Computation Orchestration

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Example: Airline

- Contact two airlines simultaneously for price quotes.
- Buy ticket from either airline if its quote is at most $300.
- Buy the cheapest ticket if both quotes are above $300.
- Buy any ticket if the other airline does not provide a timely quote.
- Notify client if neither airline provides a timely quote.

Example: workflow

- An office assistant contacts a potential visitor.
- The visitor responds, sends the date of her visit.
- The assistant books an airline ticket and
  contacts two hotels for reservation.
- After hearing from the airline and any of the hotels:
  he tells the visitor about the airline and the hotel.
- The visitor sends a confirmation which the assistant notes.

Example: workflow, contd.

After receiving the confirmation, the assistant

- confirms hotel and airline reservations.
- reserves a room for the lecture.
- announces the lecture by posting it at a web-site.
- requests a technician to check the equipment in the room.

Wide-area Computing

Acquire data from remote services.

Calculate with these data.

Invoke yet other remote services with the results.

Additionally

Invoke alternate services for failure tolerance.

Repeatedly poll a service.

Ask a service to notify the user when it acquires the appropriate data.

Download an application and invoke it locally.

Have a service call another service on behalf of the user.

The Nature of Distributed Applications

Three major components in distributed applications:

Persistent storage management

databases by the airline and the hotels.

Specification of sequential computational logic

does ticket price exceed $300?

Methods for orchestrating the computations

contact the visitor for a second time only after hearing from the airline and one of the hotels.

We look at only the third problem.

Related Models and Languages

- Process Calculi: CSP, CCS, π-calculus, Join Calculus
- Petri Net
- Statechart
- Programming Languages
  - Pict: Based on π-calculus
  - C ω: Based on Join Calculus
  - Concurrent ML, Concurrent Haskell: Based on CCS (see List Monads)
  - Esterel, Lustre

Related Work, Applications

- Workflow: Based on

  extensions to petri nets,

  π-calculus

- Busieness Process Orchestration: BPEL, OWL-S, ...

Site

Compose basic computing elements called Sites. A site is a

- function: Compress MPEG file
- method of an object: LogOn procedure at a bank
- monitor procedure: read from a buffer
- web service: CNN, get a stock quote
- transaction: check account balance
- distributed transaction: move money from one bank to another
- Humans: Send email, expect report

More on Sites

- Site calls are strict: Arguments must be defined.
- A site returns at most one value.
- A site may not respond.

  Its response at different times (for the same input) may be different.
- A site call may change states (of external servers) tentatively or permanently.

  Tentative state changes are made permanent by explicit commitment.
- A site may be an argument of a site call.

Some Fundamental Sites

$\mathbf{0}$: never responds.

$let(x, y, \cdots)$: returns a tuple of its argument values.

$if(b)$: boolean b,
returns a signal if b is true; remains silent if b is false.

$Signal$ returns a signal immediately. Same as $if($*true*$)$.

$Rtimer(t)$: integer t, $t \geq 0$, returns a signal t time units later.

Orc

An Orc expression is

1. Simple: just a site call, or
2. composition of two Orc expressions

Evaluation of Orc expression:

calls some sites,

publishes some values

Simple Orc Expression

$CNN(d)$

calls site CNN,

publishes the value, if any, returned by the site.

Composition Operators

do f and g in parallel	$f \mid g$	Symmetric composition
for all x from f do g	$f >x> g$	Sequencing
for some x from f do g	$g \text{ where } x :\in f$	Asymmetric composition

Composition Operators, Examples

- $CNN \ \mid BBC$ Symmetric composition
- $CNN \ {>}x{>} \ Email(address, x)$ Sequencing
- $(Email(address, x) \text{ where } x{:}{\in} \ (CNN \ \mid BBC))$ Asymmetric composition

Conventions

- Precedence of binding: where , $|$, $\gg$

- No arithmetic or logic capability in Orc.
  Can't write $u + v$ or $x \vee y$.
  Write $add(u, v)$ and $or(x, y)$, where add and or are sites.

- Convention: In examples, I write $u + v$ and $x \vee y$.
  Assume that a compiler converts these to $add(u, v)$ and $or(x, y)$.

Centralized Execution Model

- An expression is evaluated on a single machine (client).
- Client communicates with sites by messages.
- $Rtimer$ is local to client.
- All fundamental sites are local to the client.
  All except $Rtimer$ respond immediately.
- We show concurrent and distributed executions later.

Symmetric composition: $f \mid g$

Evaluate f and g independently.

Publish all values from both.

Example:
$CNN \mid BBC$: calls both CNN and BBC simultaneously.

Publishes values returned by both sites. (0, 1 or 2 values)

Note:

No direct communication or interaction between f and g.

They may communicate only through sites.

Sequencing: $f \; {>}x{>} \; g$

For all values published by f do g. Publish only the values from g.

- $CNN \; {>}x{>} \; Email(address, x)$

  Call CNN. Name any value returned x. Call $Email(address, x)$.

  Publish the value (a signal), if any, returned by $Email$.

- $(CNN \mid BBC) \; {>}x{>} \; Email(address, x)$

  May call $Email$ twice. Publishes up to two signals.

Notation:
Write $f \gg g$ for $f \; {>}x{>} \; g$ if x unused in g.

Notes on Sequencing

- $\gg$ is associative. $>x>$ is right associative.

- A fresh evaluation of g is started with each returned value x. Many copies of g may be executing, possibly, with f.

- If f publishes at most one value, $f \; >x> \; g$ is $f;g$.

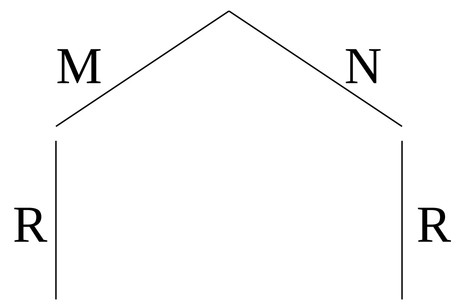
- If f publishes no value, g is never evaluated in $f \; >x> \; g$.

Questions

$$
\begin{array}{lcl}
M \mid M & \stackrel{?}{=} & M \\
(M \mid N) \gg R & \stackrel{?}{=} & M \gg R \mid N \gg R \\
M \gg (N \mid R) & \stackrel{?}{=} & M \gg N \mid M \gg R \\
\mathit{if}\,(b) \gg M \mid \mathit{if}\,(\neg b) \gg M & \stackrel{?}{=} & M
\end{array}
$$

$$\boxed{(M \mid N) \gg R \;=\; M \gg R \mid N \gg R}$$

Evaluate M and N. For each published value, call R.

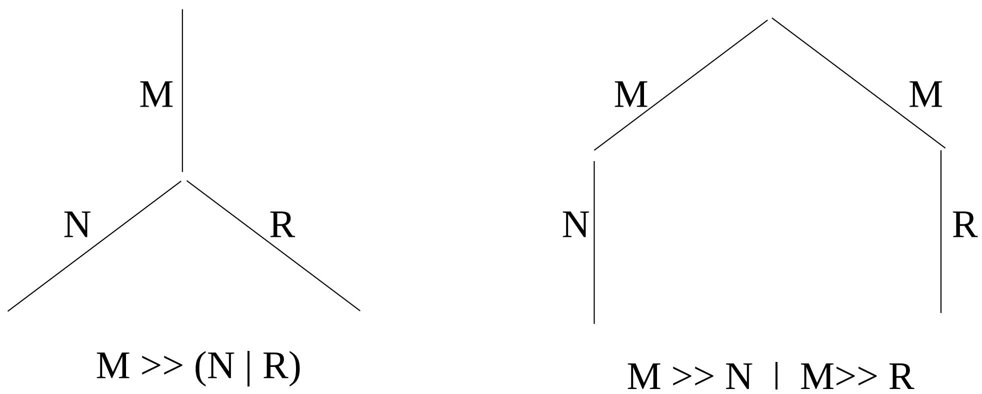


Thus, R may be called twice.

$$(Email(address1, message) \mid Email(address2, message)) \gg Notify$$

Double notification.

$$M \gg (N \mid R) \neq M \gg N \mid M \gg R$$



Asymmetric parallel composition: $(g \text{ where } x{:}\in\ f)$

For some value published by f do g. Publish only the values from g.

- Evaluate f and g in parallel.
- When f returns a value, assign it to x and terminate f.
- Any site call in g which does not name x can proceed.
  $(M \mid N(x)) \text{ where } x{:}\in\ f$
- A site calls which names x waits until x gets a value.
- Values published by g are the values of $(g \text{ where } x{:}\in\ f)$.

Pruning the computation

$(CNN \;\;|\; BBC) \;>x>\; Email(address, x)$

May send two emails.

To send just one email:

$$Email(address, x) \text{ where } x{:}{\in} \;\; (CNN \;\;|\; BBC)$$

Notify after both respond

$$(Email(address1, message) \mid Email(address2, message)) \gg Notify$$

Use

$$((let(u, v) \gg Notify$$
$$\quad \textbf{where}$$
$$\qquad u :\in \; Email(address1, message))$$
$$\quad \textbf{where}$$
$$\qquad v :\in \; Email(address2, message))$$

Adopt the notation:

$$(let(u, v) \gg Notify$$
$$\quad \textbf{where}$$
$$\qquad u :\in \; Email(address1, message)$$
$$\qquad v :\in \; Email(address2, message))$$

Eager Evaluation in $(g \text{ where } x{:}\in\ f)$

- In $M \mid N(x) \text{ where } x{:}\in\ f$:

  g is evaluated, i.e., M is called even before x has a value.

  Any response from M will be published even before x has a value.

- In $M \gg N(x) \text{ where } x{:}\in\ f$:

  f is evaluated even before the value of x is needed.

Difference in evaluation strategies

- In $f \ {>}x{>}\ g$, g is not evaluated if f is silent.
- In $(g \text{ where } x{:}{\in}\ f)$, g may be partially evaluated if f is silent.
- Analogous to difference in values of quantified expressions over empty range.

Fundamental Site $\mathbf{0}$

$\mathbf{0}$ is a site which never responds.

Example: send an email but do not wait for its response:

$$(Email(address1, message) \gg \mathbf{0} \quad | \quad Notify)$$

Expression Definition

An expression is defined like a procedure.

$$MailOnce(a) \;\underline{\Delta}$$
$$\quad Email(a,m) \;\; \text{where}\; m{:}\in \; (CNN \;\; | \;\; BBC)$$

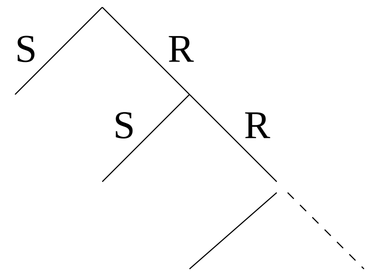
$$Ticker(a,t) \;\underline{\Delta}$$
$$\quad MailOnce(a) \;\gg\; Rtimer(t) \;\gg\; Ticker(a,t)$$

Note: $Ticker$ does not publish a value.

Metronome

Publish a signal at every time unit.

$$Metronome \ \underline{\Delta} \ Signal \mid Rtimer(1) \gg Metronome$$



Publish n signals.

$$\begin{array}{lll} BM(0) & \underline{\Delta} & \mathbf{0} \\ BM(n) & \underline{\Delta} & Signal \mid Rtimer(1) \gg BM(n-1) \end{array}$$

Example of Expression call

- Site $Query$ returns a value (different ones at different times).
- Site $Accept(x)$ returns x if x is acceptable.
- Produce all acceptable values by calling $Query$ at unit intervals forever.

$$RepeatQuery \;\underline{\Delta}\; Metronome \gg Query \;>x>\; Accept(x)$$

Asynchronous Semantics

Call sites eventually.

In $M \mid N$, the sites may be called at arbitrary times.

In $M \mid Rtimer(1)$,

$Rtimer$ is any site that returns a signal after unit time.

Synchronous Semantics

Call sites as soon as possible.

Consequently:

- In $M \mid N$, both sites are called simultaneously.
- A response is processed only if no site can be called.
- In $(g \text{ where } x :\in f)$, x gets the first value from f.

Fundamental sites get priority:

Process responses from fundamental sites before any other response.

Some Fundamental Sites

$\mathbf{0}$: never responds.

$let(x, y, \cdots)$: returns a tuple of its argument values.

$if\,(b)$: boolean b,
returns a signal if b is true; remains silent if b is false.

$Signal$ returns a signal immediately. Same as $if\,($*true*$)$.

$Rtimer(t)$: integer t, $t \geq 0$, returns a signal t time units later.

Small Examples

- Call site M four times, at unit time intervals.

$$M \quad | \quad Rtimer(1) \gg M \quad | \quad Rtimer(2) \gg M \quad | \quad Rtimer(3) \gg M$$

- Time-out: return M's response if it arrives before t, return 0 after t.

$$let(z) \text{ where } z{:}\in \; M \quad | \quad Rtimer(t) \gg let(0)$$

Priority

- Receive N's response asap, but no earlier than 1 unit from now.

$$Delay(N) \;\underline{\Delta}\; Rtimer(1) \gg let(u) \text{ where } u :\in N$$

- Call M, N together.

  If M responds within one unit, take its response.

  Else, pick the first response.

$$let(x) \text{ where } x :\in M \mid Delay(N)$$

Recursive definition with time-out

Call a list of sites.

Count the number of responses received within 10 time units.

$$
\begin{array}{lll}
tally([\,]) & \underline{\Delta} & let(0) \\
tally(M : MS) & \underline{\Delta} & \\
 & & u + v \\
 & & \quad \text{where} \\
 & & \qquad u {:}{\in}\ \ M \gg let(1) \mid Rtimer(10) \gg let(0) \\
 & & \qquad v {:}{\in}\ \ tally(MS)
\end{array}
$$

Opera Seat assignments

- An opera house has a list of patrons.
- It emails each patron a set of seats, from which the patron can choose.
- It contacts the patrons one at a time, and uses time-out if some patron does not respond.
- $Assign(x, m)$: x is a patron, m a seat. Assigns m to x.
- $Opera(ps, s)$: ps is a list of patrons (in decreasing order of priority), s a set of available seats, performs assignments.

Opera Seat assignments, contd.

$$
\begin{array}{lcl}
Opera([], \{\}) & \underline{\Delta} & \mathbf{0} \ \{\text{All patrons and seats assigned}\} \\
Opera(ps, \{\}) & \underline{\Delta} & \mathbf{0} \ \{\text{all seats assigned to patrons}\} \\
Opera([], s) & \underline{\Delta} & \mathbf{0} \ \{\text{All patrons assigned seats}\}
\end{array}
$$

$$
\begin{array}{lcl}
Opera(x : ps, s) & \underline{\Delta} & Opera(ps, t) \\
& \text{where} & \\
& & t{:}\in \ x(s) \ {>}m{>} \ Assign(x, m) \gg let(s - \{m\}) \\
& & \quad \mid \ Rtimer(1) \gg let(s)
\end{array}
$$

Sequential Computing

- $(S;\ T)$ is $(S \gg T)$

- **if** b **then** S **else** T

  is

$$if(b) \gg S \mid if(\neg b) \gg T$$

- **while** $B(x)$ **do** $x{:=}\, S(x)$

$$loop(x) \ \underline{\Delta}$$
$$B(x) >b> (if(b) \gg S(x) >y> loop(y) \mid if(\neg b) \gg let(x))$$

Kleene Star

- For a given x, produce the set of values

$$x,\ M(x),\ M(x)\ {>}y{>}\ M(y),\ M(x)\ {>}y{>}\ M(y)\ {>}z{>}\ M(z),\ \ldots$$

$$Mstar(x)\ \underline{\Delta}\ let(x)\ \mid M(x)\ {>}y{>}\ Mstar(y)$$

- Produce the same set of values without x, i.e.,

$$M(x),\ M(x)\ {>}y{>}\ M(y),\ M(x)\ {>}y{>}\ M(y)\ {>}z{>}\ M(z),\ \ldots$$

$$Mplus(x)\ \underline{\Delta}\ M(x)\ {>}y{>}\ (let(y)\ \mid Mplus(y))$$

Arbitration

In CCS: $\alpha.P + \beta.Q$

In Orc:

$$if(b) \gg P \mid if(\neg b) \gg Q$$

where

$$b :\in \; Alpha \gg let(\textit{true}) \mid Beta \gg let(\textit{false})$$

Time-out

Return $(x, \textit{true})$ if M returns x before t, and $(-, \textit{false})$ otherwise.

$let(z, b)$
where
$(z, b) :\in M \ >x> \ let(x, \textit{true}) \quad | \quad Rtimer(t) \ >x> \ let(x, \textit{false})$

Fork-join parallelism

Call M and N in parallel.

Return their values as a tuple after both respond.

$$
\begin{array}{l}
let(u, v) \\
\quad \text{where } u :\in M \\
\quad \phantom{\text{where }} v :\in N
\end{array}
$$

Return a signal after both respond.

$$
\begin{array}{l}
let(u) \gg let(v) \\
\quad \text{where } u :\in M \\
\quad \phantom{\text{where }} v :\in N
\end{array}
$$

Screen Refresh

Get: screen image, keyboard input, mouse position every time unit.

Call $Draw$ with this triple.

$$
\begin{array}{lll}
 & Metronome & \\
\gg & (\ let(i, k, m) & \\
 & \quad \text{where } i \ :\in\ Image & \\
 & \qquad\qquad\ k \ :\in\ Keyboard & \\
 & \qquad\qquad\ m :\in\ Mouse & \\
 &) & \\
>x> & Draw(x) &
\end{array}
$$

Barrier Synchronization

Synchronize $M \gg f$ and $N \gg g$:

f and g start only after both M and N complete.

Rendezvous of CSP or CCS; M and N are complementary actions.

$$
\begin{array}{ll}
(& let(u,v) \\
 & \text{where } u{:}\in M \\
 & \qquad\quad\; v{:}\in N) \\
\gg (f \mid g) &
\end{array}
$$

To pass values from M and N to f and g, modify last line:

$$>(u,v)> \ (f \mid g)$$

Interrupt handling

- Orc statement can not be directly interrupted.
- $Interrupt$ site: a monitor.
- $Interrupt.set$: to interrupt the Orc statement
- $Interrupt.get$: responds after $Interrupt.set$ has been called.

Use

$$let(z)\ \text{where}\ z{:}\in\ f \quad | \quad Interrupt.get$$

Interrupt; contd.

Determine if there has been an interrupt:

$$
\begin{array}{l}
callM \;\underline{\Delta} \\
\quad (let(z,b) \\
\quad\quad \text{where} \\
\quad\quad\quad (z,b) :\in\; M \;>x>\; let(x,\textsf{true}) \;\;|\;\; Interrupt.get \;>x>\; let(x,\textsf{false}) \\
\quad)
\end{array}
$$

Process Interrupt:

$$
\begin{array}{l}
\quad\quad callM \\
>(z,b)> \\
\quad\quad (\;\; if(b) \;\gg\; \text{“Normal processing with value } z\text{”} \\
\quad\quad\;\; |\; if(\neg b) \;\gg\; \text{“Interrupt Processing”} \;\;)
\end{array}
$$

Parallel or

Sites M and N return booleans. Compute their parallel or.

Below $ift(b) = if(b) \gg let(\textbf{true})$.
$ift(b)$ returns ***true*** if b is ***true***; silent otherwise.

$$ift(x) \quad | \quad ift(y) \quad | \quad or(x, y)$$
where
$$x{:}\in M, \; y{:}\in N$$

Return just one value.

$$let(z)$$
where
$$z{:}\in ift(x) \quad | \quad ift(y) \quad | \quad or(x, y)$$
$$x{:}\in M, \; y{:}\in N$$

Airline quotes: Application of Parallel or

Contact airlines A and B.

Return any quote if it is below c as soon as it is available, otherwise return the minimum quote.

$threshold(x)$ returns x if $x < c$; silent otherwise.
$Min(x, y)$ returns the minimum of x and y.

$$
\begin{array}{l}
let(z) \\
\quad \text{where} \\
\qquad z :\in \ threshold(x) \ \mid \ threshold(y) \ \mid \ Min(x,y) \\
\qquad x :\in \ A \\
\qquad y :\in \ B
\end{array}
$$

Backtracking: Eight queens

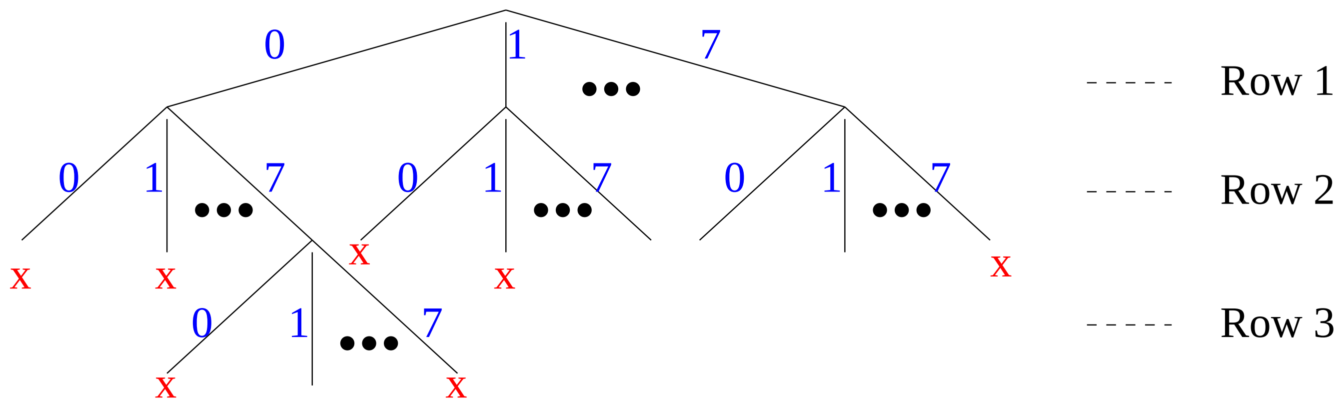


Figure 1: Backtrack Search for Eight queens

Eight queens; contd.

- configuration: placement of queens in the last i rows.
- Represent a configuration by a list of integers j, $0 \leq j \leq 7$.
- Valid configuration: no queen captures another.

Eight queens; contd.

- Site $check(x{:}xs)$: Given xs is valid,

  return $x{:}xs$, if it is valid; remain silent otherwise

- Produce all valid extensions of z by placing n additional queens:

  z is a valid configuration, $1 \le n$ and $|z| + n \le 8$

- Define $extend(z, n)$

$$
\begin{array}{lcl}
extend(z, 1) & \underline{\Delta} & check(0{:}z) \mid check(1{:}z) \mid \cdots \mid check(7{:}z) \\
extend(z, n) & \underline{\Delta} & extend(z, 1) > y > extend(y, n - 1)
\end{array}
$$

- Solve the original problem by calling $extend([\,], 8)$.

Processes

- Processes typically communicate via channels.
- For channel c, treat $c.put$ and $c.get$ as site calls.
- $c.get$ is blocking. In our examples, $c.put$ is non-blocking.
- Other kinds of channels can be programmed as sites.

Typical Iterative Process

Forever: Read x from channel c, compute with x, output result on e:

$$P(c,e) \;\underline{\Delta}\; c.get \;>x>\; Compute(x) \;>y>\; e.put(y) \;\gg\; P(c,e)$$

Process (network) to read from both c and d and write on e:

$$Net(c,d,e) \;\underline{\Delta}\; P(c,e) \;|\; P(d,e)$$

Multiplexor, from Hoare

- A mulitiplexor receives messages from several channels, $c[i]$, $0 \le i \le N$.
- It reproduces all messages on outgoing channel e.
- It stops reading from a channel after seeing an eos message.

Solution:

$$
\begin{array}{lll}
mux & \underline{\Delta} & P_0 \mid P_1 \mid \cdots \mid P_N \\
P_i & \underline{\Delta} & c[i].get \ {>}x{>} \ \mathit{if}\,(x \neq eos) \gg e.put(x) \gg P_i
\end{array}
$$

Example

Run a dialog with the client.

Forever: client inputs an integer on channel p

Process outputs *true* on channel q iff it is prime.

Sites: $c.get$ and $c.put$, for channel c.

$Prime?(x)$ returns *true* iff x is prime.

$$
\begin{array}{ll}
Dialog(p,q) \;\underline{\Delta} & \\
\quad p.get & >x> \\
\quad Prime?(x) & >b> \\
\quad q.put(b) & \gg \\
\quad Dialog(p,q) &
\end{array}
$$

Push, Pull

- $f \;{>}x{>}\; g$ may run many g in parallel, one for each publication of f.

- Run one copy of g at any time (iterate g with values from f):
  - f may publish at arbitrary speed.
  - Start an iteration only on completion of an iteration.
  - Assume g publishes at most one value.

- f writes to channel c.
  Read a new value from c only after processing the previous value.

$$(f \;{>}y{>}\; c.put(y) \gg \mathbf{0}) \mid Rg$$
$$Rg \;\underline{\Delta}\; c.get \;{>}x{>}\; g \gg Rg$$

Mutual Exclusion

- Process i writes a site name on channel c_i.
  $Multiplexor_i$ collects inputs from c_i, writes on e.

$$Multiplexor_i \ \underline{\Delta} \ c_i.get \ >x> \ e.put(x) \ \gg \ Multiplexor_i$$

- $Arbiter$ picks an item g from e; grants resource by calling g.
  g responds after the process completes the resource usage.

$$Arbiter \ \underline{\Delta} \ e.get \ >g> \ g \ \gg \ Arbiter$$

- $Mutex$ coordinates all the activities.

$$Mutex \ \underline{\Delta} \ (\ | \ i :: Multiplexor_i) \ | \ Arbiter$$

Dining Philosophers

A philosopher's life is depicted by

$$
\begin{array}{l}
P_i \;\underline{\Delta} \\
\qquad (let(x, y) \;\gg\; Eat \;\gg\; Fork_i.put \;\gg\; Fork_{i'}.put \\
\qquad\quad \text{where} \quad x{:}\in \; Fork_i.get \\
\qquad\qquad\qquad\;\; y{:}\in \; Fork_{i'}.get \\
\qquad) \\
\quad \gg \; P_i
\end{array}
$$

where $Fork_i$ and $Fork_i'$ are sites, returning signals.

Represent the ensemble of N philosophers by

$$DP \;\underline{\Delta}\; (\;|\; i{:}\; 0 \le i < N{:}\; P_i)$$

Synchronized Communication: Byzantine Protocol

- Process i sends values to j over channel c_{ij}.

$$Send_i(v) \quad \underline{\Delta} \quad (\mid j{::}\ c_{ij}.put(v) \gg \mathbf{0})$$
$$Read_i \quad \underline{\Delta} \quad (let(X) \text{ where } (\forall j{::}\ X_j :\in c_{ji}.get))$$

- $Round_i(v, n)$: For process i to run n rounds with initial value v.

$$Round_i(v, 0) \quad \underline{\Delta} \quad let(v)$$
$$Round_i(v, n) \quad \underline{\Delta}$$
$$(Send_i(v) \mid Read_i) \ {>}X{>}\ Compute_i(X) \ {>}u{>}\ Round_i(u, n-1)$$

- $Byz(V, n)$: All processes run n rounds; initial value vector is V.

$$Byz(V, n) \quad \underline{\Delta} \quad (\mid i{::}\ Round_i(V_i, n))$$