Concurrency in Verona

PLISS 2023

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Attending ▾ Tracks ▾ Organization ▾ Search Series ▾

When Concurrency Matters

Behaviour-Oriented Concurrency

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[illegible]ETAR, Microsoft

[illegible]ordination is central for modern concurrent programming. Many m
[illegible] coordination. However, the design decisions for these two
[illegible]ardependence of these two mechanisms should b
[illegible]We are not the first to realise this: the p
[illegible]h fine-grained decomposition
[illegible]wever, actor model pro
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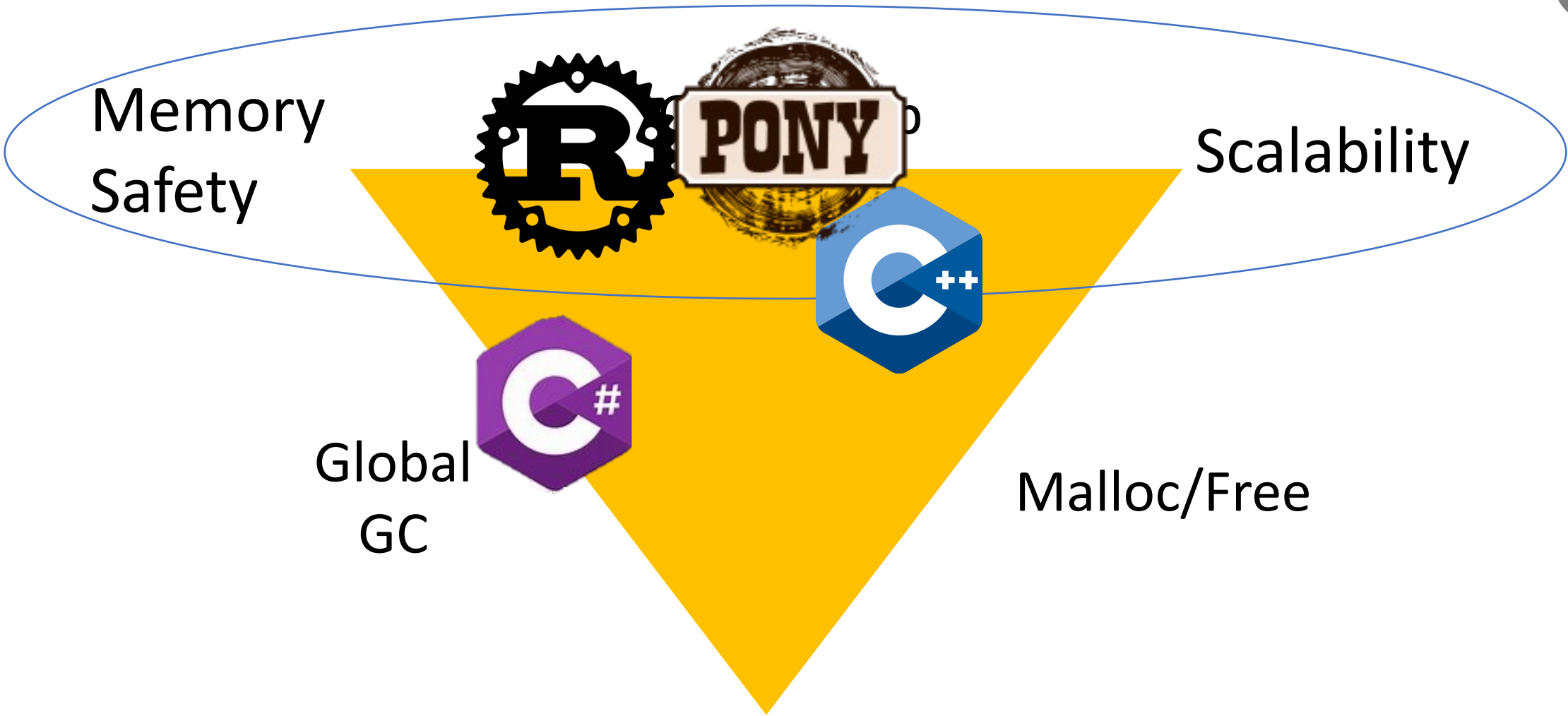
History: Project Snowflake

Manual Memory Management for .NET

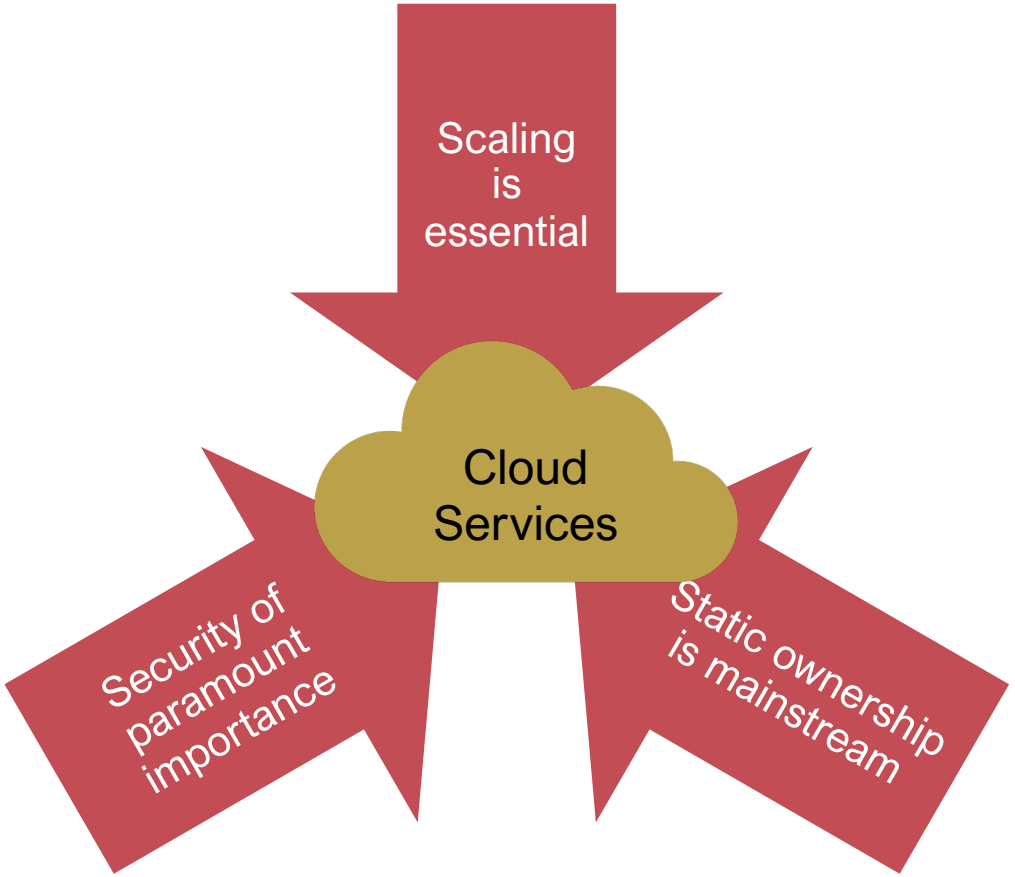

Memory
Safety
PONY
Scalability
Global
GC
Malloc/Free
Concurrent
Mutation

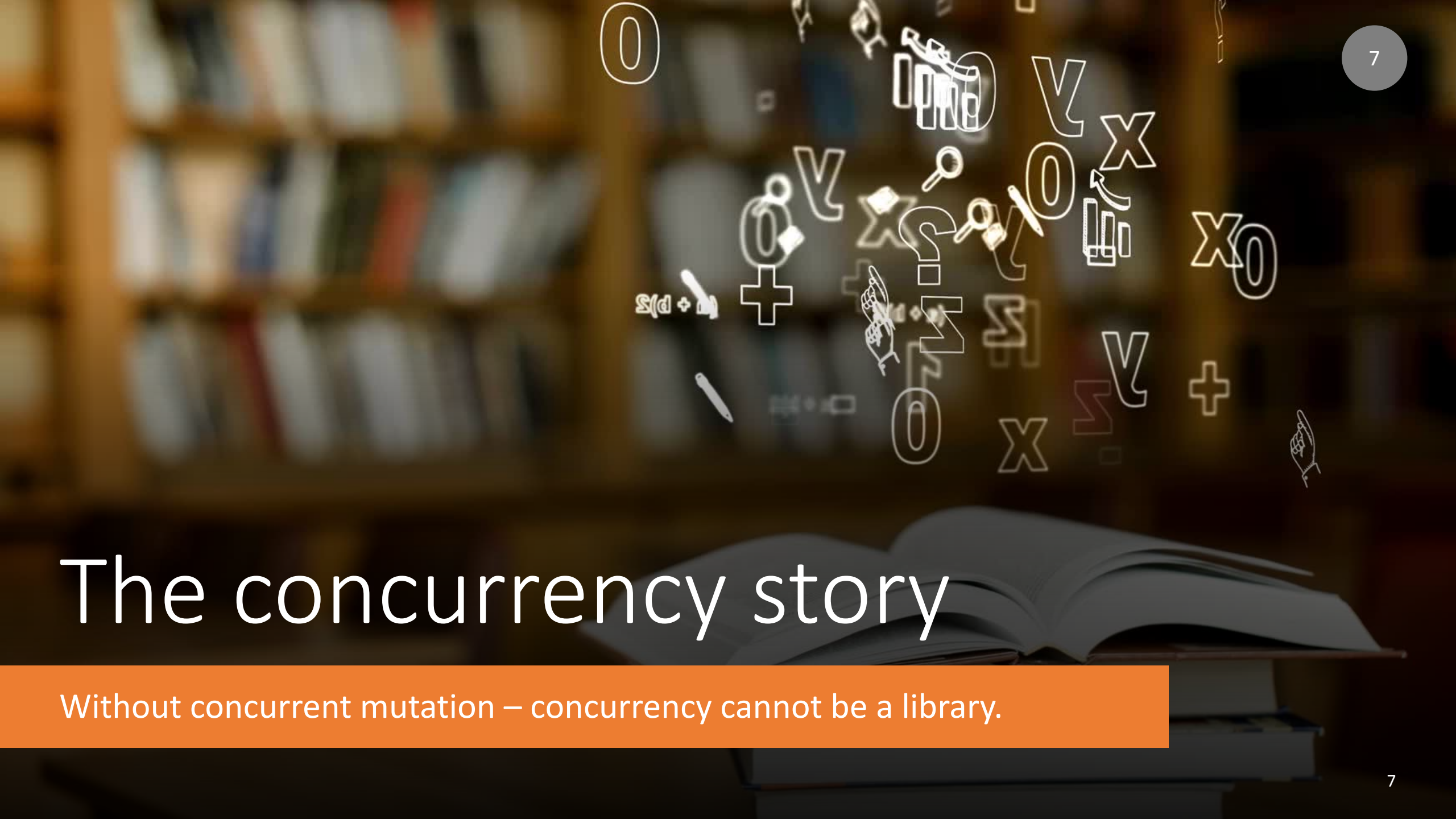
What is Project Verona?

Language design project

Key aim:

Provide safe, **local** memory management.



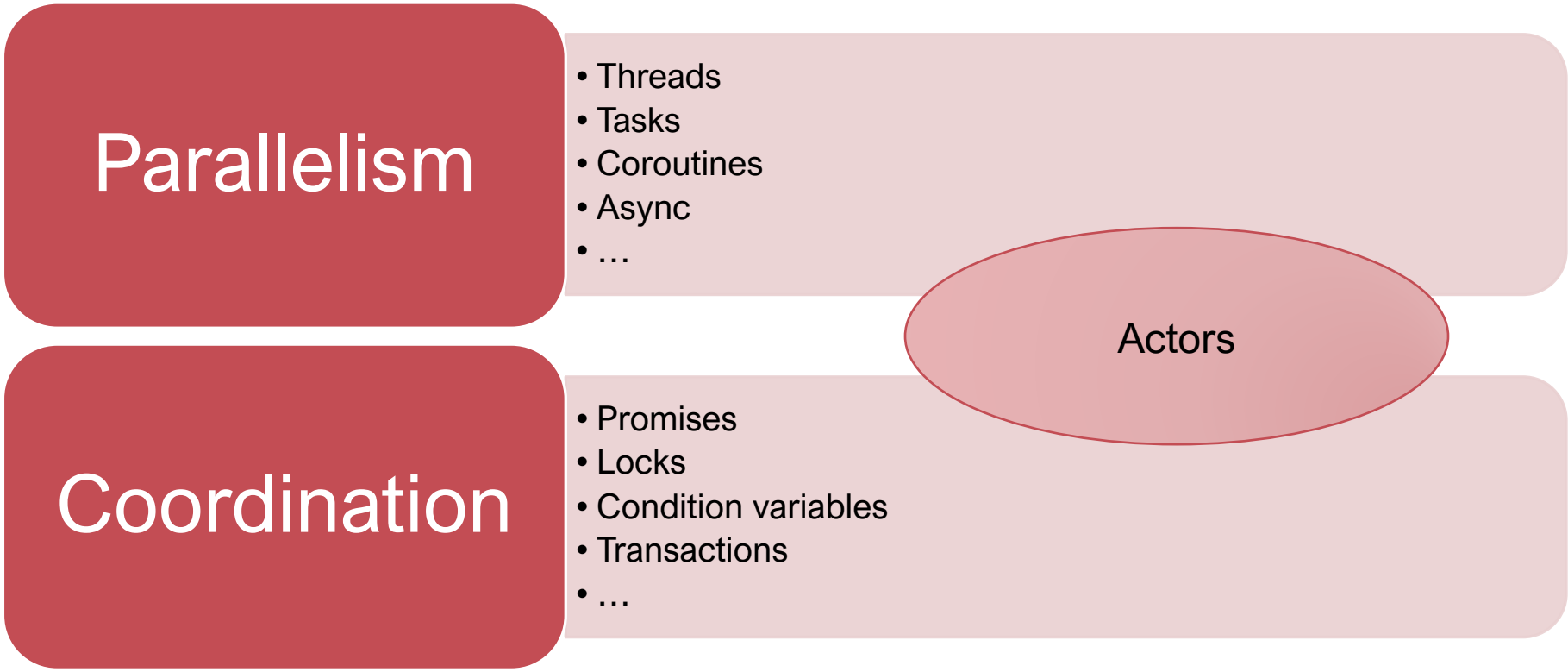


The concurrency story

Without concurrent mutation – concurrency cannot be a library.

Why revisit concurrency?

Without concurrent mutation – concurrency cannot be a library.



The origins
Why revisit concurrency?

- Matt: So how would you build a database with Actor Model Programming
- Sylvan: What do you mean?
- Matt: How do you represent a transaction over multiple tables with Actors?
- Sylvan: Yeah, that's hard!

- And thus Verona Concurrency was born

Today’s talk

- BOC in a nutshell
- BOC by example
- Semantics
- Implementation
- Evaluation

Behaviour-oriented concurrency – in a nutshell --

Cown - protects data

Behaviour - sole unit of execution; concurrent

Order - of behaviour execution

Behaviour-oriented concurrency – in a nutshell --

Cown – protects piece of separated data, ie provides unique external access to that data
- is *unavailable* (ie acquired by exactly one behaviour), or *available.*
- a behaviour may read/write only data protected by one of its acquired cowns.

Behaviour – the unit of (concurrent) execution.
- may be *spawned* with a list of required cowns.
- once spawned, a behaviour may *run* when all its required cowns are available
- while behaviour is running all its required cowns are un-available.
- when behaviour terminates, all it required cowns become available.
- cows are acquired/released atomically

Order – a behaviour may run only after all previously spawned behaviours with overlapping cowns have terminated.

Behaviour-oriented concurrency is PL parametric

Cown – protects piece of separated data, ie provides unique external access to that data

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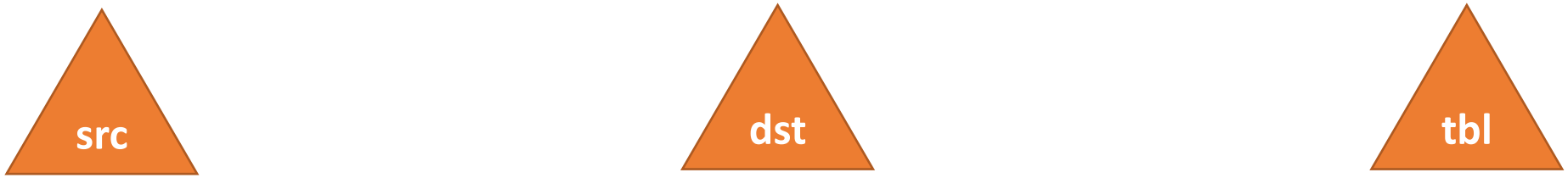
Cowns and protection

Cown – protects data, providing unique external read/write access to that data.



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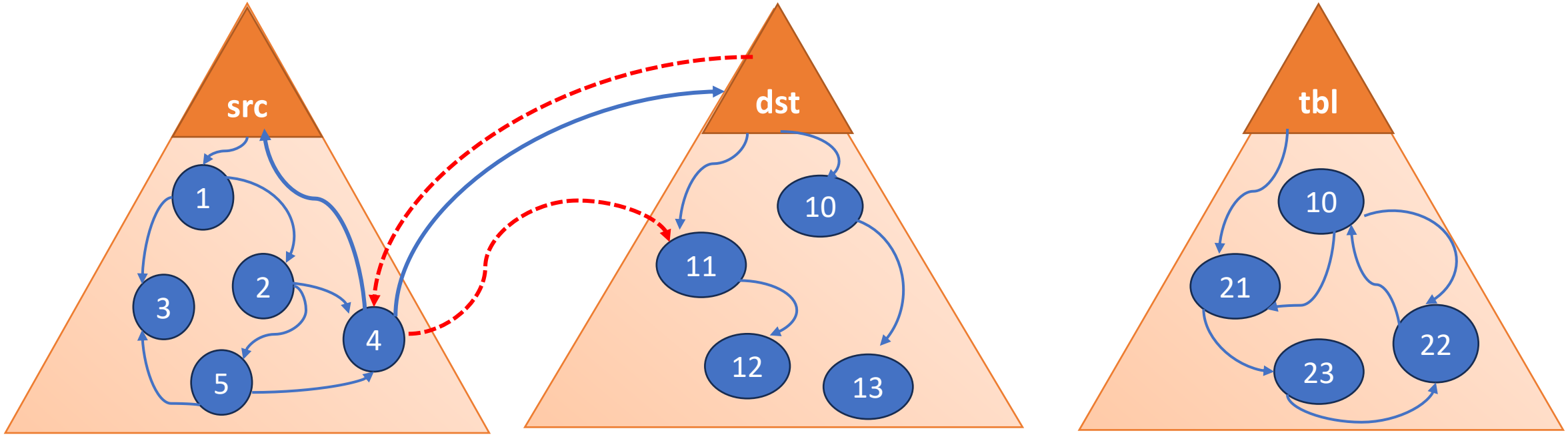

… the remit of the underlying PL's static/dynamic type system

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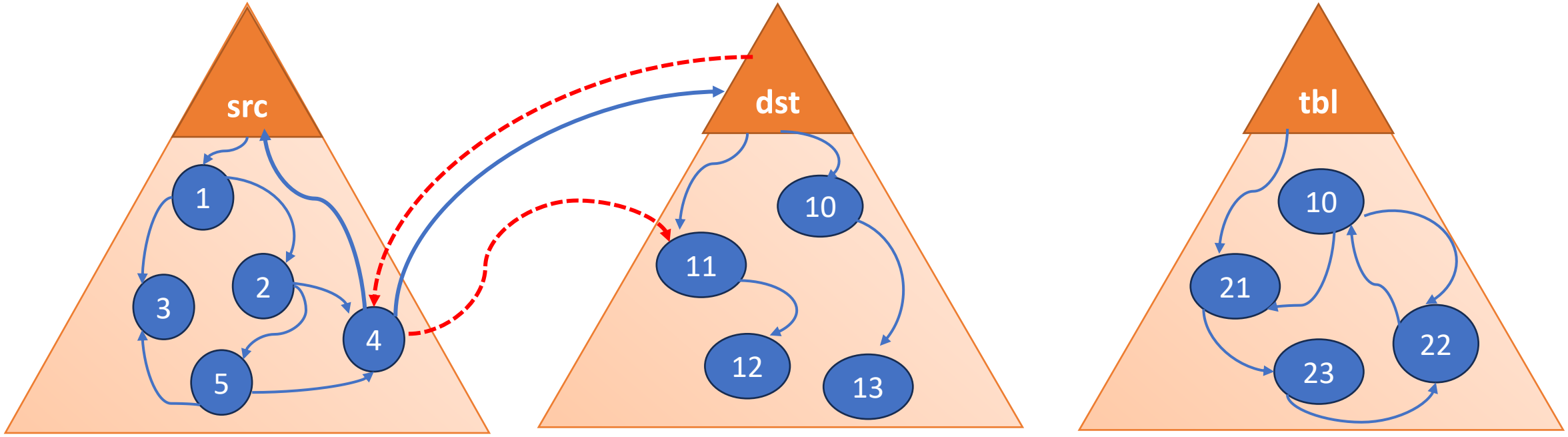

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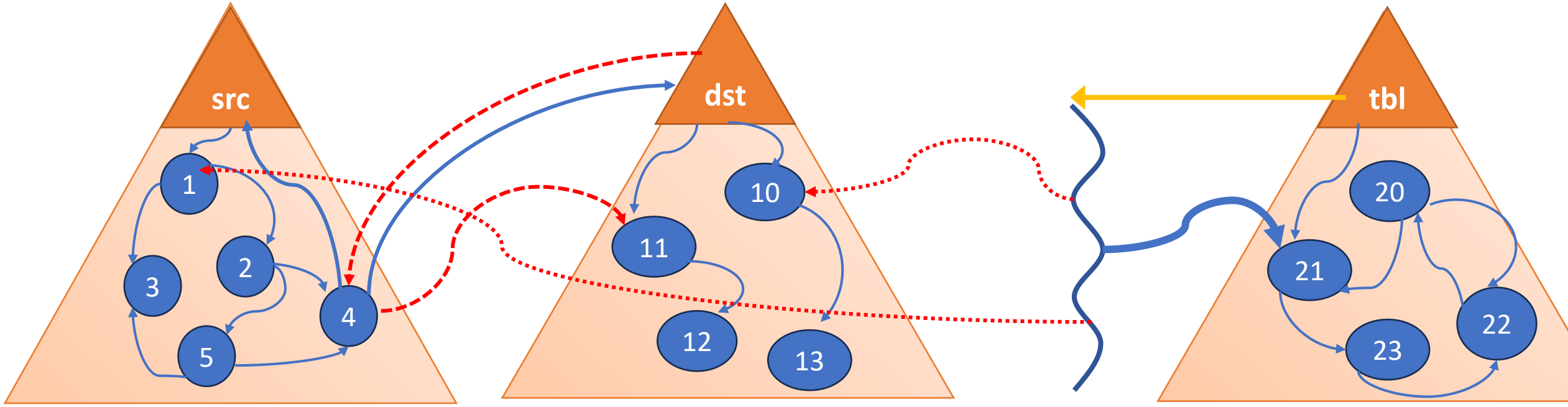
Cowns and protection

Cown – a behaviour may read/write only data protected by cowns it has acquired.



… a behaviour which has acquired tbl, may read/write 20, 21, … but *not* 10, 11, .. 1, 2, …

Cowns and protection

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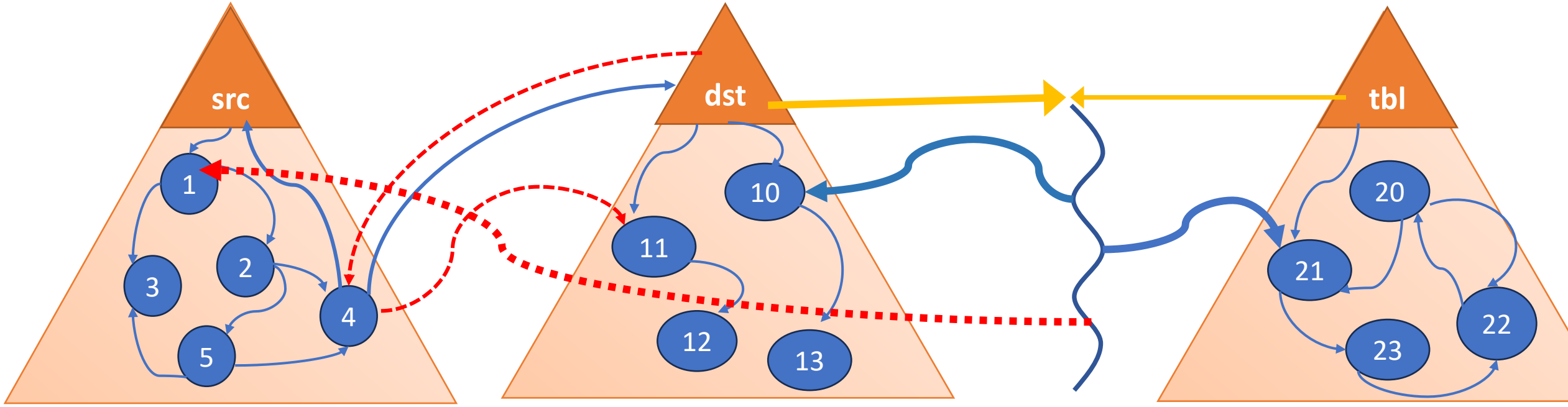

… a behaviour which has acquired tbl and dst may read/write 20, 21, … 10, 11 but *not* 1, 2, …

Cowns and protection

1. Cown protects piece of separated data, ie provides unique external access to that data.

2. Behaviour may only read/write data protected by its cowns.

3. Cown is *unavailable* (ie acquired by exactly one behaviour), or available (not acquired).

Therefore, Behaviour Oriented Concurrency is **free from data-races.**

1, 2 is the remit of the underlying PL's static/dynamic type system.

3 is the remit of the Behaviour Oriented Concurrency extension.

Behaviour execution

Behaviour – the unit of (concurrent) execution.

- may be *spawned* with a list of required cowns.
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- while behaviour is running all its required cowns are un-available.
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- cows are acquired/released atomically

Order – a behaviour may run only after all previously spawned behaviours with overlapping cowns have terminated.

Therefore, Behaviour Oriented Concurrency is **free from deadlocks**.

Behaviour oriented programming by example

Creating Concurrent Owners (Cowns)

```
1.    var src = cown.create(Account.create(0));
2.    src.balance += 50; // illegal access
3.
4.    when (src) {
5.        src.balance -= amount;
6.  };
```

spawn behaviour

Creating Concurrent Owners (Cowns)

```
1.    var src = cown.create(Account.create(0));
2.    src.balance += 50; // illegal access
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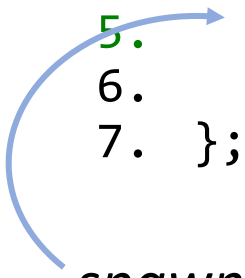

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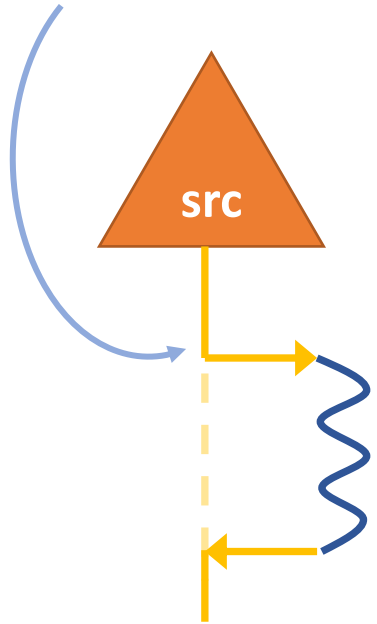
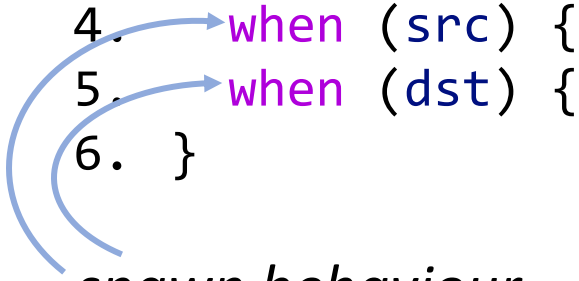
spawn behaviour

dispatch behaviour



Spawning and Dispatching behaviours

```
1.    transfer(src: cown[Account],
2.             dst: cown[Account],
3.             amount: U64) {
4.      when (src) { src.balance -= amount; };
5.      when (dst) { dst.balance += amount; };
6.  }
```



spawn behaviour

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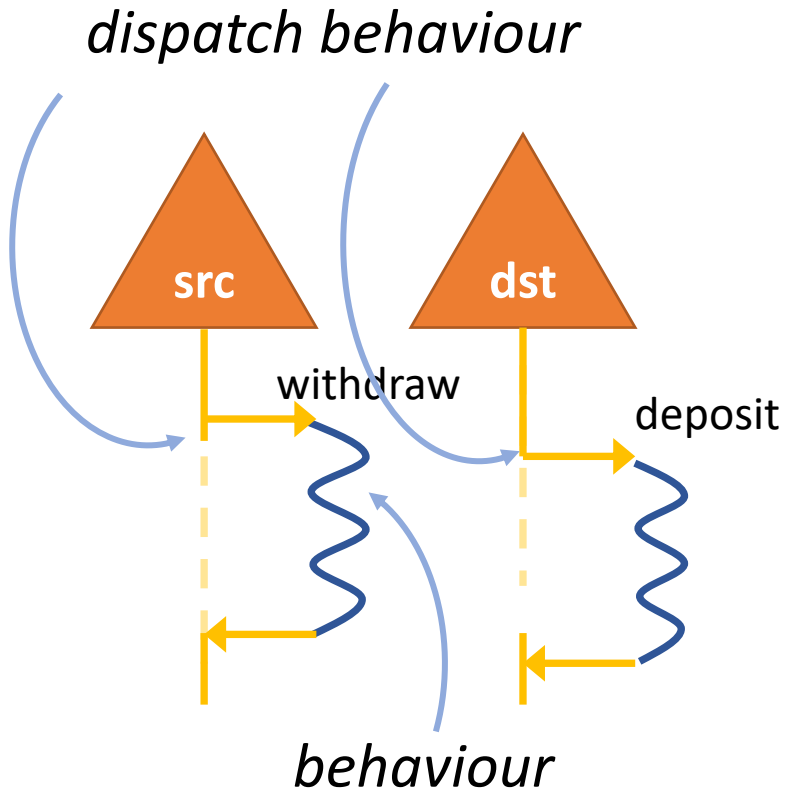
spawn behaviour



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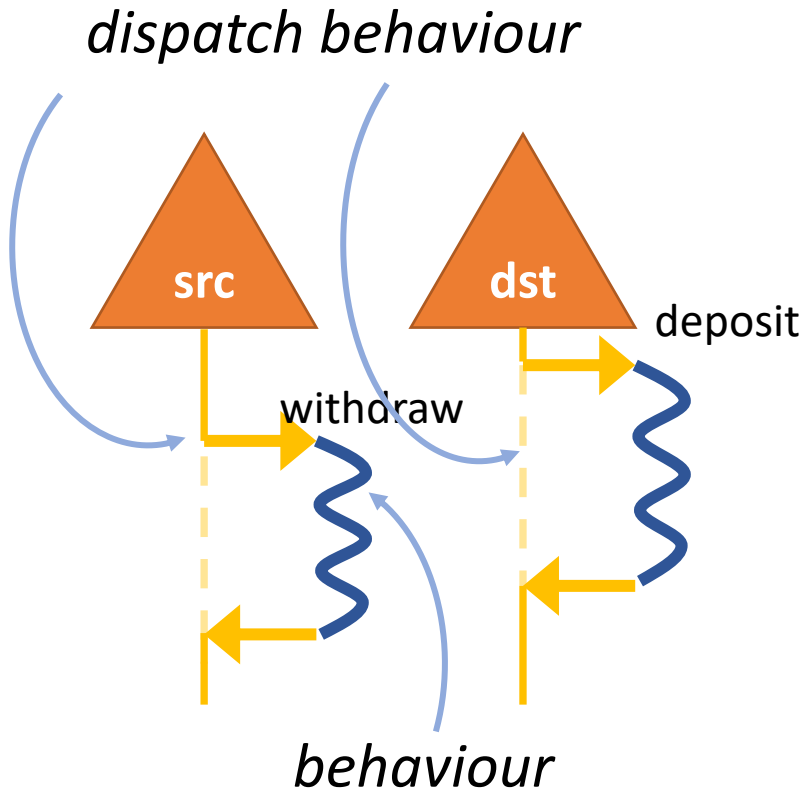
spawn behaviour



Is it possible that withdraw runs after deposit?

Order – a behaviour may run only after all previously spawned behaviours with overlapping cowns have terminated.

Spawning and Dispatching behaviours

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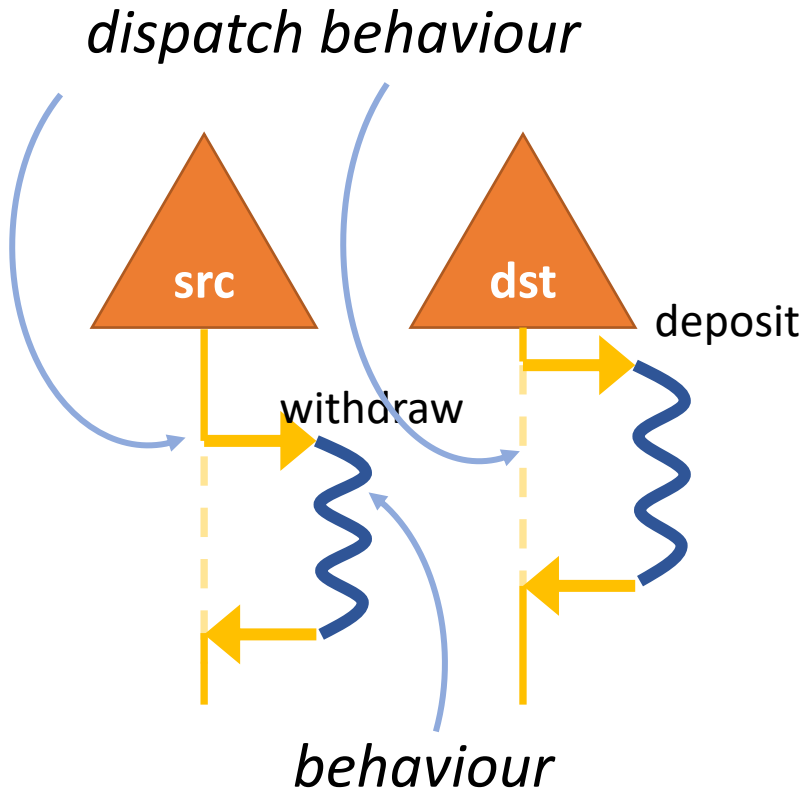
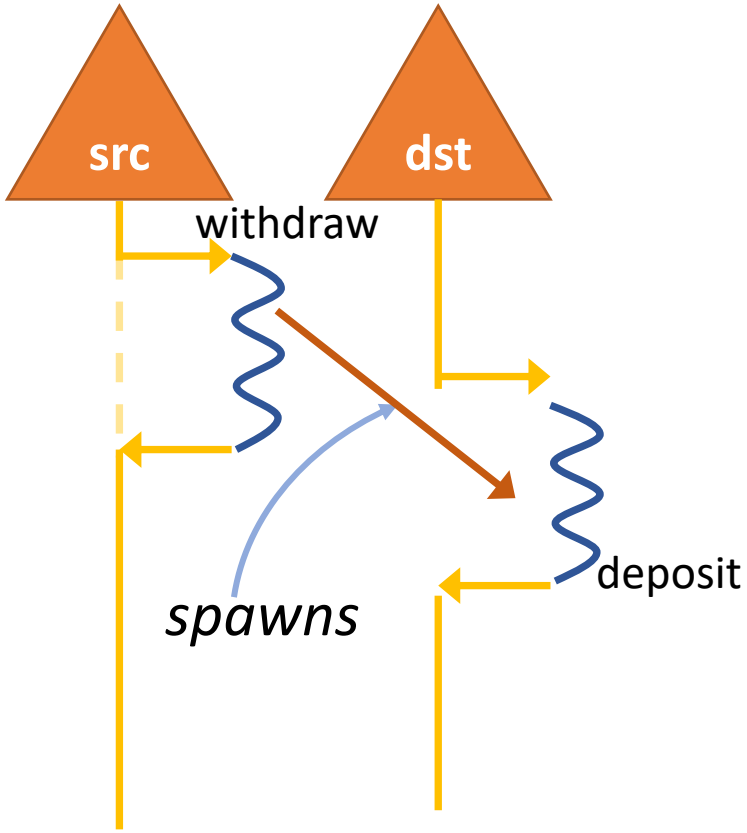


Is it possible that withdraw runs after deposit? **YES**

Spawning is synchronous, dispatching is asynchronous

Behaviours spawning behaviours

```
1.    transfer(src: cown[Account],
2.             dst: cown[Account],
3.             amount: U64) {
4.    when (src) {
5.      if (src.balance >= amount) {
6.        src.balance -= amount;
7.        when (dst) { dst.balance += amount; }
8.      }
9.    }
10.}
```



Behaviours spawning behaviours

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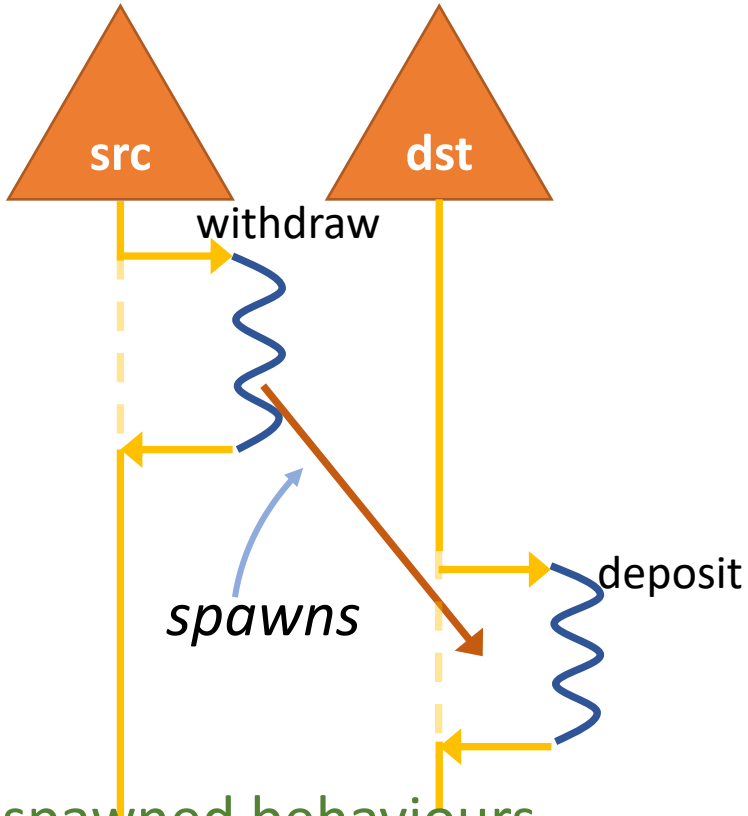

Is this execution possible? **YES**

Order – a behaviour may run only after all previously spawned behaviours with overlapping cowns have terminated.

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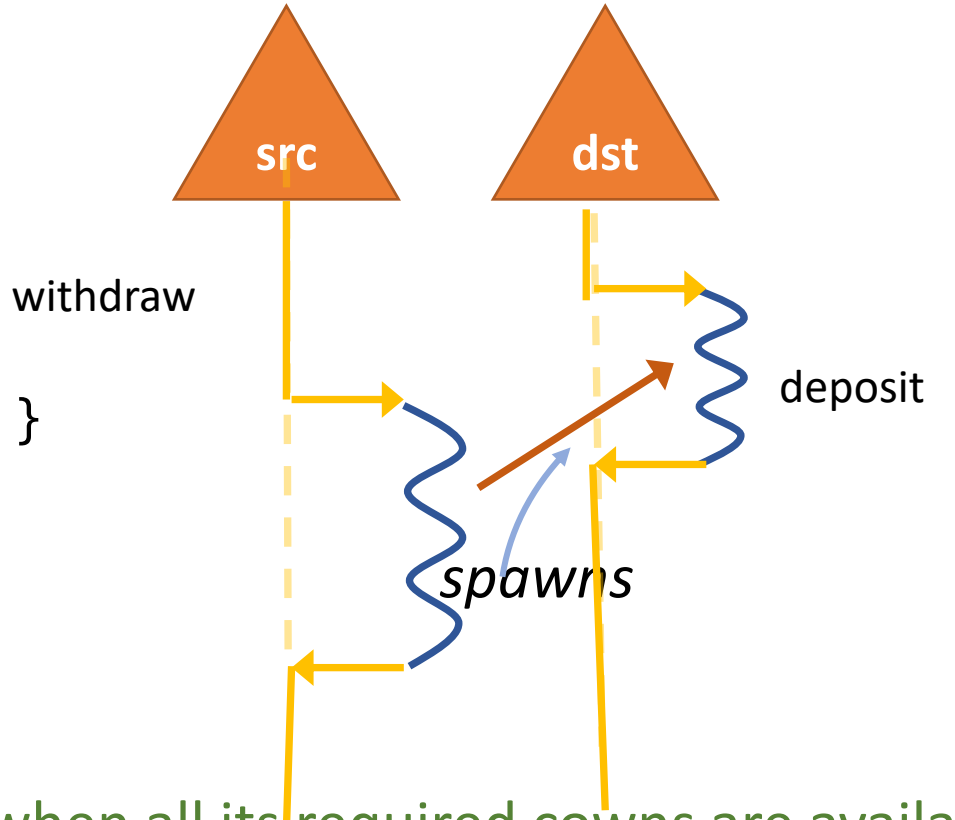

Is this execution possible? **NO**

Behaviour - once spawned, a behaviour may *run* when all its required cowns are available.

Behaviours spawning behaviours – data race freedom

```
1.    transfer(src: cown[Account],
2.             dst: cown[Account],
3.             amount: U64) {
4.    when (src) {
5.      if (src.balance >= amount) {
6.        src.balance -= amount;
7.        when (dst) { dst.balance += amount; }
8.      }
9.    }
10. }
```

`src` is cown[Account] here

`src` Account here

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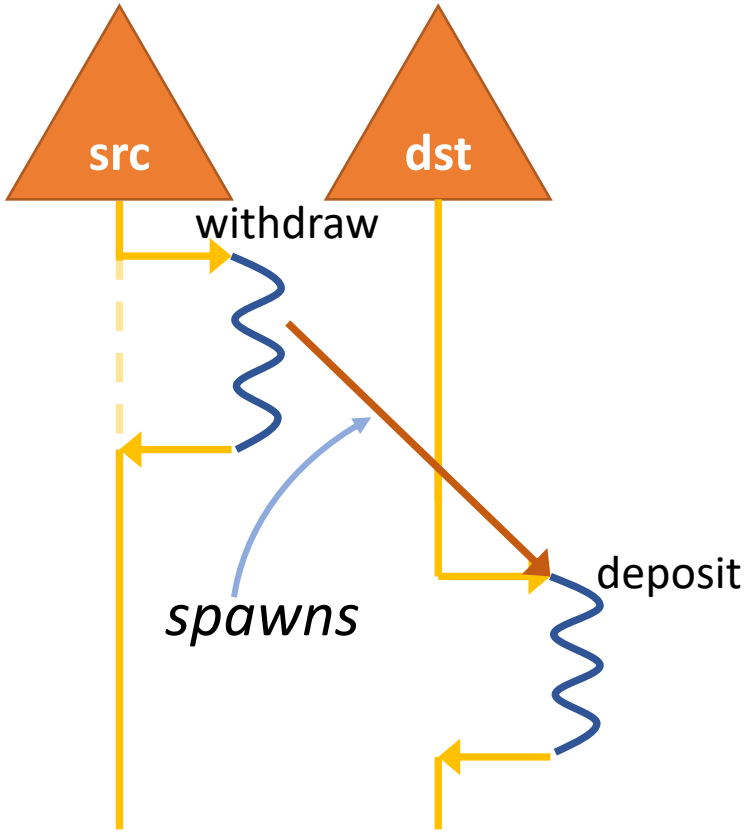

Behaviours spawning behaviours – Deadlock Freedom

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1.    transfer(src: cown[Account],
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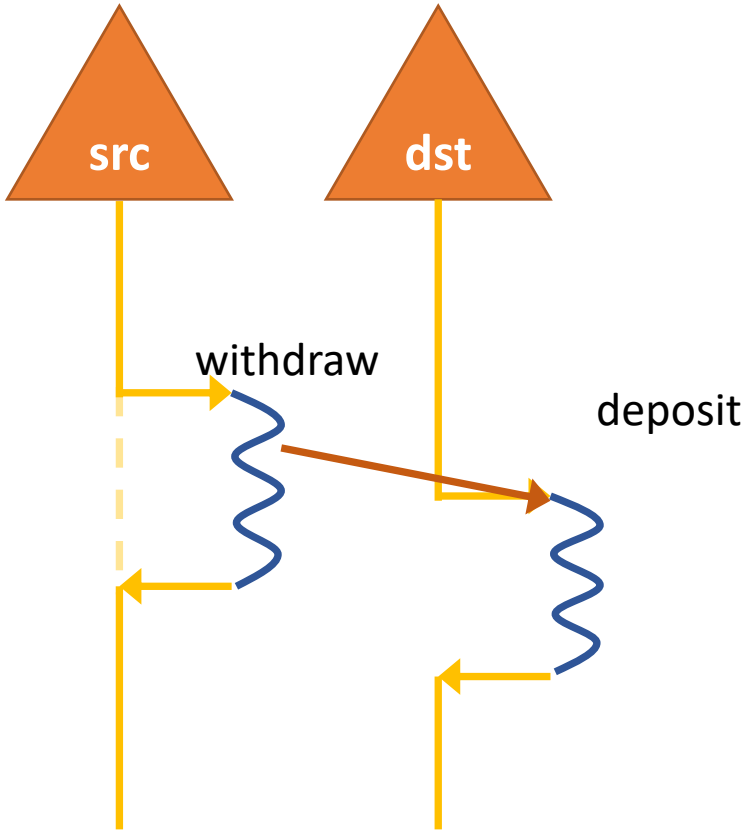

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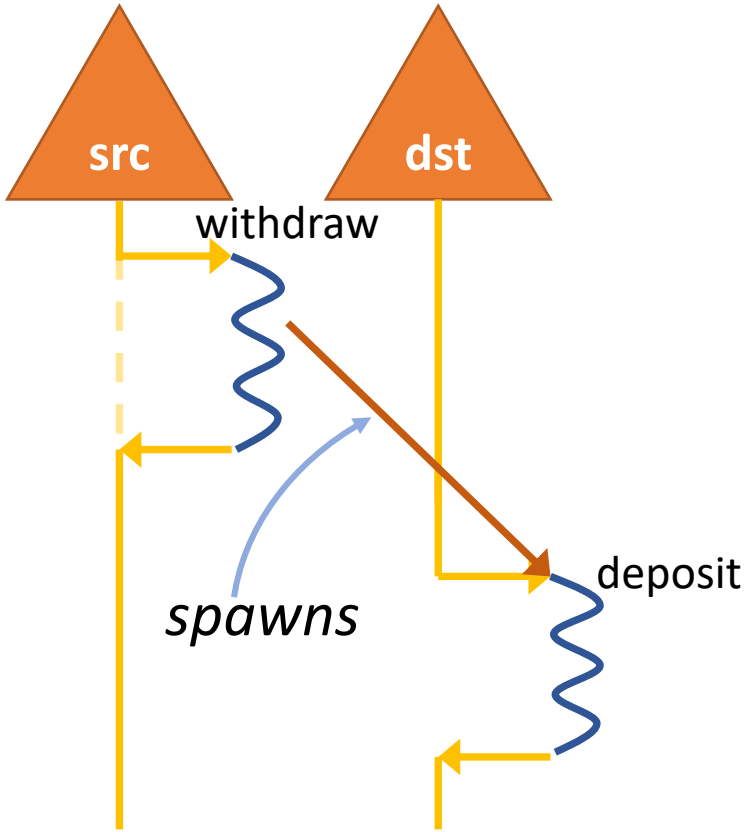

Deadlock Freedom - more

```
1.    transfer(src: cown[Account],
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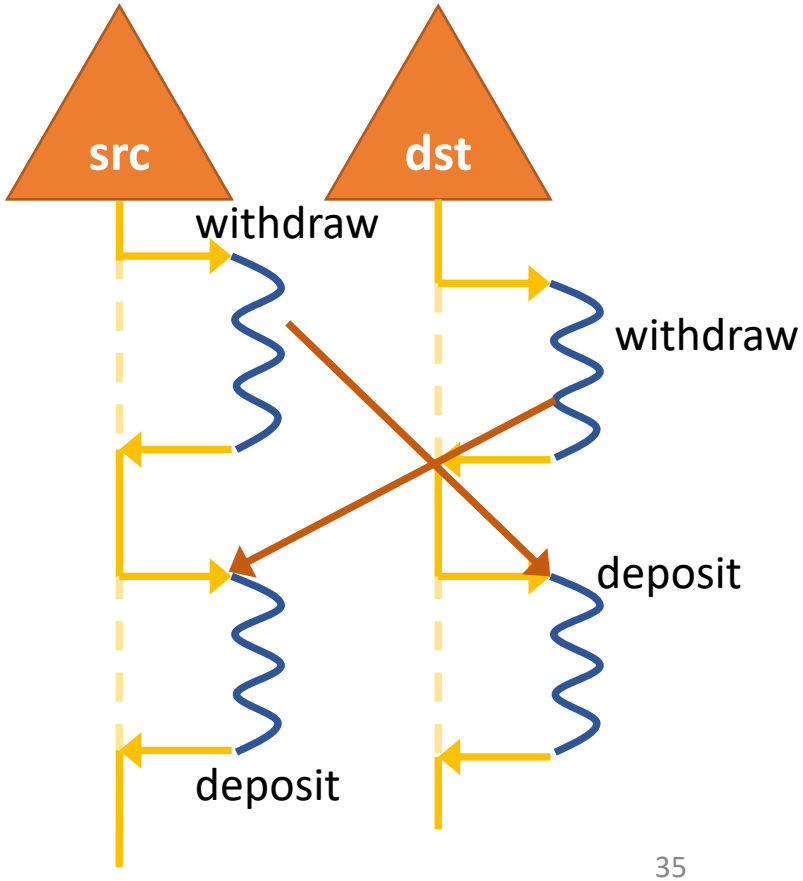
6.        src.balance -= amount;
7.        when (dst) { dst.balance += amount; }
8.      }
9.    }
10.}

11.…
12.  transfer(src, dst, 10);
13.  transfer(dst, src, 20);
```



Behaviours acquiring multiple cowns -- Flexible Coordination

```
1.    transfer(src: cown[Account],
2.             dst: cown[Account],
3.             amount: U64) {
4.    when (src, dst) {
5.      if (src.balance >= amount) {
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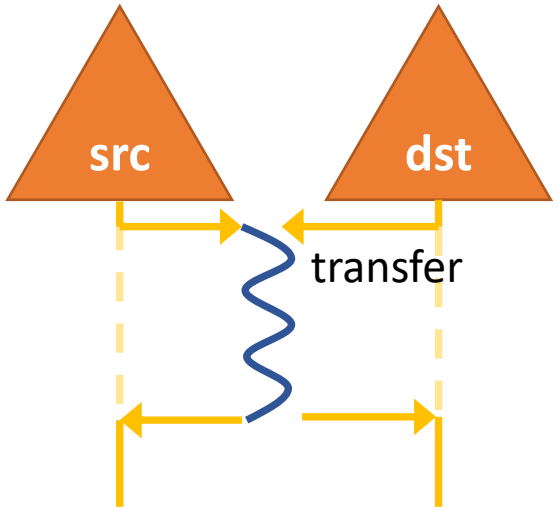
8.      }
9.    }
10.}
```



Order Matters

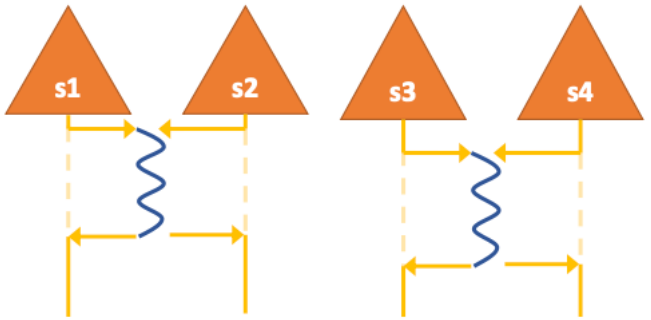
```
1.  main(a1, a2, a3: cown[Account]) {
2.    ….
3.        transfer(a1,a2,100);  // transfer_1
4.        transfer(a2,a3,300);  // transfer_2
5.    …
6.  }
```

Can transfer_1 and transfer_2 execute concurrently?	**NO**
Does it matter whether transfer_1 or transfer_2 execute first?	**YES**
May transfer_1 execute before transfer_2?	**YES**
May transfer_2 execute before transfer_1?	**NO**

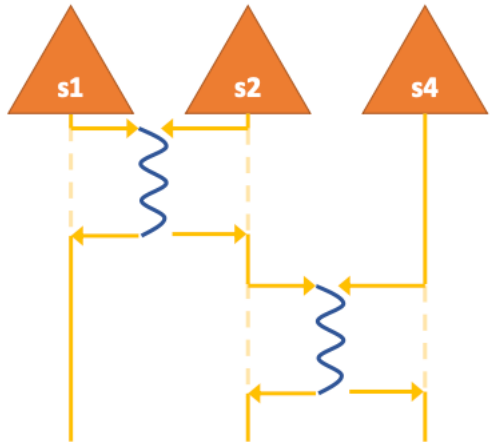
Order is dynamically determined

```
1.  main(s1, s2, s3, s4: cown[Account]) {
2.    ….
3.        transfer(s1,s2,100);  // transfer_1
4.        transfer(s3,s4,300);  // transfer_2
5.    …
6.  }
```

No aliases

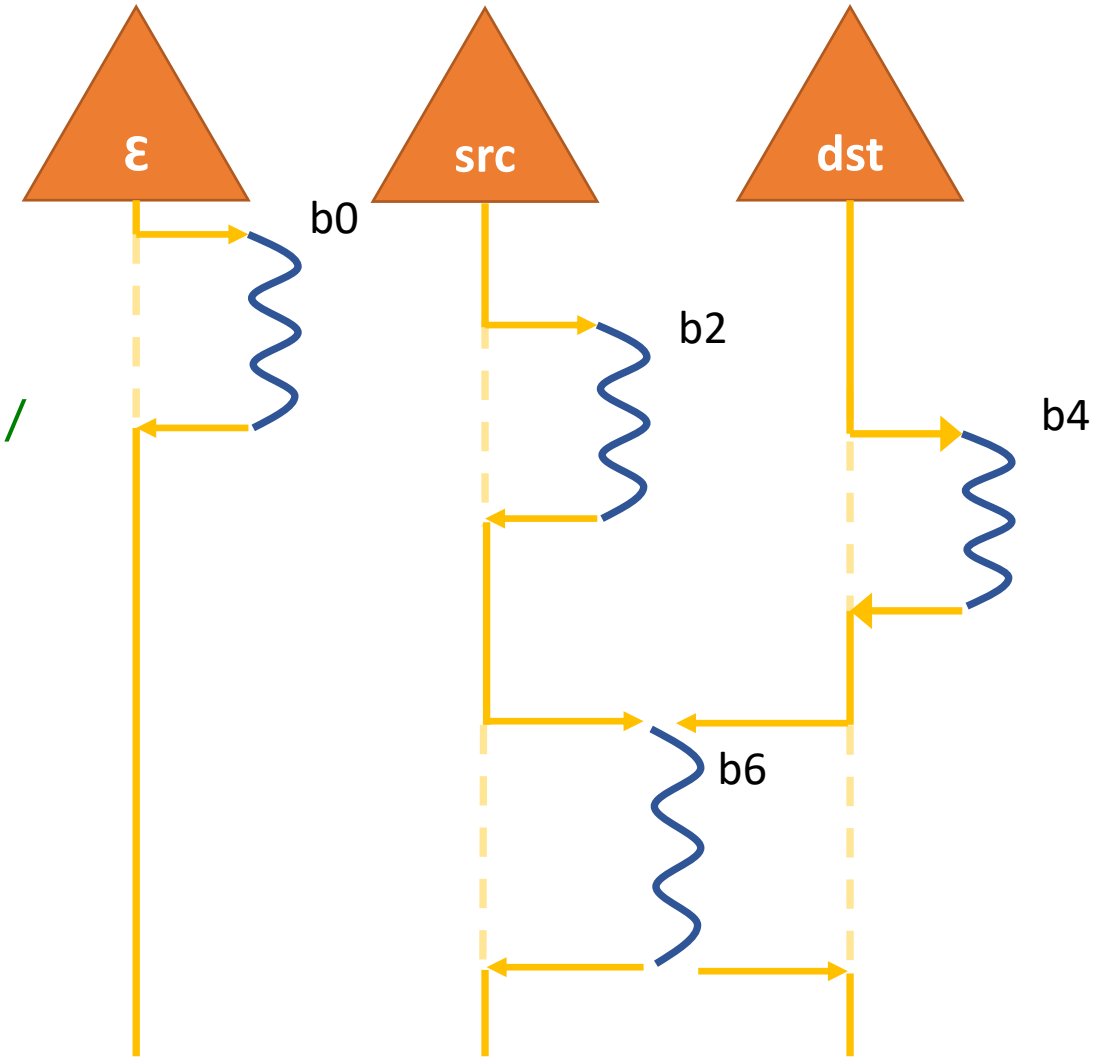


s2 and s3 are aliases, and no other aliases



Restricted Determinism

```
1.    main(src: cown[Account],
2.         dst: cown[Account]) { /* b0 */
3.    when (src) { /* b2 */ };
4.    when (dst) { /* b4 */ };
5.    when (src, dst) { /* b6 */ }
6. }
```



Restricted Determinism

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1.    main(src: cown[Account],
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5.    when (src, dst) { /* b6 */ }
6. }
```
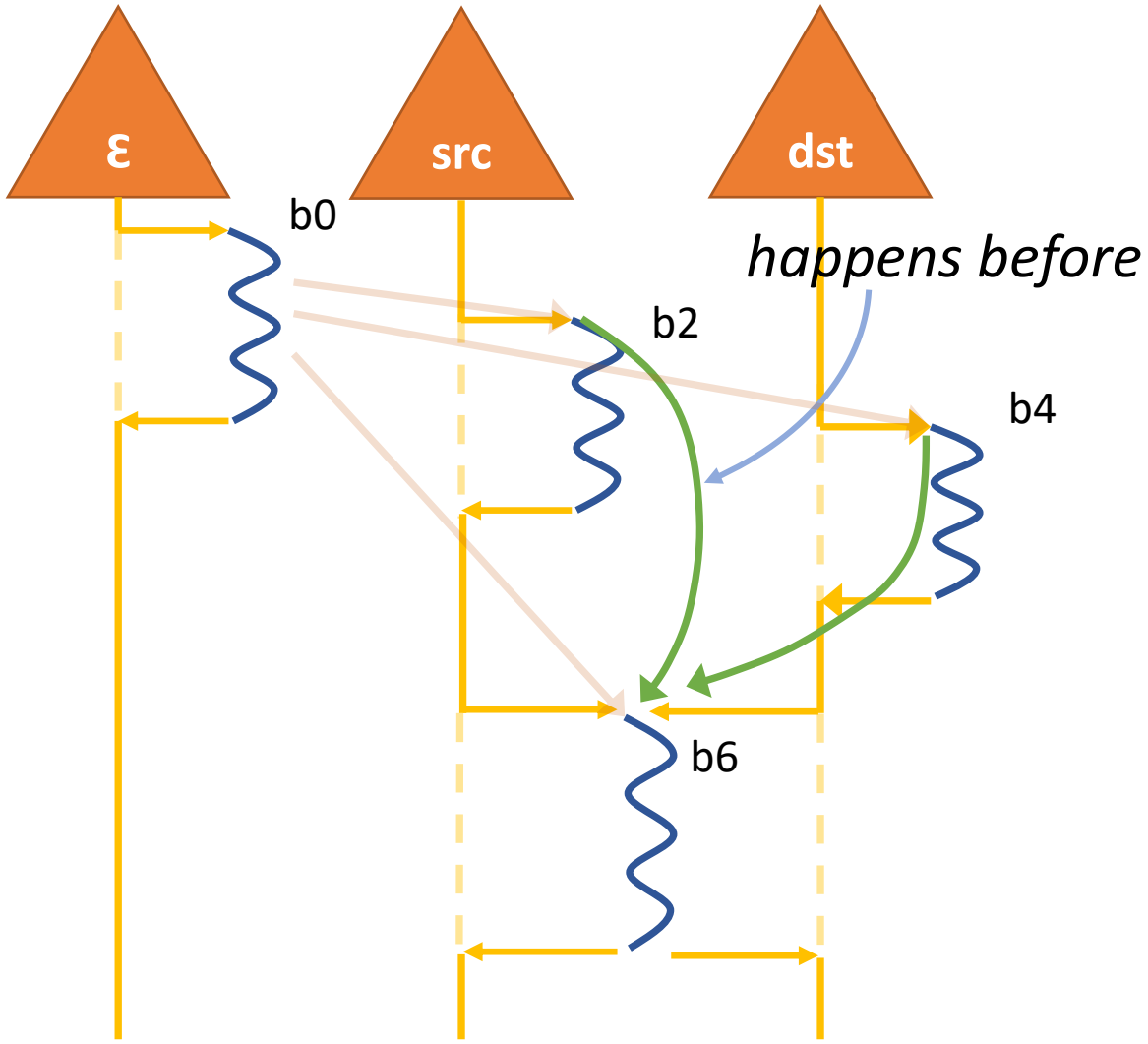
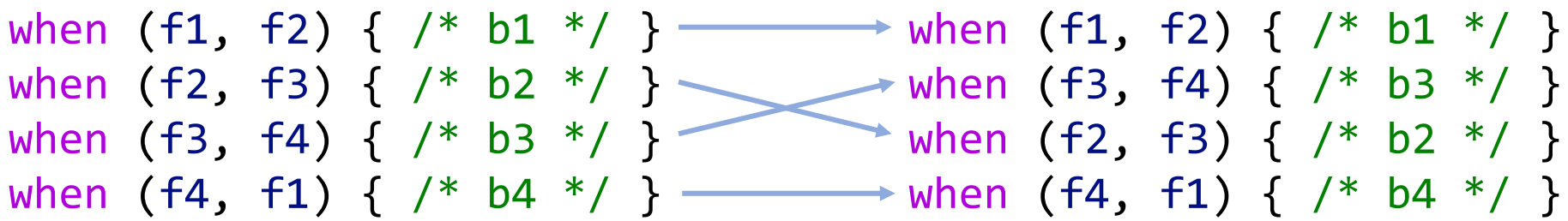



A challenge for the audience

```
when (f1, f2) { /* b1 */ }
when (f2, f3) { /* b2 */ }
when (f3, f4) { /* b3 */ }
when (f4, f1) { /* b4 */ }
```

What can execute in parallel?

An improvement to the solution



Optimal parallelism can be obtained using the paradigm


Semantics

Underlying Sequential Semantics

E Underlying sequential configuration, i.e. a closure

h Global state of the memory

$E, h \hookrightarrow E', h'$ Underlying sequential step

$finished(E)$ Predicate for termination

$E \hookrightarrow_{\text{when } (\overline{\kappa'}) \{E''\}} E'$ Trigger behaviour

Concurent Semantics

R Set of running behaviours (pairs of cowns and a closure $(\overline{\kappa}, E)$)

P List of pending behaviours (pairs of cowns and a closure $(\overline{\kappa}, E)$)

Concurrent Semantics

$$R, P, h \rightsquigarrow R, P, h$$

Concurrent Semantics

$$R, P, h \rightsquigarrow R, P, h$$

$$\textbf{STEP}\ \frac{E, h \hookrightarrow E', h'}{R \uplus (\overline{\kappa}, E), P, h \rightsquigarrow R \uplus (\overline{\kappa}, E'), P, h'} \qquad \textbf{SPAWN}\ \frac{E \hookrightarrow_{\text{when } (\overline{\kappa'})\ \{E''\}} E'}{R \uplus (\overline{\kappa}, E), P, h \rightsquigarrow R \uplus (\overline{\kappa}, E'), P : (\overline{\kappa'}, E''), h}$$

$$\textbf{RUN}\ \frac{\left(\bigcup_{(\overline{\kappa'}, \_) \in (P' \cup R)} \overline{\kappa'}\right) \cap \overline{\kappa} = \varnothing}{R, P' : (\overline{\kappa}, E) : P'', h \rightsquigarrow R \uplus (\overline{\kappa}, E), P' : P'', h} \qquad \textbf{END}\ \frac{\mathit{finished}(E)}{R \uplus (\overline{\kappa}, E), P, h \rightsquigarrow R, P, h}$$

Execution – Deadlock freedom

Execution – Deadlock freedom

$$\{(\varnothing, \texttt{transfer(s1, s2, 1); transfer(s2, s1, 2)})\}, [], h \rightsquigarrow^*$$

$$\varnothing, [(\{s1\}, \texttt{w1; when(s2) \{ d2 \}}), (\{s2\}, \texttt{w2; when(s1) \{ d1 \}})], h \rightsquigarrow$$

$$\{(\{s2\}, \texttt{w2; when(s1) \{ d1 \}})\}, [(\{s1\}, \texttt{w1; when(s2) \{ d2 \}})], h \rightsquigarrow$$

$$\varnothing, [(\{s1\}, \texttt{w1; when(s2) \{ d2 \}}), (\{s1\}, \texttt{d1})], h' \rightsquigarrow^*$$

$$\{(\{s1\}, \texttt{w1; when(s2) \{ d2 \}})\}, [(\{s1\}, \texttt{d1})], h' \rightsquigarrow^*$$

$$\varnothing, [(\{s1\}, \texttt{d1}), (\{s2\}, \texttt{d2})], h' \rightsquigarrow^*$$

$$\{(\{s1\}, \texttt{d1}), (\{s2\}, \texttt{d2})\}, [], h''$$


Implementing the runtime

Main implementation challenges: represent *P*

$$\textsc{step}\ \frac{E, h \hookrightarrow E', h'}{R \uplus (\overline{\kappa}, E), P, h \rightsquigarrow R \uplus (\overline{\kappa}, E'), P, h'} \qquad \textsc{spawn}\ \frac{E \hookrightarrow_{\text{when } (\overline{\kappa'})\ \{E''\}} E'}{R \uplus (\overline{\kappa}, E), P, h \rightsquigarrow R \uplus (\overline{\kappa}, E'), P : (\overline{\kappa'}, E''), h}$$

$$\textsc{run}\ \frac{\left(\bigcup_{(\overline{\kappa'}, \_) \in (P' \cup R)} \overline{\kappa'}\right) \cap \overline{\kappa} = \varnothing}{R, P' : (\overline{\kappa}, E) : P'', h \rightsquigarrow R \uplus (\overline{\kappa}, E), P' : P'', h} \qquad \textsc{end}\ \frac{\mathit{finished}(E)}{R \uplus (\overline{\kappa}, E), P, h \rightsquigarrow R, P, h}$$

Efficient selection of a behaviour to dispatch

Efficient appending of spawned behaviours to end of queue

Concurrent updates of *P*

Atomicity of updates of *P*

Representing *P*

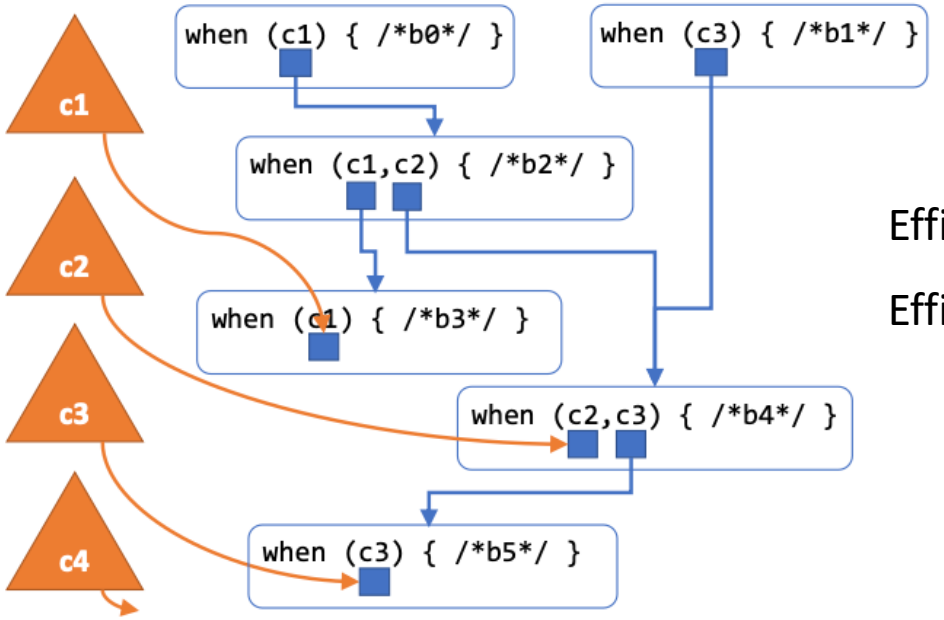
P is represented through a “dependency” graph; edges represent holding of a requested cown.

A behaviour requiring n cowns has n’ predecessors (n’<=n), meaning that it has already acquired n-n’ cowns.

We can dispatch any behaviour with no predecessors.

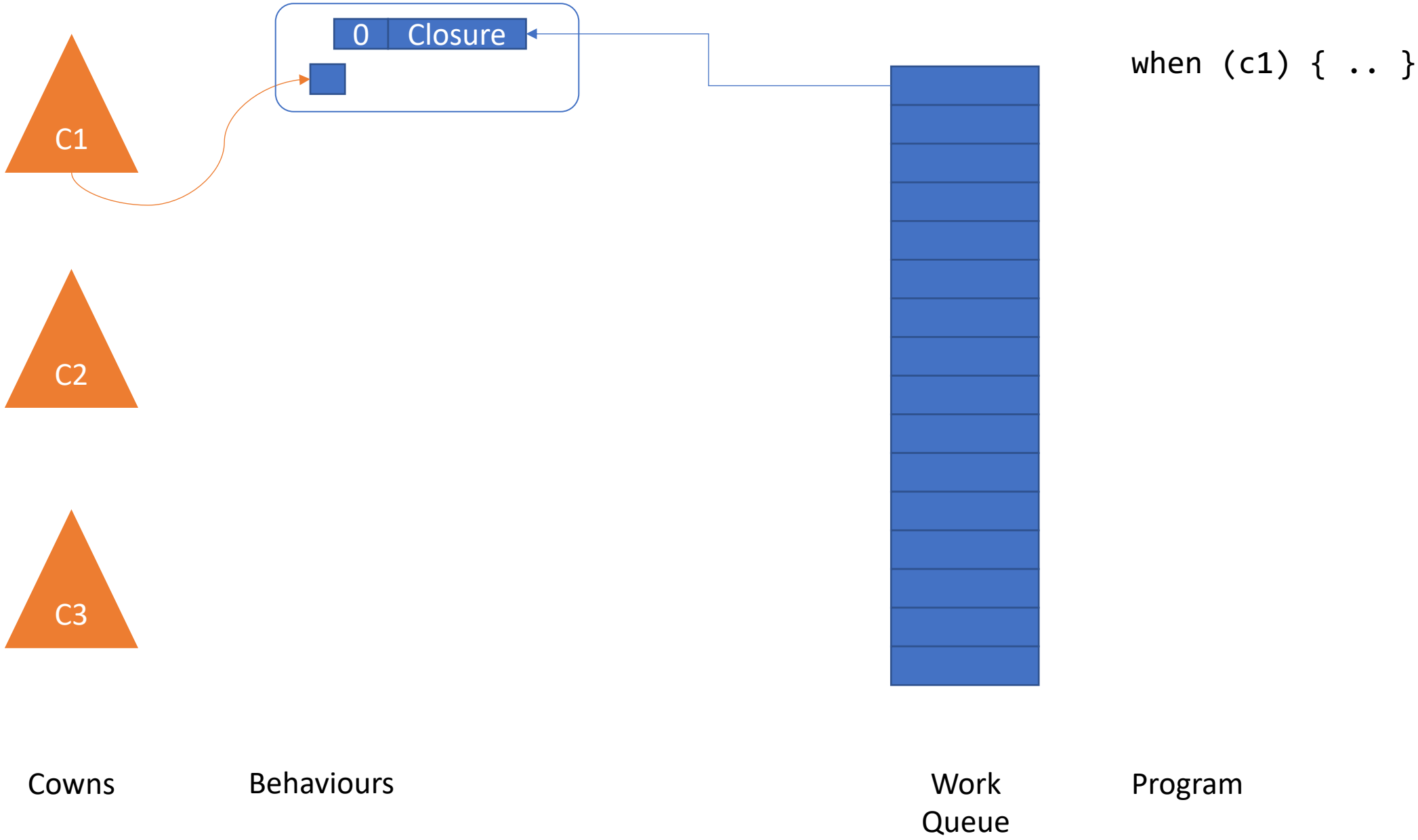
Spawning a behaviour attaches it to the ends of the queues of all its required cowns

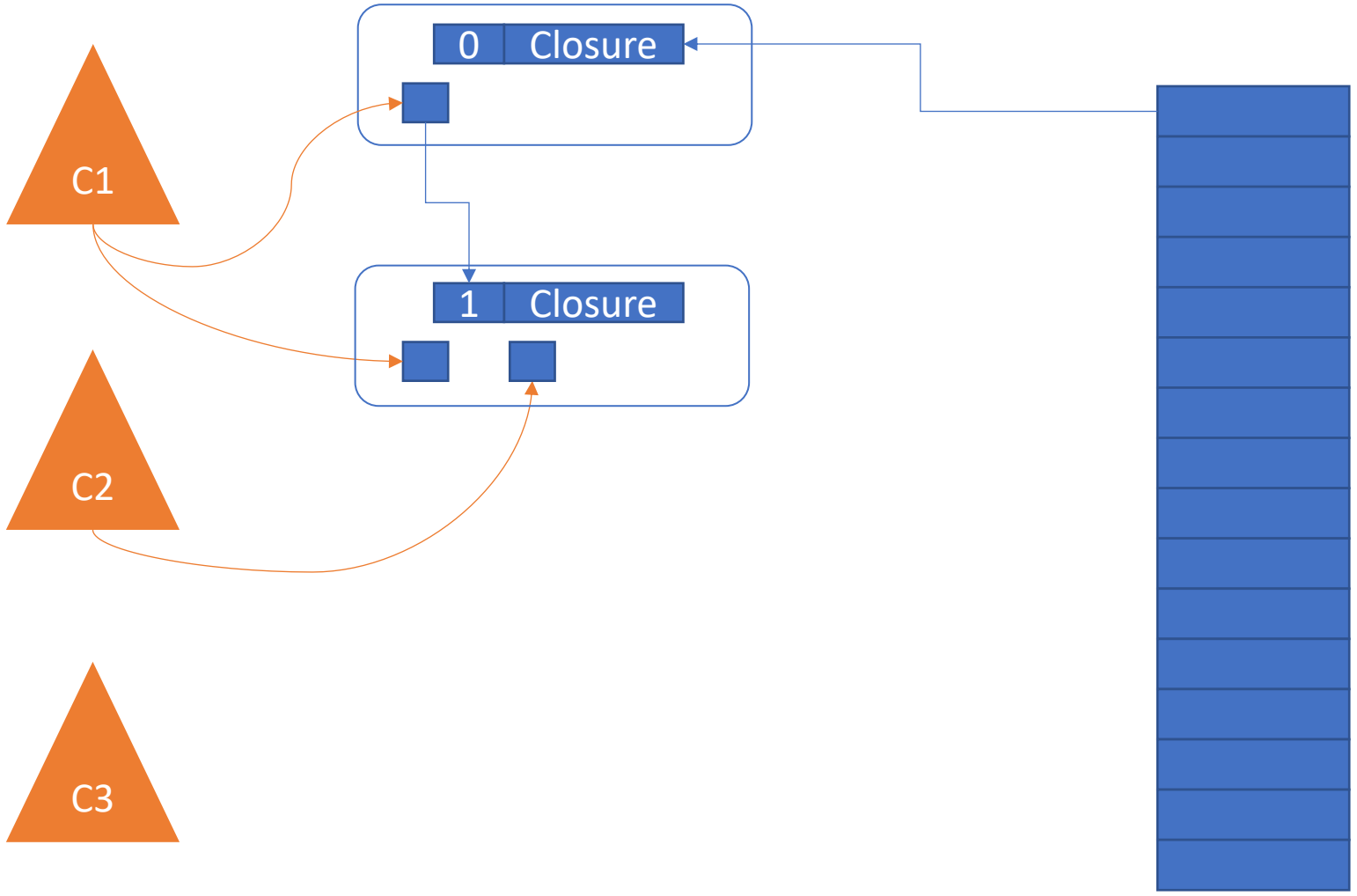
```
1
2   when (c1) { /* b0 */ }
3
4   when (c3) { /* b1 */ }
5
6   when (c1, c2) { /* b2 */ }
7
8   when (c1) { /* b3 */ }
9
10  when (c2, c3) { /* b4 */ }
11
12  when (c3) { /* b5 */ }
```



Efficient behaviour dispatch

Efficient behaviour spawning


0
Closure
C1
C2
C3
when (c1) { .. }
Cowns
Behaviours
Work Queue
Program



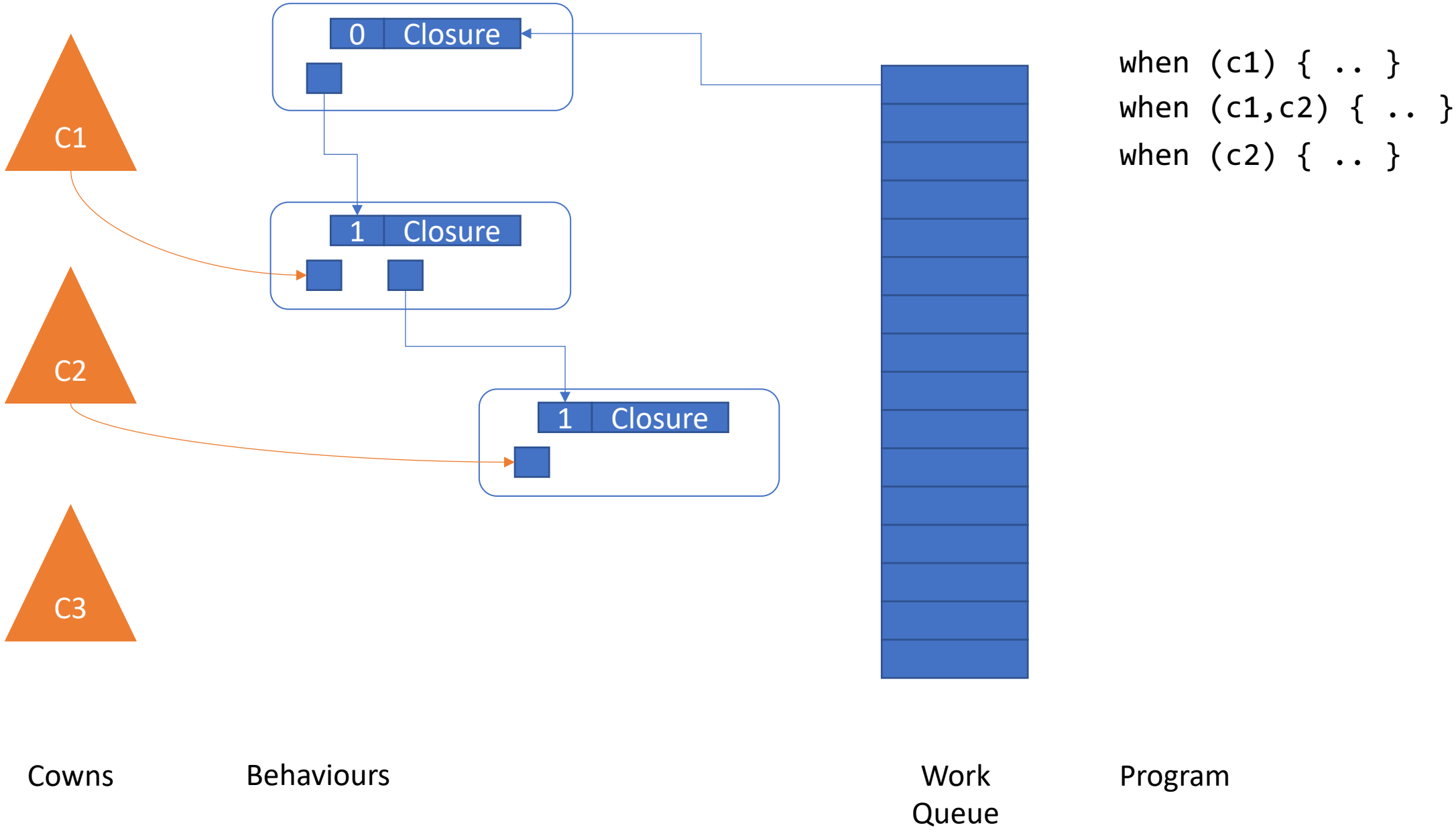

```
when (c1) { .. }
when (c1,c2) { .. }
```

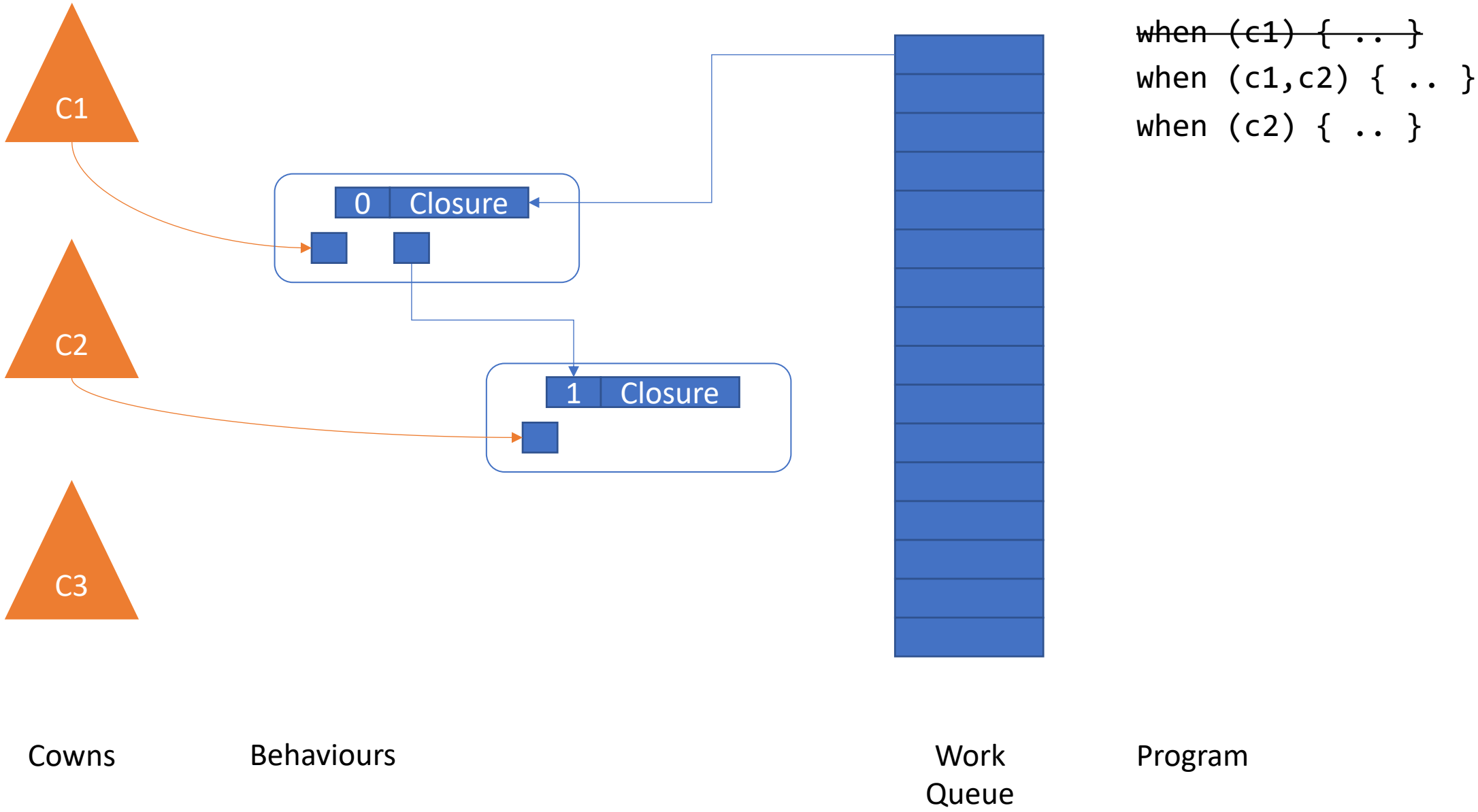
Cowns

Behaviours

Work Queue

Program


0 Closure
1 Closure
1 Closure
C1
C2
C3
when (c1) { .. }
when (c1,c2) { .. }
when (c2) { .. }
Cowns
Behaviours
Work Queue
Program



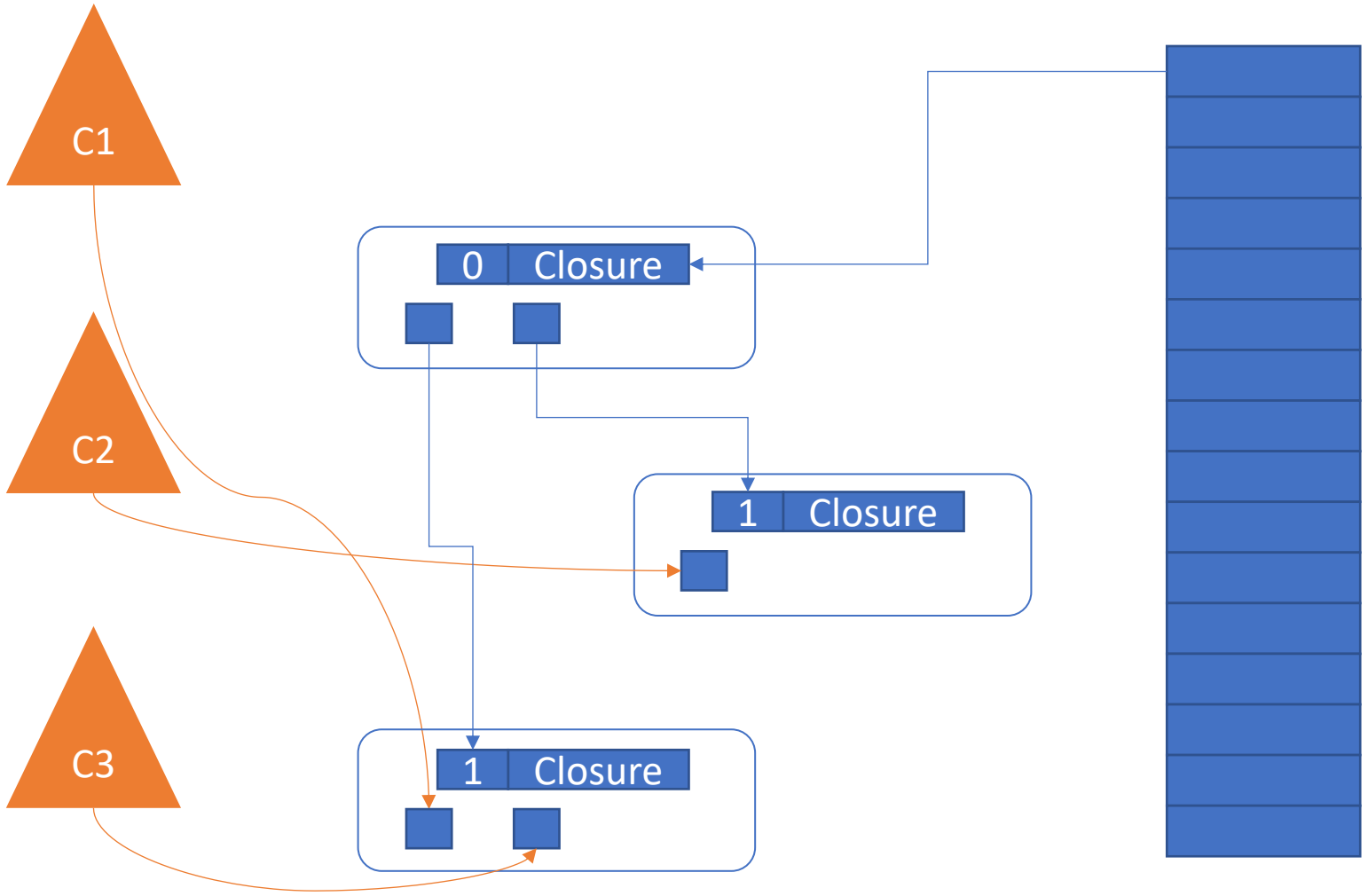
~~when (c1) { .. }~~
when (c1,c2) { .. }
when (c2) { .. }

Cowns

Behaviours

Work Queue

Program



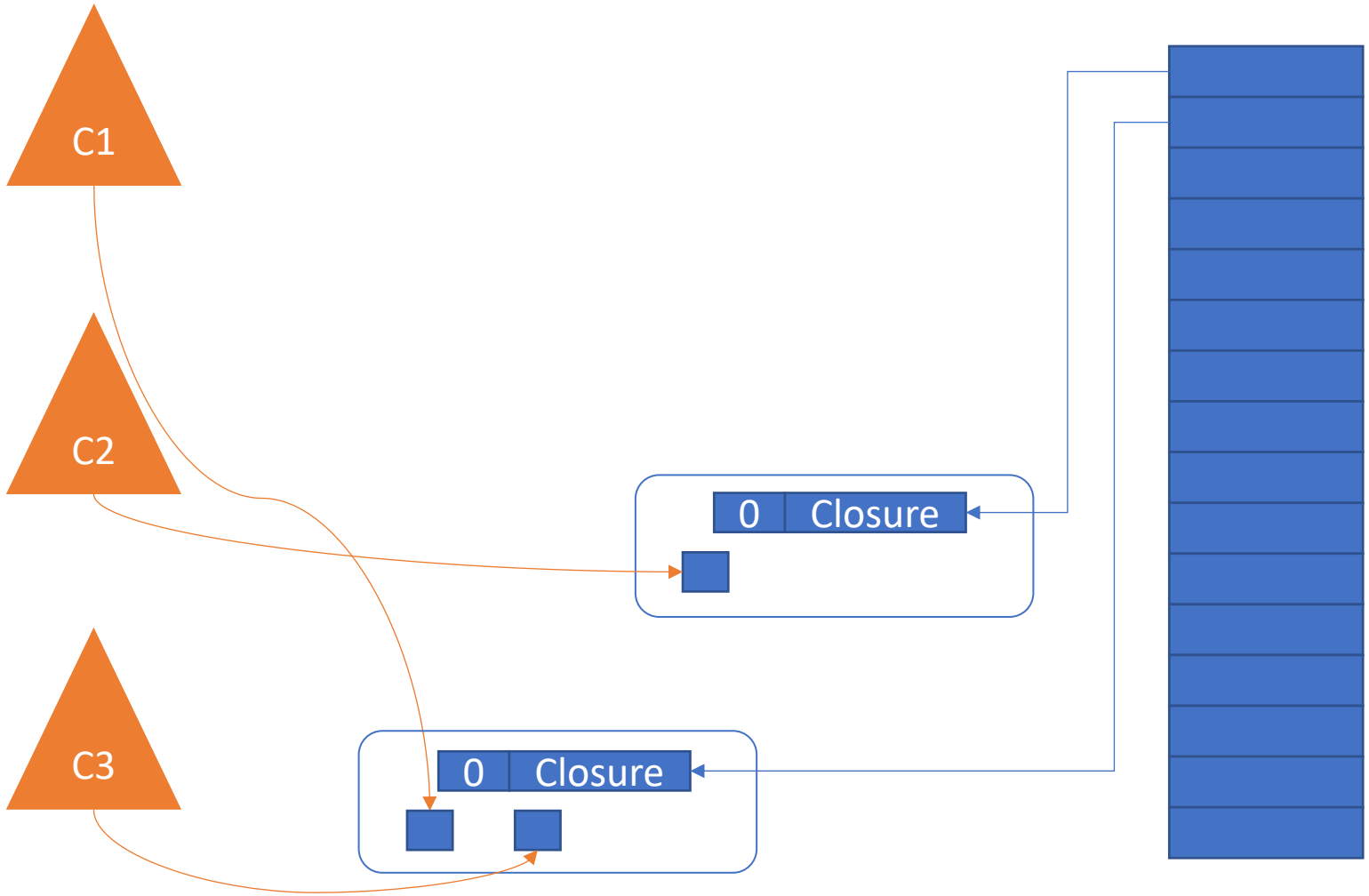
~~when (c1) { .. }~~
when (c1,c2) { .. }
when (c2) { .. }
when (c1,c3) { .. }

Cowns

Behaviours

Work Queue

Program



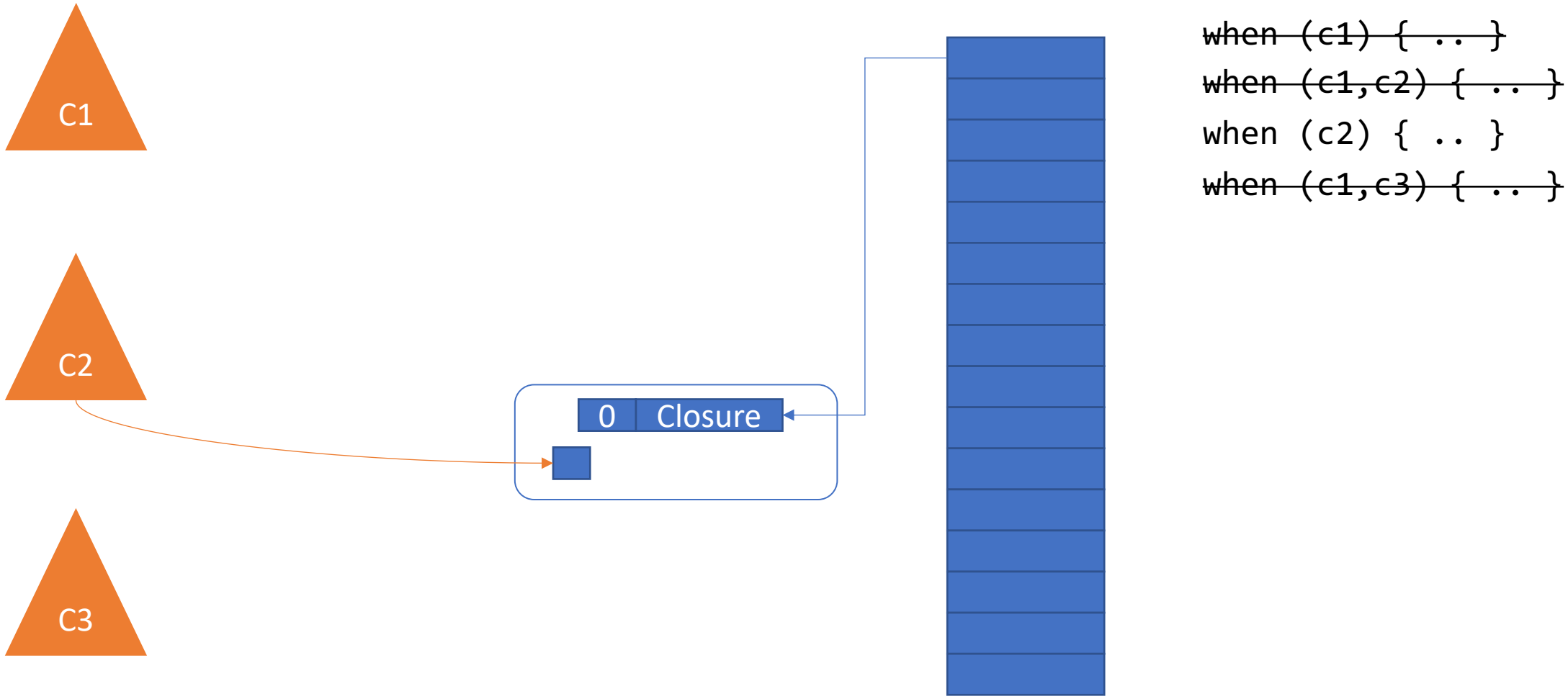
~~when (c1) { .. }~~
~~when (c1,c2) { .. }~~
when (c2) { .. }
when (c1,c3) { .. }

Cowns

Behaviours

Work Queue

Program



~~when (c1) { .. }~~
~~when (c1,c2) { .. }~~
when (c2) { .. }
~~when (c1,c3) { .. }~~

Cowns

Behaviours

Work Queue

Program

Main implementation challenges: represent *P*

$$\textsc{step}\ \frac{E, h \hookrightarrow E', h'}{R \uplus (\overline{\kappa}, E), P, h \rightsquigarrow R \uplus (\overline{\kappa}, E'), P, h'} \qquad \textsc{spawn}\ \frac{E \hookrightarrow_{\text{when } (\overline{\kappa'})\ \{E''\}} E'}{R \uplus (\overline{\kappa}, E), P, h \rightsquigarrow R \uplus (\overline{\kappa}, E'), P : (\overline{\kappa'}, E''), h}$$

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~~Efficient behaviour dispatch~~

~~Efficient behaviour spawning~~

Concurrent updates of *P*

Atomicity of updates of *P*

Key ideas

- MCS-Queue Lock
- Two phase “enqueue”

```
class CownBase : StableOrder {
  volatile Request? last = null;
}

class Request {
  volatile Behaviour? next = null;
  volatile bool scheduled = false;
  CownBase target;

  Request(CownBase t) { target = t; }

  void StartEnqueue(Behaviour behaviour) {
    var prev = Exchange(ref target.last, this);

    if (prev == null) {
      behaviour.ResolveOne();
      return;
    }
    while (!prev.scheduled) { /*spin*/ }
    prev.next = behaviour;
  }

  void FinishEnqueue() { scheduled = true; }

  void Release() {
    if (next == null) {
      if (CompareExchange(ref target.last,
                          null, this) == this)
        return;
      while (next == null) { /*spin*/ }
    }
    next.ResolveOne();
  }
}
```

```
class Behaviour {
  Action thunk;
  int count;
  Request[] requests;

  Behaviour(Action t, CownBase[] cowns) {
    thunk = t;
    requests = new Request[cowns.Length];
    for (int i = 0; i < cowns.Length; i++)
      requests[i] = new Request(cowns[i]);
  }

  static void Schedule(Action t,
                       params CownBase[] cowns) {
    Array.Sort(cowns);
    var behaviour = new Behaviour(t, cowns);
    behaviour.count = cowns.Length + 1;
    foreach (var r in behaviour.requests)
      r.StartEnqueue(behaviour);
    foreach (var r in behaviour.requests)
      r.FinishEnqueue();
    behaviour.ResolveOne();
  }

  void ResolveOne() {
    if (Decrement(ref count) != 0)
      return;
    Task.Run(() => {
      thunk();
      foreach (var r in requests)
        r.Release();
    });
} }
```

https://github.com/microsoft/verona-rt/blob/main/docs/internal/concurrency/modelimpl/When.cs

Evaluation of C++ implementation

https://github.com/Microsoft/verona-rt

Savina: BoC versus Actors

Table 2. Average runtime (ms) on selected Savina benchmarks

	BoC (Actor)					BoC (Full)					
										behaviours	
Benchmark	LoC	1 core (ms)	8 cores (ms)	cowns	behaviours	LoC	1 core (ms)	8 cores (ms)	cowns	1 cown	2 cowns
Banking	117	19.8 ± 0.6	22.6 ± 1.6	1001	252407	78	**7.9** ± 1.2	9.3 ± 4.5	1001	50001	50000
Chameneos	105	**46.1** ± 0.2	94.5 ± 1.4	101	800300	85	49.2 ± 0.3	122.1 ± 1.7	101	400100	200100
Count	40	46.1 ± 0.4	47.7 ± 0.4	2	1000002	30	**45.4** ± 0.4	46.9 ± 0.6	2	1000000	1
Dining Philosophers	94	73.3 ± 0.2	164.9 ± 0.9	21	1350118	61	22.2 ± 0.7	**16.6** ± 0.8	41	200020	199980
Fib	51	29.3 ± 0.3	19.4 ± 0.7	150049	300097	28	**10.9** ± 0.4	13.5 ± 0.8	75025	0	75024
Fork-Join Create	42	10.5 ± 0.4	12.4 ± 0.4	40001	80000	42	**9.6** ± 0.3	11.8 ± 0.3	40001	40000	40000
Fork-Join Throughput	53	53.4 ± 0.9	100.8 ± 0.6	61	1200000	52	**35.8** ± 1.2	45.8 ± 2.2	61	600000	60
Logistic Map Series	133	39.0 ± 0.4	41.2 ± 4.0	21	750022	52	**17.4** ± 1.0	19.8 ± 0.9	21	0	250010
Quicksort	121	124.7 ± 0.3	**58.8** ± 0.4	1935	3869	85	105.9 ± 0.3	78.6 ± 0.4	968	968	967
Sleeping Barber	127	1660 ± 0.1	3544 ± 0.9	5003	24027388	106	**12.5** ± 7.7	16.5 ± 10.2	5003	68077	10000
Trapezoid	72	970.0 ± 0.1	**172.0** ± 0.1	101	201	68	958.3 ± 0.1	172.6 ± 0.1	100	100	99

Savina-inspired: Banking

”Reasonable” Banking

- Several Tellers may issue transfers between shared accounts
- Transfers must be atomic
- Order of transfers per teller executed in the order issued
- No deadlock; no livelock

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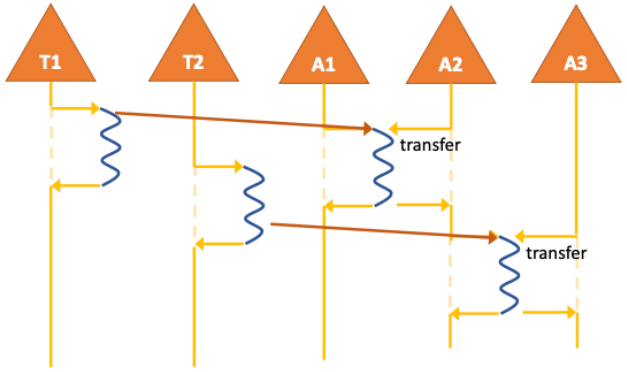
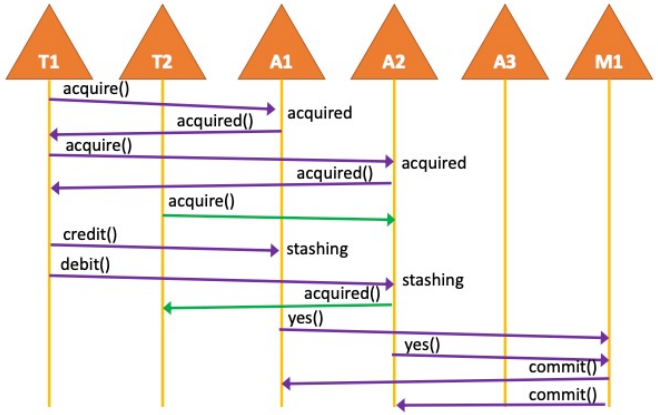


(a) with BoC (Full)



(b) with Actors

Savina-inspired: Banking

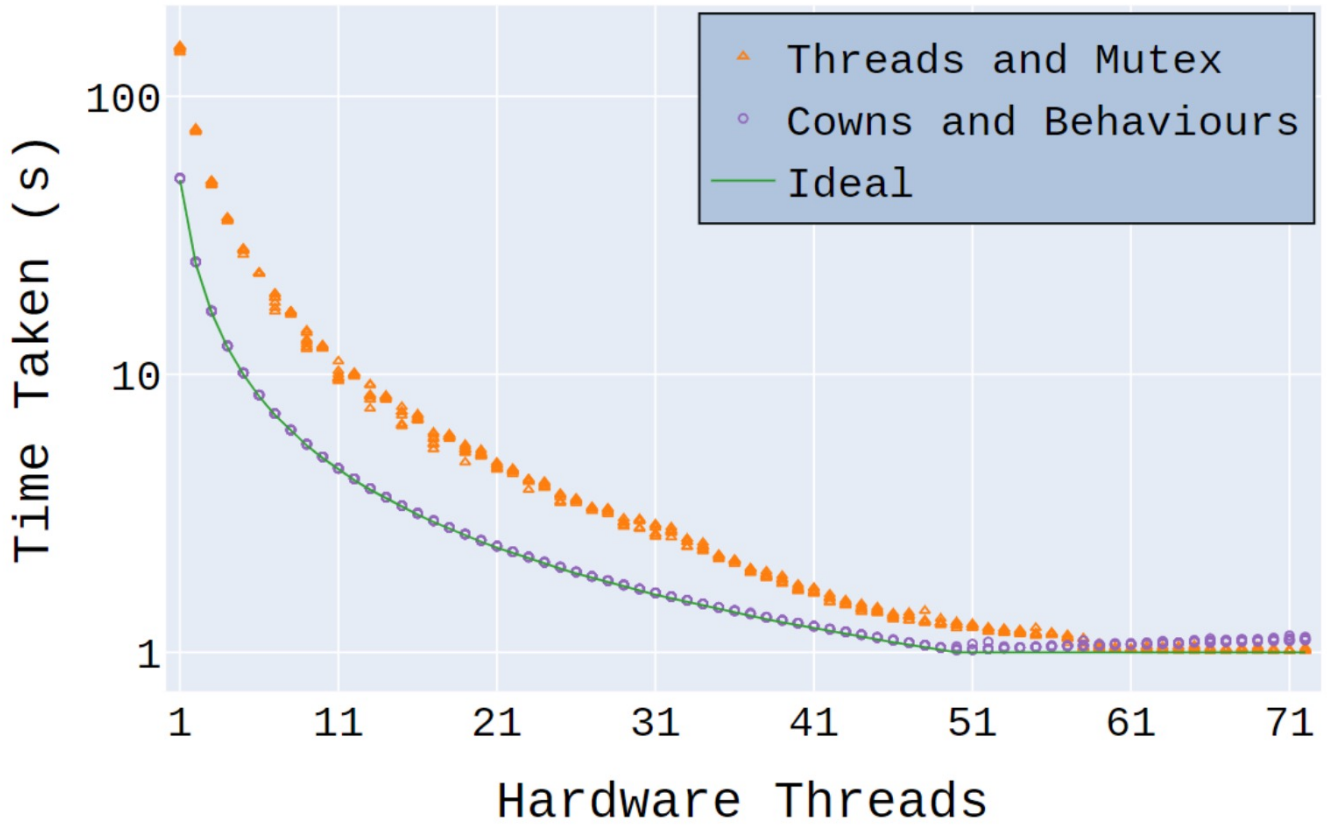
”Reasonable” Banking

- Several Tellers may issue transfers between shared accounts
- Transfers must be atomic
- Order of transfers per teller executed in the order issued
- No deadlock; no livelock

Table 4. Average runtime (ms) and lines of code (LoC) of ReasonableBanking benchmark

BoC (Full)			Pony		
LoC	1 core (ms)	8 cores (ms)	LoC	1 core (ms)	8 cores (ms)
78	7.9 ± 1.2	9.3 ± 4.5	226	987.9 ± 0.33	344.717 ± 0.35

Scaling- Dining Philosophers



What more is happening

Model implementation in C#

Full implementation in C++

Prototype implementation for Python

Performance comparison with Pony on Actor based benchmarks

Integration with ownership-based type systems

Relation to memory models

Promises and Whiteboards

Reasoning with Behaviour Oriented Concurrency

Conclusion: **`when`**, can we have it?

`when`

- is simple, intuitive and expressive,
- provides a single mechanism for both parallelism and coordination,
- it addresses the issue of the Actor model
- combines with ownership types

Why is concurrency important?

Cannot be a library without data-races

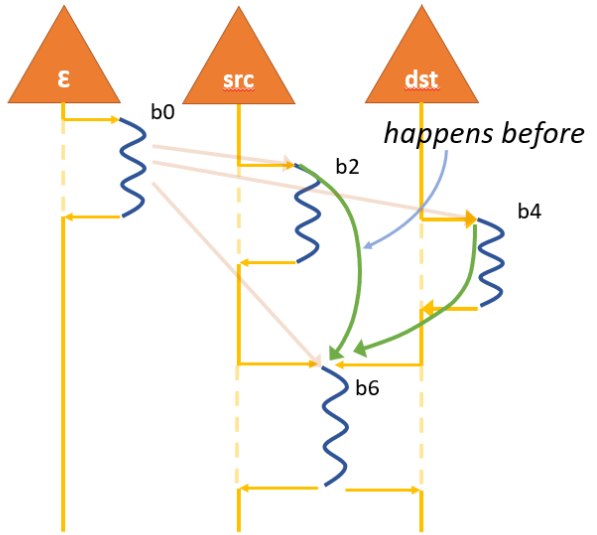
Parallelism
- Threads
- Tasks
- Coroutines
- …

Coordination
- Locks
- Queues
- Transactions
- …

Actors

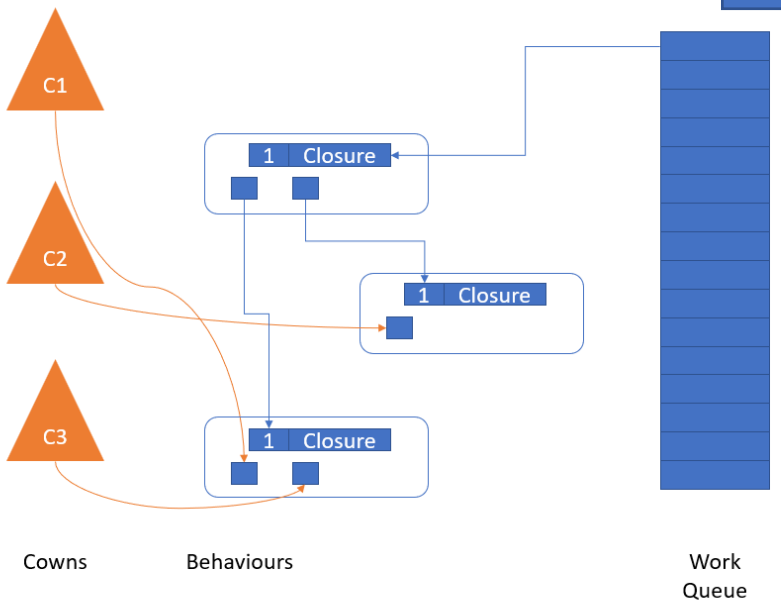
Restricted Determinism

```
1. main(src: cown[Account],
2.      dst: cown[Account]) { /* b0 */
3.   when (src) { /* b2 */ };
4.   when (dst) { /* b4 */ };
5.   when (src, dst) { /* b6 */ }
6. }
```



∀ b, b' . b happens before b' iff cownsof(b) ∩ cownsof(b') = ∅ and ∃ b_0 s.t. b_0 spawns b and subsequently b_0 spawns* b',

http://github.com/Microsoft/verona-rt




```
when (c1) { .. }
when (c1,c2) { .. }
when (c2) { .. }
when (c1,c3) { .. }
```

Program

Scaling- Dining Philosophers