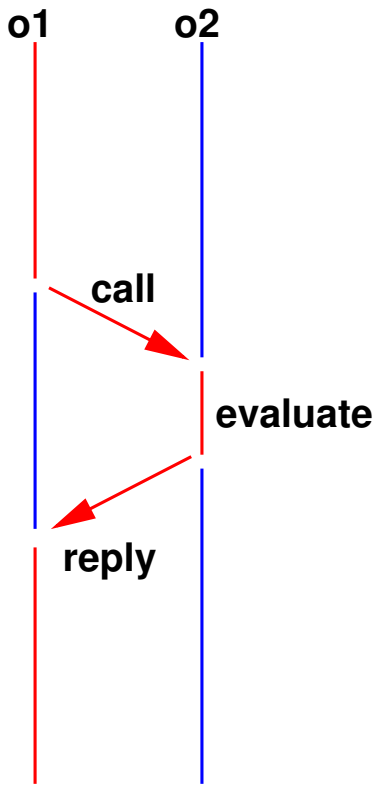
Shared Variables and Concurrency (2)

- **Concurrent systems**
- Challenging to maintain a consistent state!
- Necessary for **reasoning control**
- Solution: **locks**
  - **Interleaved atomic sections**: less non-determinism
  - Locks enforce very **low-level** style of programming!
  - Easy to make **mistakes**
  - Semaphores, monitors
  - Problem to ensure enough signalling (try to prove this!)
- **"Synchronized" methods** (Java)
  - The (synchronized) threads use a **per-object object**
  - Not all methods need to be synchronized
  - Very coarse-grained
  - What happens if a method gets "stuck"?

Shared Variables and Concurrency (3)

- Modern approaches are more high-level
- Harder to make mistakes, easier for the programmer (?)
- **Ownership systems**
- **Transactional memory systems**
- **Distribution still a challenge**
  - Do we keep multiple copies of objects in the state?
  - Ownership, transactional memory, locking disciplines...
    can be used to allow under-the-hood sharing
  - We here abstract from data sharing in the distributed setting
  - Focus on concurrency and synchronization aspects
- **Distributed systems based on message passing**
  - No shared state between different objects
  - All interaction by (asynchronous) message passing
  - But what about method calls?
  - ...and synchronization?

Method Calls and Distribution



Our approach

- Show / exploit distribution!
- **Asynchronous method calls**
  - more efficient in distributed environments
  - *triggers* of concurrent activity
- **Special cases:**
  - *Asynchronous message sending:*
    the caller doesn't care about the reply
  - *Synchronized communication:*
    the caller decides to wait for the reply
  - *Sequential computation:*
    only synchronized computation

Active and Passive Objects

Passive objects

- Execute their methods in the caller's thread of control (e.g., Java)
- In multithreaded applications, we must take care of proper synchronization
- If two objects call the same object, race condition may occur

Active (or concurrent) objects

- Execute their methods in their own thread of control (e.g., Actors)
- Communication is asynchronous
- Call and return are decoupled (in Creol: future variables)
- Usually, active objects use cooperative multitasking
- Cooperative multitasking is specified using schedulers

Creol: A Concurrent Object Model

Some underlying assumptions

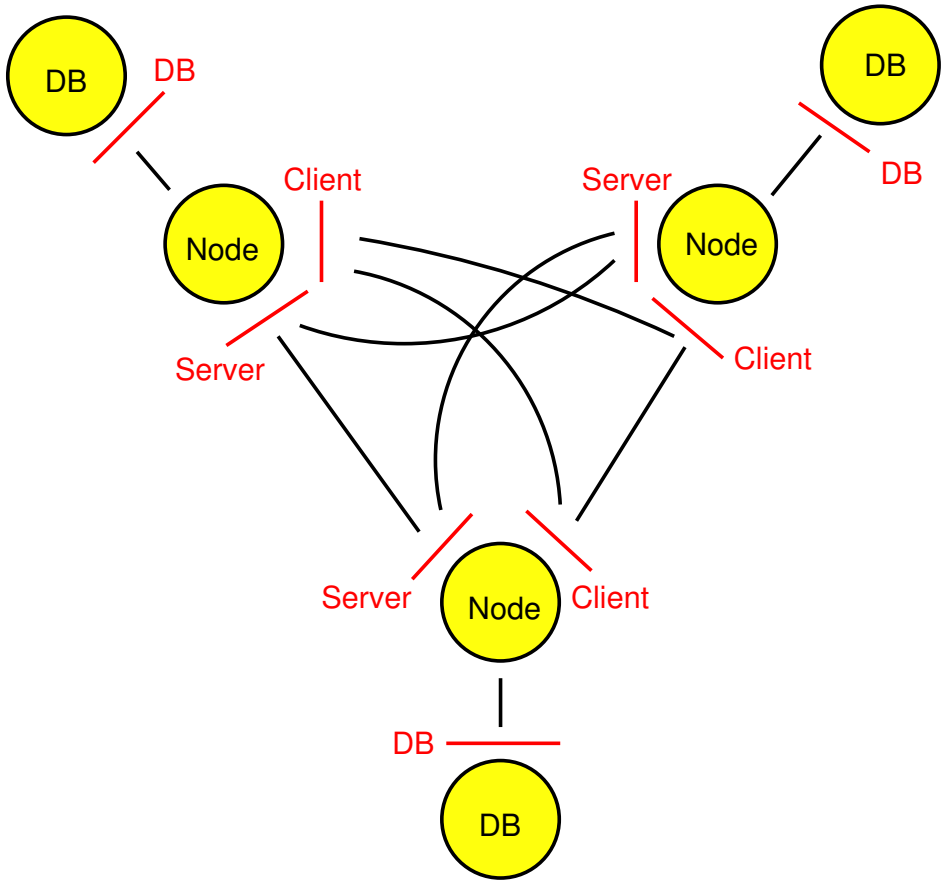
- All objects are **active** (or concurrent), but may receive requests
  - Need easy way to combine active and passive/reactive behavior
- We don't always know how objects are implemented
  - Separate specification (interface) from implementation (class)
  - Object variables are **typed by interface**, not by class
- **No assumptions** about the (network) environment
  - Communication may be unordered
  - Communication may be delayed
  - Execution should adapt to possible delays in the environment
- Execution in objects should be **flexible**
- Synchronization should be decided by the caller
  - **Method invocations** may be *synchronous* or *asynchronous*
- Systems **evolve at runtime**
  - Need support for **dynamic reprogramming**

Interfaces as types

- Object variables (pointers) are *typed by interfaces*
  (other variables are typed by data types)
- All object interaction is *controlled* by interfaces
  - *No explicit hiding* needed at the class level
  - Interfaces provide "aspect-oriented" specifications
  - A class may implement a number of interfaces
- *Mutual dependency*: An interface may require a *cointerface*
  - Explicit keyword *caller*
  - Supports callbacks to the caller through the cointerface
  - Protocol-like behaviour
- **Type safety**: no "method not understood" errors

Example: A Peer To Peer Network

- Consider a P2P file sharing network
- Nodes in the network exchange files
- Each node may be involved in several uploads/downloads simultaneously
- Nodes may appear, disappear, and reappear
- Interfaces describe the different aspects of the system: **DB**, **Client**, **Server**



P2P Example: The Data Base

The database stores file locally for a **Server** node and provides a **DB** interface

- getFile: retrieve file from database
- storeFile: store file in database
- listFile: list available files in database
- getLength: get length of given file

```
interface DB
begin
  with Server
    op getFile(in fId: String; out file: List[String])
    op getLength(in fId: String; out length: Int)
    op storeFile(in fId: String, file: List[String])
    op listFiles(out fSet: Set[String])
end
```

P2P Example: The Client

The **Client** interface of the nodes provides services to other **Clients**

- availFiles: which files are avilable in P2P network?
- reqFile: request a given file from a given server

```
interface Client
begin
  with Client
    op availFiles (in sList: List[Server]; out files: List[[Server, Set[String]]])
    op reqFile(in sId: Server, fId: String)
end
```

P2P Example: The Server

A **Server** interface of the nodes provides services to other **Servers**

- enquire: list available files at the given server
- getLength: length of a given file in the server
- getPack: get a part of a given file from the server

```
interface Server
begin
  with Server
    op enquire(out files: Set[String])
    op getLength(in fId: String; out lth: Int)
    op getPack(in fId: String, pNbr: Int; out pack: String)
end
```

P2P Example: The Node

A **Peer** is both a **Server** and a **Client**

```
interface Peer
  inherits Client, Server
begin end
```

Object Communication in Creol

- Objects communicate through method invocations *only*
- *Different ways to invoke* a method m
- Decided by caller — *not* at method declaration time
- **Asynchronous** invocation: $l!o.m(In)$
- **Polling** for method result: **await** $l?$
- **Reading** the method result: $l?(Out)$
- **Guarded** invocation: $l!o.m(In); \ldots;$ **await** $l?; l?(Out)$
- **Label free abbreviations** for standard patterns:
  - $o.m(In; Out) = l!o.m(In); l?(Out)$ — **synchronous call**
  - **await** $o.m(In; Out) =$ **await** $l!o.m(In); l?; l?(Out)$
  - $!o.m(In)$ — no reply needed
- **Internal calls:** $m(In; Out)$, $l!m(In)$, $!m(In)$
  Internal calls may also be asynchronous/guarded

Async. mtd. calls useful to combine OO with distribution

- Synchronous calls defined by asynchronous calls
- Extends the notion of **future variables** [Yonezawa86, ...] with polling:

$$l!m(In); \ldots; l?(Out)$$
$$l!m(In); \ldots; \textbf{await } l?; \ldots; l?(Out)$$

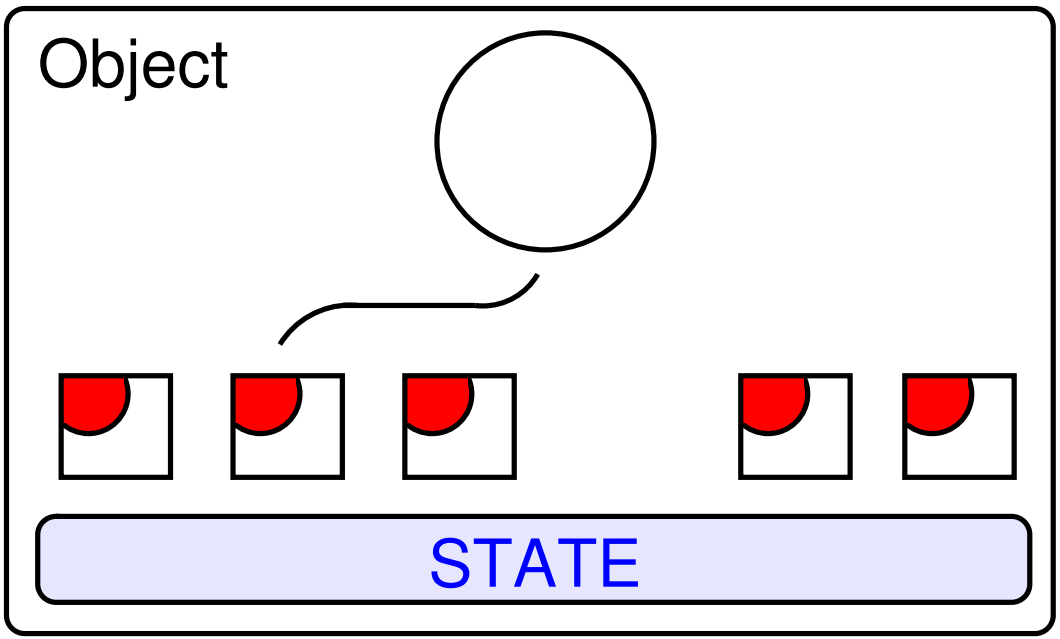
- Provides the *efficiency* of async. message passing
- All inter-object communication by method calls,
  no need for a separate concept of message
- Any method may be called *synchronously* or *asynchronously*
- Labels are first-class values and may be passed around

$$l!m(In); \ldots; !o.p(l); \ldots; l?(Out)$$

- **Cointerfaces**: mutual dep. / callback / availability restriction
- **Inheritance will be as usual for OO:**
  may inherit/redefine methods in subclasses

Execution inside a Creol Object

- **Concurrent objects** encapsulate a processor
- Execution in objects should *adapt* to environment delays
- At most *one active process* at a time
- *Implicit scheduling* between internal processes inside an object



Internal Processes in Concurrent Objects

- **Process**: code + local variable bindings (method activation)
- **Object**: *state* + *active* process + *suspended* processes
- **Suspension** by means of await statements: **await** *guard*
- **Guards** are combinations of:
  - $l?$ ∈ Guard, where l : Label
  - ϕ ∈ Guard, where ϕ : *Local state* → Bool
- If g evaluates to false the active process is *suspended*
- If no process is active, any suspended process may be *activated* if its guard evaluates to true.
- Inner guards enable *interleaving* of *active* and *reactive* code
- Remark: No need for signaling / notification / pulse

Creol Language Constructs

Syntactic categories.

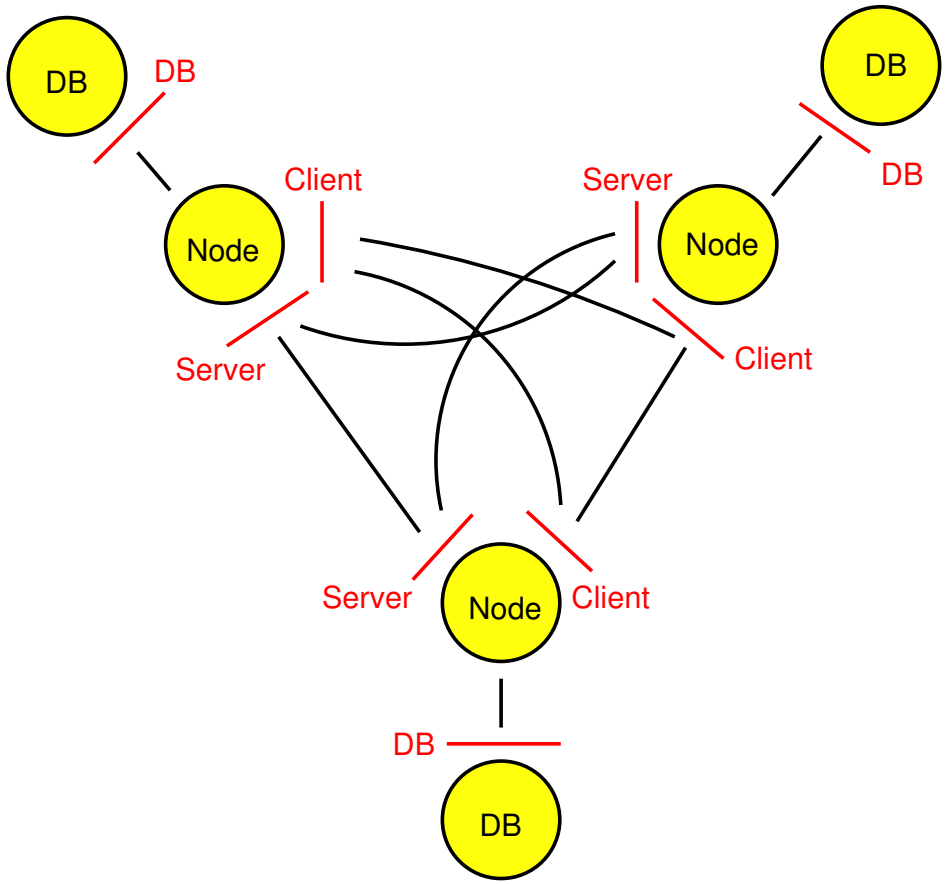
l in Label
g in Guard
p in MtdCall
S in ComList
s in Com
x in VarList
e in ExprList
m in Mtd
o in ObjExpr
b in BoolExpr

Definitions.

$$g ::= \phi \mid l? \mid g_1 \wedge g_2$$
$$p ::= o.m \mid m$$
$$\mathsf{S} ::= s \mid s; \mathsf{S}$$
$$s ::= \textbf{skip} \mid \textbf{begin } \mathsf{S} \textbf{ end} \mid \mathsf{S}_1 \Box \mathsf{S}_2$$
$$\mid x := e \mid x := \textbf{new } \mathit{classname}(e)$$
$$\mid \textbf{if } b \textbf{ then } \mathsf{S}_1 \textbf{ else } \mathsf{S}_2 \textbf{ end}$$
$$\mid \textbf{while } b \textbf{ do } \mathsf{S} \textbf{ end}$$
$$\mid !p(e) \mid l!p(e) \mid l?(x) \mid p(e; x)$$
$$\mid \textbf{await } g \mid \textbf{await } p(e; x)$$
$$\mid \textbf{release}$$

- Omit the functional language for expressions **e** here: this, caller, strings, integers, lists, sets, maps, etc

Recall the P2P Example



We now look at how to model the classes **DataBase** and **Node**.

The Database

```
interface DB
begin with Server
    op getFile(in fId: String; out file: List[String])
    op getLength(in fId: String; out length: Int)
    op storeFile(in fId: String, file: List[String])
    op listFiles(out fSet: Set[String])
end
```

One possible implementation of the DB interface:

```
class DataBase(db : Map[String, List[String]]) implements DB
begin with Server
    op getFile(in fId: String; out file: List[String])== file := get(db, fId)
    op getLength(in fId: String; out length: Int)==
            length := #(get(db,fId))
    op storeFile(in fId: String, file: List[String])==
            db := insert(db, fId, file)
    op listFiles(out fSet: Set[String])== fSet := keys(db)
end
```

The Nodes

```
class Node(db: DB, admin:P2P, file:String) implements Peer
begin
  var catalog : List[[Server, Set[String]]];

  op findServer(in fld:String, catalog : List[[Server, Set[String]]];
                out server:Server)==
     if isempty(catalog) then server := null
       else if (fld in snd(head(catalog))) then server := fst(head(catalog))
         else findServer(fld, tail(catalog); server) end end

  op run ==
    var l:Label[List[[Server, Set[String]]]];
      var neighbors: List[Server]; var server:Server;
        admin.getNeighbors(;neighbors);
          l!this.availFiles(neighbors); await l?; l?(catalog);
            findServer(file,catalog; server); this.reqFile(server,file;)
```

Implementing the Server interface

```
with Server
  op enquire(out files: Set[String]) == await db.listFiles(; files)
  op getLength(in fId: String; out lth: Int) == await db.getLength(fId; lth)
  op getPack(in fId: String, pNbr: Int; out pack: String) ==
    var f: List[String]; await db.getFile(fId; f); pack := nth(f, pNbr)
```

Implementing the Client interface

```
with Client
  op availFiles (in sList: List[Server]; out files: List[[Server, Set[String]]]) ==
    var l1: Label[Set[String]]; var l2: Label[List[[Server, Set[String]]]] ;
      var fList: Set[String];
        if (sList = nil) then files := nil
          else l1!head(sList).enquire(); l2!this.availFiles(tail(sList));
            await l1? ∧ l2?; l1?(fList); l2?(files);
              files := files ⊢ (head(sList), fList) end

  op reqFile(in sId: Server, fId: String) ==
    var file: List[String] := nil; var pack: String; var lth: Int;
      await sId.getLength(fId; lth);
        while (lth > 0) do await sId.getPack(fId, lth; pack);
                                file := pack ⊣ file; lth := lth - 1 end;
          !db.storeFile(fId, file)
end
```

Semantics defined in **Rewriting Logic** (RL) [Meseguer 92]:

- *Static specification*: algebraic specification with equations E
- *Dynamic specification*: (conditional) transition rules:

$$\textit{subconfiguration} \longrightarrow \textit{subconfiguration } \textbf{\textit{if}} \textit{ condition}$$

- Rules applicable to non-overlapping subconfigurations, can be executed in a *concurrent rewrite step*

$$\frac{[t_1]_E \longrightarrow t_1' \quad \ldots \quad [t_n]_E \longrightarrow t_n'}{f([t_1]_E, \ldots, [t_n]_E) \longrightarrow f(t_1', \ldots, t_n')} \ (\text{Par})$$

- Rewriting modulo equational theory
- Many concurrency models represented in RL:
  Petri nets, CCS, Actors, Unity, ...
- RL supported by execution engine: **Maude** [Clavel *et al.* 02]

The Runtime Syntax (1)

- **Substitutions** bind variable names to values
- **Expressions**

```
sort Label Data Expr .
subsort Label < Data < Expr .
op label: Oid Nat -> Label [ctor] .
```

- **Statements**

```
sorts Stmt StmList .
subsort Stm < StmList .
op await_ : Expr -> Stmt .

op nil : -> StmList .
op _;_ : StmList StmList -> StmList [ctor] .

op if_th_el_fi : Expr StmtList StmtList -> Stmt [ctor] .
op _[]_ : StmtList StmtList -> SuspStmt [ctor comm assoc] .
```

The Runtime Syntax (2)

- **Processes**

```
sort Process .

op idle : -> Process [ctor] .
notFound : -> Process [ctor] .
op {_|_} : Subst StmtList -> Process [ctor] .

var L : Subst .
eq { L | noStmt } = idle .
```

- **Objects, Methods, Classes, etc**

```
op <_:_ | Att:_, Pr:_, PrQ:_, Lcnt:_> :
   Oid Cid Subst Process MProc Nat -> Object [ctor] .

op <_: Class | Inh:_, Param:_, Att:_, Mtds:_, Ocnt:_> :
   Cid InhList VidList Subst MMtd Nat -> Class [ctor] .
```

- **Messages** between objects and classes

Multiset Rewriting

Basic idea: rewriting applies to multisets of objects, classes, and messages

```
sorts Msg Class Object Configuration .
subsorts Class Msg Object < Configuration .

op none : -> Configuration [ctor] .
op _ _ : Configuration Configuration -> Configuration
  [ctor assoc comm id: none] .
```

AC-rewriting on multisets

- Matching of the rewrite rules is modulo AC
- We don't need to reorder the multisets to fire rules!

Rules rewrite multisets to multisets and typically have the form

- obj $\longrightarrow$ obj'
- obj $\longrightarrow$ obj' msg
- obj msg $\longrightarrow$ obj'

Rewriting Creol Configurations

System state: a multiset of terms of the following types

- Classes: $\langle Id : Class \mid Inh, Param, Att, Mtds, Ocnt \rangle$
- Messages : $invoc(l, o_2, m, In)$ **to** o_1 and $comp(l, Out)$
- Objects: $\langle Id : Cl \mid Att, Pr, PrQ, Lcnt \rangle$ and queues,
  where the process $Pr = \{Lvar \mid Code\}$

Transition rules capture object activity

- Rules that execute code from the active process
- Rules that activate pending processes
- Object creation
- Transport rules (for messages between objects and classes)

Method Calls

All invocation mechanisms are handled *uniformly*
using the primitives for asynchronous communication.

Synchronous invocations are expanded by an equation

$$\textbf{eq}\ o.m(\mathrm{E};\mathrm{V}) = l!o.m(\mathrm{E}); l?(\mathrm{V})$$

for some fresh label identifier l.

Asynchronous invocation

$\langle o \mid Att : \mathrm{A}, Pr : \{\mathrm{L}|(t!x.m(\mathrm{E});\mathrm{S})\}, Lcnt : n\rangle$

$\longrightarrow$

$\langle o \mid Att : \mathrm{A}, Pr : \{\mathrm{L}|(t := n;\mathrm{S})\}, Lcnt : next(n)\rangle$
$invoc(m, (o\ label(o,n)\ eval(\mathrm{E}, (\mathrm{A};\mathrm{L}))))\ \textbf{to}\ eval(x, (\mathrm{A};\mathrm{L}))$

Method Calls

Method loading — Late binding

$\langle o : C \mid PrQ : \mathrm{W} \rangle \; invoc(m, \mathrm{E})$ **to** o

$\langle C : Class \mid Mtds : \mathrm{M} \rangle$

$\longrightarrow$

$\langle o : C \mid PrQ : (\mathrm{W} \; bind(m, \mathrm{M}, \mathrm{E})) \rangle \; \langle C : Class \mid Mtds : \mathrm{M} \rangle$

(Remark: omitted inheritance, need to traverse the inheritance tree)

Method completion — Active waiting

$\langle o : C \mid Att : \mathrm{A}, Pr : \{\mathrm{L} | (t \; ? \; (\mathrm{V}); \mathrm{S})\} \rangle \; comp(n, \mathrm{E})$

$\longrightarrow$

$\langle o : C \mid Pr : \{\mathrm{L} | (\mathrm{V} := \mathrm{E}; \mathrm{S})\} \rangle \; comp(n, \mathrm{E})$

if $n = eval(t, \mathrm{A}; \mathrm{L})$

Suspension Points

Let Q collect all comp-messages in the configuration

Reply guard — Proceed

$$\langle o : C \mid Att : \mathsf{A}, Pr : \{\mathsf{L}|(\mathit{await}\ t?; \mathsf{S})\}\rangle$$
$$\longrightarrow$$
$$\langle o : C \mid Att : \mathsf{A}, Pr : \{\mathsf{L}|\mathsf{S}\}\rangle$$
$$\textbf{\textit{if}}\ \mathit{contains}(\mathit{eval}(t, \mathsf{A}; \mathsf{L}), \mathsf{Q})$$

Reply guard — Suspend (passive waiting)

$$\langle o : C \mid Att : \mathsf{A}, Pr : \{\mathsf{L}|(\mathit{await}\ t?; \mathsf{S})\}\rangle, PrQ : \mathsf{W}\rangle$$
$$\longrightarrow$$
$$\langle o : C \mid Att : \mathsf{A}, Pr : \mathit{idle}, PrQ : (\mathsf{W}\ \{\mathsf{L}|(\mathit{await}\ t?; \mathsf{S})\}\rangle)\rangle$$
$$\textbf{\textit{if}}\ \mathit{not\ contains}(\mathit{eval}(t, \mathsf{A}; \mathsf{L}), \mathsf{Q})$$

Object Creation

$$\langle o : C' \mid Att : \mathsf{A}, Pr : \{\mathsf{L}|(x := new\ C(\mathsf{E}); \mathsf{S})\}\rangle$$
$$\langle C : Class \mid Param : \mathsf{V}, Att : \mathsf{A}', Ocnt : n\rangle$$
$$\longrightarrow$$
$$\langle o : C' \mid Att : \mathsf{A}, Pr : \{\mathsf{L}|(x := (C; n); \mathsf{S})\}\rangle$$
$$\langle (C; n) : C \mid Att : \varepsilon,$$
$$Pr : \{\varepsilon|(\mathsf{V} := eval(\mathsf{E}, (\mathsf{A}; \mathsf{L})); self := (C; n); init(\mathsf{A}'); !run)\},$$
$$PrQ : \varepsilon, Lcnt : 0\rangle$$
$$\langle C : Class \mid Param : \mathsf{V}, Att : \mathsf{A}', Ocnt : next(n)\rangle$$

With inheritance, the instantiation of the local state must be handled with more care...

- pass parameters from subclass to superclass
- initialize from superclass to subclass

Guided simulation

- Simulation
- Custom rewriting strategies
- Search for reachable state
- States may become large
- Visualization of the runtime state...

DEMO!