A Personal Perspective on Concurrency

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This talk is not about:

- A survey of the concurrency literature.
- Efficient algorithms for multicore computing.
- Proofs of protocols.

This talk is about:

- My view of asynchronous concurrency.
- How my views have shaped my research (with subtle commercials).
- Why the entire area needs significant new research.

Traditional view of concurrency in the 70s, early 80s

- add-on to traditional sequential programming,
- handled by enumerating threads:

  device controller, background monitor, timer, ...
- threads can fork to create new threads (not too many), interrupt others, ...
- fork, join paradigm for structuring.

Relevant questions Then

- How many machines?
- Topology of connection?
- Synchronization mechanism:
  Semaphore, Conditional critical region, Monitor, ...?
- Communication mechanism:
  Shared memory/message passing/broadcast interaction?
- Latency and bandwidths compared to in-memory interactions?

Reasoning methods

- Mostly ad-hoc.
- Enumeration of scenarios.
- Assertions at/before/after program control points.
- Interesting properties:
  Mutual exclusion, absence of deadlock, starvation, ...

Some powerful ideas from the 80s

- Process calculi: CSP, CCS:
  structured enumeration of threads.
- Reasoning method of Owicki and Gries,
  using thread non-interference.
- Classification of program properties:
  Safety, progress
- Temporal logic.

CSP, 1978

- Process network with message passing.
  Shared memory regarded as a process.
- Rendezvous-based synchronization and communication.
- Simultaneous waiting on multiple channels.
- Process spawning.

Concurrency questions can be cast in completely machine-independent form.

Simulation of a Telephone switch

- Multiple processors in the switch.
- Multiple customer devices: handsets, fax machines, local switches.
- Multiple calls.

Possible partitioning into processes along many dimensions, none attractive.

Alternate view of structuring

A common misconception in program structuring is that a *process* —whose code can be executed on a single processor, or which can be viewed as a unit of computation, as in a transaction processing system, for instance— constitutes a "natural" decomposition of a system; therefore, it is argued that a system should be understood (i.e., specified) process by process.

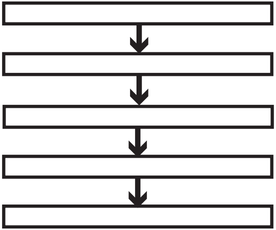
> Parallel Program Design: A Foundation (1988)
> K. Mani Chandy, J. Misra

Pamela Zave's view of Networking

CLASSIC LAYERS OR OSI REFERENCE MODEL

there is a fixed number of layers

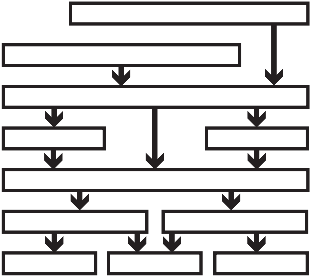
each layer has a distinct and indispensable function



THE GEOMORPHIC VIEW OF NETWORKING

each layer is a microcosm of networking, containing all the basic functions (state components and mechanisms)

there can be any number of levels, each with any number of layers



the layers are modules, providing orderly, fine-grained separation of concerns

Unity

Goals:

- Structure a solution so that it admits:
  multiple views of problem decomposition.
- Structure a solution so that it admits:
  implementations on multiple platforms.
- Strong reasoning methods for safety and progress properties.
- Strong reasoning methods about program composition.

Common Meeting Time

- A set of students each with a personal calendar function f:

  $f(t)$ is the next time at/after t when the student can meet.

- Find the earliest common meeting time, if one exists.

Some solutions

- Passing around a scratch pad.
- Bidding.
- Recursive decomposition.

An abstract solution

- initially $t = 0$ $\quad --$ earliest common meeting time $\geq t$

  $t := f_0(t) \ [] \ t := f_1(t) \ [] \ \cdots \ [] \ t := f_n(t)$

- Execute the actions in arbitrary order forever.

  Execute each action infinitely often.

- There is a common meeting time: eventually t set to the earliest. No action has any effect thereafter; so, t does not change.

- There is no common meeting time: t keeps increasing.

- Previous solutions are restrictions of this program.

Unity

- Discard the notion of a process.
- Replace concurrency by non-determinacy.
  Each indivisible unit of computation in any thread is an action.
- Reason about infinite sequences of actions using Unity logic,
  a form of linear temporal logic.
- An implementation will restrict non-determinacy.
- Any restriction that is fair retains all properties of the original program.

Structuring is manual

- Partition the set of actions into processes.
  Partitioning of variables across process boundaries.
  Shared variables.

- Hierarchies of partitioning.

- Point-point channel: variable with *put*s and *get*s.

- Broadcast channel: *get* does not remove the item from the channel.

Reasoning

- Safety: Invariant-based; induction on the number of execution steps.
- Progress (liveness): Induction on elementary proof steps.
- Reasoning about composite programs: Modular proofs.
    - Properties, not code, of components used in the proof.
    - Safety properties completely handled.
    - Progress properties almost completely handled.

Unity is applicable:

- Event processing is the primary function.
- In process control (telephony, train controllers ...)

- Mars Rover software: A fixed set of threads.
  Each thread is in an infinite loop:
  Receives a message.
  Processes the message; may send messages.
  Accepts the next message only on completion of processing.
  Each processing step guaranteed to terminate.

- Event-B
- TLA$^+$
- Admits simpler model checking: UV, Murphi

Disclaimer: Unity may not have inspired any of this work.

Structured Programming

- Structured Programming:

  Structured programming circa 1968 (Dijkstra)

  = Component integration in a sequential world.

- Structured Programming:

  Structured programming circa 2014

  = Component integration in a concurrent world.

Concurrency is fundamental

- As fundamental as sequencing, branching and looping.
- Dynamic thread creation essential:
  Reasoning about individual threads is not scalable.
- A spectrum of synchronization and communication:
  from tightly-coupled OS processes to loosely-coupled applications.
- Separation of logical and physical across vast magnitude:
  mobility, names and domains, connections, ...

How to structure large concurrent programs

- Extremely simple structuring mechanism in UNITY.
- Consequently, UNITY inadequate for complex problems.
- More elaborate structuring in CSP, CCS, π-calculus.

Orc: a component integration system

Components:

- from many vendors,
- for many platforms,
- written in many languages,
- may run in real-time.

Integration: Sequential and/or concurrent executions of components.

Component Integration; contd.

- Data types and Structures: Boolean, List, Relational database, Objects
- Small components: add two numbers, print a file ...
- Large components: Linux, email server, a simulator, Web services ...
- Time-based components: clock, alarm, stopwatch, ...
- Cyberphysical devices: actuators, sensors, robots ...
- Fast and Slow components
- Short-lived and Long-lived components
- Humans

Orc Calculus

- Site: Basic component. External to the calculus.

- Combinators for integrating expressions.

Interleaving:	$f \mid g$
Spawning/sequencing:	$f \;>x>\; g$
Interruption:	$f \;<x<\; g$
Bulk Synchronization:	$f \;;\; g$

- Definitions of sites in Orc.

Orc Calculus

- Calculus includes nothing other than the combinators and definitions.
- No data type, thread, process, channel, rendezvous $\cdots$
- New concepts are programmed in Orc using sites.
- No mutable store in the calculus.

Sites

- A site is called like a procedure with parameters.
- Site returns (publishes) any number of values at different times.
- A time-based site publishes at specific real time.

Examples of Sites

- Constants: 3, 7.2, true, "Orc" ...
- Arithmetic, logical operators: $+ \; - \; * \; \&\& \; || \; = \ldots$
- Data structures: tuple, record, list, set, ...
- Mutable actions: `Println`, `Random`, `Prompt`, `Email` ...
- Instances of shared variables : Ref, Semaphore, Channel, ...
- Timer
- External Services: Google Search, MySpace, CNN, Web services...
- Any Java Class instance, Any Orc Program
- Factory sites; Sites that create sites: `Semaphore`, `Channel` ...
- Humans ... (Not a factory site, yet.)

Interleaving, Spawning

- Do f and g in parallel $\quad f \mid g$

Evaluate f and g independently. Publish all values from both.

- For all x from f do g $\quad f > x > g$

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

Notation: $f \gg g$ for $f > x > g$, if x is unused in g.

Right Associative: $f > x > g > y > h$ is $f > x > (g > y > h)$

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Schematic of Sequential composition

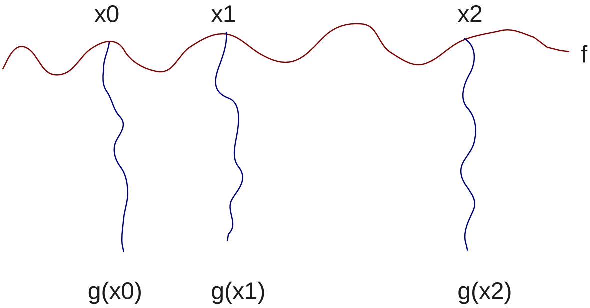

Figure: Schematic of $f \;{>}x{>}\; g$

Subset Sum

Given integer n and list of integers xs.

$parsum(n, xs)$ publishes all sublists of xs that sum to n.

`parsum(5,[1,2,1,2]) = [1,2,2], [2,1,2]`

`parsum(5,[1,2,1])` is silent.

All examples shown in this talk are irrelevant in practice.

An Orc program for Subset Sum

$$def\ \ parsum(0, [\,]) = [\,]$$

$$def\ \ parsum(n, [\,]) = stop$$

$$def\ \ parsum(n, x : xs) =$$

$$parsum(n, xs) \qquad\qquad -- \text{ all sublists that do not include } x$$

$$|\ parsum(n - x, xs)\ \ {>}ys{>}\ x : ys \quad -- \text{ all sublists that include } x$$

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Interleaving, Spawning, Bulk Synchrony

Do f and g in parallel $\qquad f \mid g$

Evaluate f and g independently. Publish all values from both.

For all x from f do g $\qquad f > x > g$

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

- Do f. If f halts without publishing do g. $\qquad f \,;\, g$

Subset Sum (Contd.), Backtracking

Given integer n and list of integers xs.

$seqsum(n, xs)$ publishes the first sublist of xs that sums to n.

"First" is smallest by index, lexicographically.

`seqsum(5,[1,2,1,2]) = [1,2,2]`

`seqsum(5,[1,2,1])` is silent.

Program for Subset Sum, Backtracking

$$\textit{def}\ \ seqsum(0, [\,]) = [\,]$$

$$\textit{def}\ \ seqsum(n, [\,]) = \textit{stop}$$

$$\textit{def}\ \ seqsum(n, x : xs) =$$

$$x : seqsum(n - x, xs)$$

$$;\ seqsum(n, xs)$$

Interleaving, Spawning, Bulk Synchrony, Pruning

Do f and g in parallel $\qquad f \mid g$

Evaluate f and g independently. Publish all values from both.

For all x from f do g $\qquad f > x > g$

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

Do f. If f halts without publishing do g. $\qquad f\ ;\ g$

- For some x from g do f $\qquad f < x < g$

Pruning: $f \ <x< \ g$

For some value published by g do f.

- Evaluate f and g in parallel.
- Site calls that need x are suspended.
- When g returns a (first) value:
  - Bind the value to x.
  - Kill g.
  - Resume suspended calls.
- Values published by f are the values of $(f \ <x< \ g)$.

Notation: $f \ll g$ for $f \ <x< \ g$, if x is unused in f.

Left Associative: $f \ <x< \ g \ <y< \ h$ is $(f \ <x< \ g) \ <y< \ h$

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Subset Sum (Contd.), Concurrent Backtracking

Publish the first sublist of xs that sums to n.

Run the searches concurrently.

$$def\ \ parseqsum(0, [\,]) = [\,]$$

$$def\ \ parseqsum(n, [\,]) = stop$$

$$\begin{aligned}
&def\ \ parseqsum(n, x : xs) = \\
&\quad (p \mathbin{;} q) \\
&\qquad <p< x : parseqsum(n-x, xs) \\
&\qquad <q< parseqsum(n, xs)
\end{aligned}$$

Note: Neither search in the last clause may succeed.

Subset Sum (Contd.), Concurrent Backtracking

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\end{aligned}$$

Note: Neither search in the last clause may succeed.

Angelic + Demonic non-determinism

Programs to solve combinatorial search problems may often be simply written by using multiple-valued functions. Such programs, although impossible to execute directly on conventional computers, may be converted in a mechanical way into conventional backtracking programs.

– R.W. Floyd, 1968

- $f \;\; >x> \; g$ — — Angelic: Explore all paths
- $f \;\; <x< \; g$ — — Demonic: Explore some path, prune others.
- Any combination of these.

On Evaluating Programming Theories

- (Easier) Establish properties of the theory: Introspection
  - Internal consistency, through a semantics
  - Basic Identities
  - Proof theory
- (Harder) Establish applicability of the theory: Extrospection
  - Encode accepted programming paradigms
  - Explore limitations
  - Validate intentions empirically

Identities of $|$, $\gg$, $\ll$ and $;$

(Zero and $|$) $\quad f \mid stop = f$

(Commutativity of $|$) $\quad f \mid g = g \mid f$

(Associativity of $|$) $\quad (f \mid g) \mid h = f \mid (g \mid h)$

(Left zero of $\gg$) $\quad stop \gg f = stop$

(Associativity of $\gg$) if h is x-free

$$(f \;{>}x{>}\; g) \;{>}y{>}\; h = f \;{>}x{>}\; (g \;{>}y{>}\; h)$$

(Right zero of $\ll$) $\quad f \ll stop = f$

(generalization of right zero)

$$f \ll g = f \ll (stop \ll g) = f \mid (stop \ll g)$$

(relation between $\ll$ and $<x<$)

$$f \ll g = f \;{<}x{<}\; g, \quad \text{if } x \notin free(f).$$

(commutativity) $\quad (f \;{<}x{<}\; g) \;{<}y{<}\; h = (f \;{<}y{<}\; h) \;{<}x{<}\; g$

if $x \notin free(h)$, $y \notin free(g)$, and x, y are distinct.

(associativity of $;$) $\quad (f \,;\, g) \,;\, h = f \,;\, (g \,;\, h)$

Distributivity Identities

($\mid$ over $>x>$; left distributivity)

$$(f \mid g) \; >x> \; h = f \; >x> \; h \mid g \; >x> \; h$$

($\mid$ over $<x<$) $(f \mid g) \; <x< \; h = (f \; <x< \; h) \mid g$, if $x \notin \mathit{free}(g)$.

($>y>$ over $<x<$) $(f \; >y> \; g) \; <x< \; h = (f \; <x< \; h) \; >y> \; g$
if $x \notin \mathit{free}(g)$, and x and y are distinct.

($<x<$ over $;$) $(f \; <x< \; g) \; ; h = (f \; ; h) \; <x< \; g$, if $x \notin \mathit{free}(h)$.

Identities that don't hold

(Idempotence of $|$) $\quad f \mid f = f$

(Right zero of $\gg$) $\quad f \gg \mathit{stop} = \mathit{stop}$

(Left Distributivity of $\gg$ over $|$)

$$f \gg (g \mid h) = (f \gg g) \mid (f \gg h)$$

Baby steps towards a Proof Theory

Example: Commutative, associative fold $+$ on a set

$def\;\; fold(S, n) =\quad --$ set S has n elements.

$--\;\; f(k)$ folds and reduces set size by k.

$def\;\; f(0) = stop$

$def\;\; f(1) = (S.get(), S.get()) \; >(x, y)> \; S.put(x + y) \; \gg stop$

$def\;\; f(k) = f(1) \mid f(k-1)$

$f(n-1)$

Surprisingly: Unity proof theory seems appropriate.

Baby steps towards a Proof Theory

Example: Commutative, associative fold $+$ on a set

$$def\ \ fold(S, n) = \qquad --\ \text{set}\ \ S\ \text{has}\ \ n\ \text{elements.}$$

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$$f(n - 1)$$

Surprisingly: Unity proof theory seems appropriate.

I will show some programming paradigms encoded in Orc

- Implicit concurrency
- Synchronization
- Process network
- Real time
- Virtual time

Orc Language

- Data Types: Number, Boolean, String, with Java operators
- Data structures: Tuple, List, Record
- Pattern Matching; Clausal Definition
- Closure
- Class; active objects

All features implemented as macros and/or calls to library sites.

Site arguments are concurrently evaluated

- $f(g,h)$ is translated to:
- $$\begin{array}{l} (f(x,y) \ {<}x{<}\ g) \\ \qquad\qquad\ {<}y{<}\ h \end{array}$$
- From semantics of $\ll$, g and h concurrently evaluated.

Implicit Concurrency

- An experiment tosses two dice; success if sum of throws is 7.
- $exp(n)$ runs n experiments and reports the number of successes.

$$def \ \ toss() = Random(6) + 1$$

$--$ $toss$ returns a random number between 1 and 6.

$$def \ \ exp(0) = 0$$

$$\begin{aligned} def \ \ exp(n) = {} & exp(n-1) \\ & + (if \ \ toss() + toss() = 7 \ then \ \ 1 \ else \ \ 0) \end{aligned}$$

Number of concurrent calls to $toss$ = ?

Synchronization: Pure Rendezvous

$val\ \ s = \ Semaphore(0)$ $\ --\ $ s is a sempahore with initial value 0.
$val\ \ t = \ Semaphore(0)$

$def\ \ put() = \ s.acquire() \gg t.release()$
$def\ \ get() = \ s.release() \gg t.acquire()$

Typical Iterative Process

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

$$def\ \ p(c,e) = c.get() \ \ >x>\ \ Compute(x)\ \ >y>\ \ e.put(y)\ \ \gg\ \ p(c,e)$$

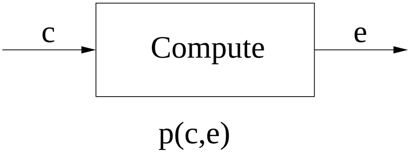


Figure: Iterative Process

Composing Processes into a Network

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

$$\mathit{def}\ \ net(c,d,e) = \ p(c,e) \mid p(d,e)$$

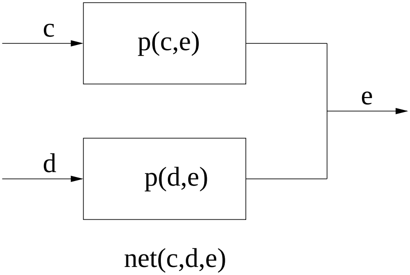


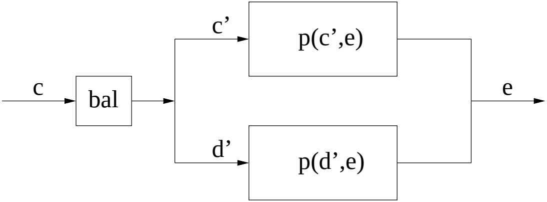
Figure: Network of Iterative Processes

Workload Balancing

Read from c, assign work randomly to one of the processes.

$$\begin{aligned} def\ \ bal(c, c', d') = \quad & c.get()\ \ {>}x{>}\ random(2)\ \ {>}t{>} \\ & (if\ \ t = 0\ then\ \ c'.put(x)\ else\ \ d'.put(x)) \gg \\ & bal(c, c', d') \end{aligned}$$

$$\begin{aligned} def\ \ workbal(c, e) = \ & val\ \ c' = \ Channel() \\ & val\ \ d' = \ Channel() \\ & bal(c, c', d') \mid net(c', d', e) \end{aligned}$$



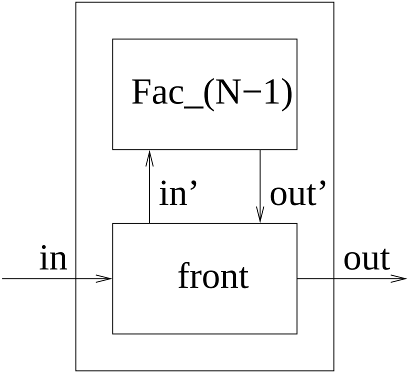
workBal(c,e)

Recursive Pipeline network

Consider computing factorial of each input.

$$fac(x) = \begin{cases} 1 & \text{if} \quad x = 0 \\ x \times fac(x-1) & \text{if} \quad x > 0 \end{cases}$$

Suppose $x \leq N$, for some given N.

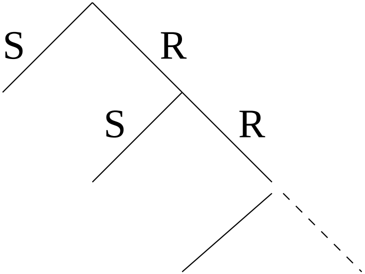


Fac_(N)

Real time: Metronome

External site $Rwait(t)$ returns a signal after t time units.
$metronome$ publishes a $signal$ every time unit.

$$def \;\; metronome() = \underbrace{signal}_{S} \;|\; (\underbrace{Rwait(1) \gg metronome()}_{R})$$



Parallel Auction

- A list of bidders in a single-round auction.
- Ask for bids from all bidders, then publish the highest bid.
- $b.ask()$ requests a bid from bidder b.
  All bidders called simultaneously.
- Bid is 0 if no response from a bidder within 8 seconds.

$$
\begin{array}{l}
\mathit{def}\ \ auction([\,]) = 0 \\[1em]
\mathit{def}\ \ auction(b : bs) = \\
\quad max(\qquad\qquad\qquad\qquad\qquad\qquad\qquad -- \text{ both arguments run in parallel} \\
\qquad\quad b.ask() \mid (Rwait(8000) \gg 0), \quad -- \text{ timeout alternative} \\
\qquad\quad auction(bs) \\
\quad\ )
\end{array}
$$

The Subtle Commercial

- Orc web site:
  http://orc.csres.utexas.edu/
- Reference manual, user guide and research papers.
- Web site at which Orc programs can be submitted.
- Download Orc to your computer.
- Student Projects.

The Subtle Commercial; contd.

- All known synchronization communication protocols coded in Orc.
- Several student projects covering different application areas: Twitter search, Music composition, Trip manager, Workflow.
- Current work in Robotics, two robots patrolling a perimeter.

Shortest Path Algorithm with Lights and Mirrors

- Source node sends rays of light to each neighbor.
- Edge weight is the time for the ray to traverse the edge.
- When a node receives its first ray, sends rays to all neighbors. Ignores subsequent rays.
- Shortest path length = time for sink to receive its first ray. Shortest path length to node i = time for i to receive its first ray.

Graph structure in $Succ()$

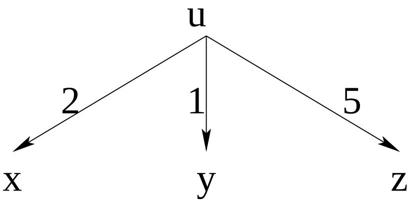


Figure: Graph Structure

$Succ(u)$ publishes $(x, 2)$, $(y, 1)$, $(z, 5)$.

Algorithm

$def \;\; eval(u, t) =$ record value t for u $\gg$
for every successor v with d = length of (u, v) :
wait for d time units $\gg$
$eval(v, t + d)$

$Goal:$ $eval(source, 0) \mid$
read the value recorded for the $sink$

Record path lengths for node u in FIFO channel u.

Algorithm(contd.)

$def\ \ eval(u, t) =$ record value t for u $\gg$
for every successor v with d = length of (u, v) :
wait for d time units $\gg$
$eval(v, t + d)$

$Goal:$ $eval(source, 0)$ $|$
read the value recorded for the $sink$

A cell for each node where the shortest path length is stored.

$def\ \ eval(u, t) =$ $u := t \gg$
$Succ(u) \ >(v, d)>$
$Rwait(d) \gg$
$eval(v, t + d)$

{- $Goal:$ -} $eval(source, 0)$ $|$ read $sink$

Algorithm(contd.)

$$
\begin{aligned}
\mathit{def} \;\; \mathit{eval}(u,t) = \quad & u := t \gg \\
& \mathit{Succ}(u) \;\; >(v,d)> \\
& \mathit{Rwait}(d) \;\; \gg \\
& \mathit{eval}(v, t+d)
\end{aligned}
$$

`{-` *Goal* : `-}` $\quad \mathit{eval}(\mathit{source}, 0) \mid$ read *sink*

- Any call to $\mathit{eval}(u,t)$: Length of a path from source to u is t.
- First call to $\mathit{eval}(u,t)$: Length of the shortest path from source to u is t.
- *eval* does not publish.

Drawbacks of this algorithm

- Running time proportional to shortest path length.
- Executions of *Succ*, *put* and *get* should take no time.

Simulation: Bank

- Bank with two tellers and one queue for customers.
- Customers generated by a *source* process.
- When free, a teller serves the first customer in the queue.
- Service times vary for customers.
- Determine
  - Average wait time for a customer.
  - Queue length distribution.
  - Average idle time for a teller.

Description of Bank

$$
\begin{array}{lcl}
def\ Bank() & = & (Customers() \mid Teller() \mid Teller()) \gg stop \\
\\
def\ Customers() & = & Source()\ >c>\ enter(c) \\
\\
def\ Teller() & = & next()\ >c> \\
 & & Vwait(c.ServTime) \gg \\
 & & Teller() \\
\\
def\ enter(c) & = & q.put(c) \\
def\ next() & = & q.get()
\end{array}
$$

A Significant research area: Programming

- Obliterate the distinction between programming and concurrent programming.
- Structuring is fundamental.
- Orc suggests one mechanism, orchestration of components.
- Components should be coded in the most efficient way, perhaps in other languages.
- Intrinsic merit of concurrency as a field of study, apart from its applications in
  Robotics, Mobile computing, smart city management, ...

Role of universities in the age of MOOCS: Where I can get diverse expertise.

- at UT,
    - Lorenzo Alvisi
    - Don Batory
    - William Cook
    - Isil Dillig
    - Tom Dillig
    - Allen Emerson
    - Mohamed Gouda
    - Warren Hunt
    - Matt Kaufmann
    - Simon S. Lam
    - Vladimir Lifschitz
    - Calvin Lin
    - J Moore
    - Keshav Pingali
    - Peter Stone
    - David Zuckerman