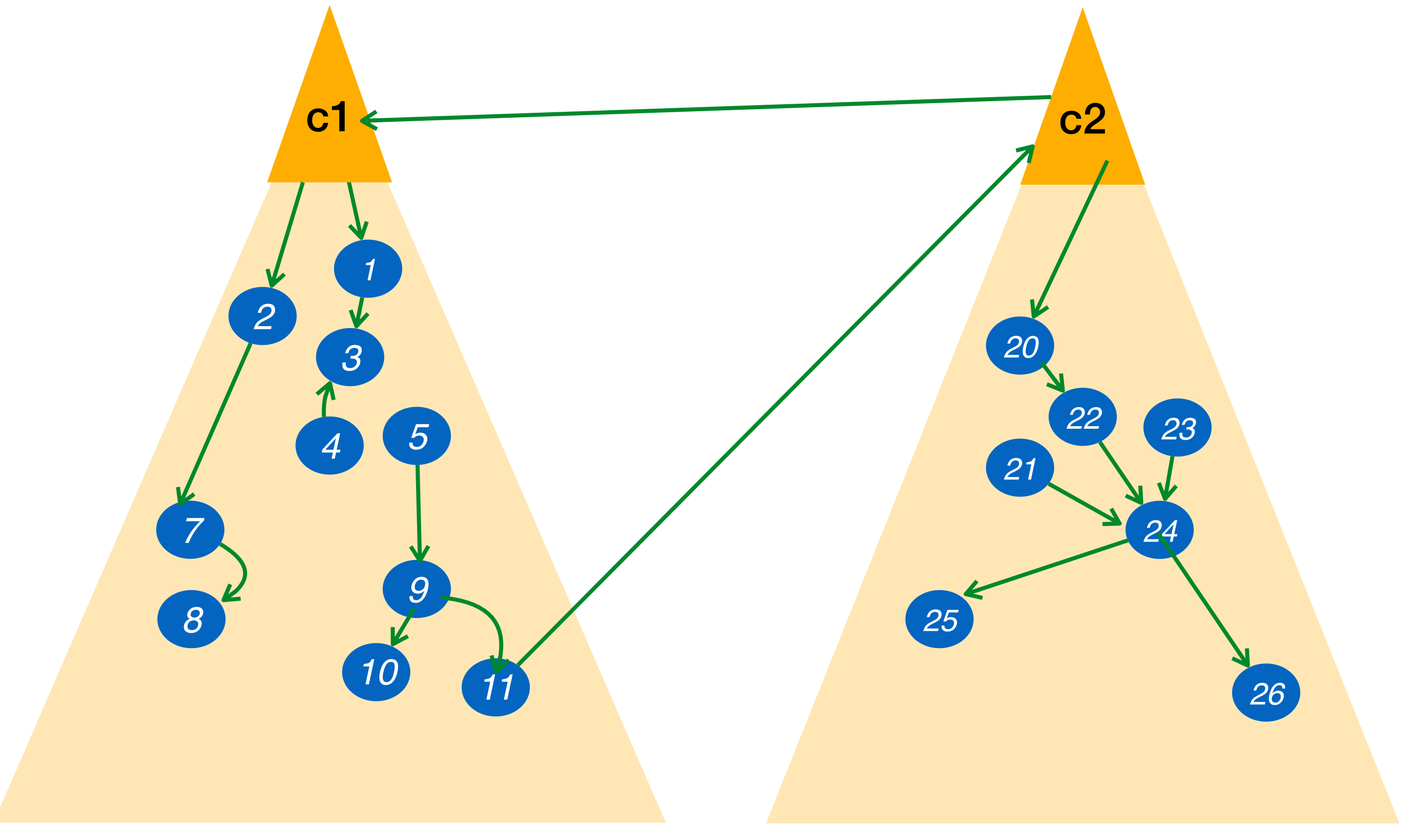
Putting Separation to work

In Pony and in Verona

Sophia Drossopoulou and Tobias Wrigstad, PLISS 2023

Separation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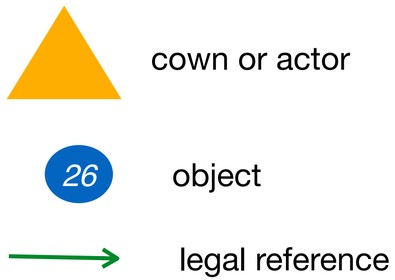
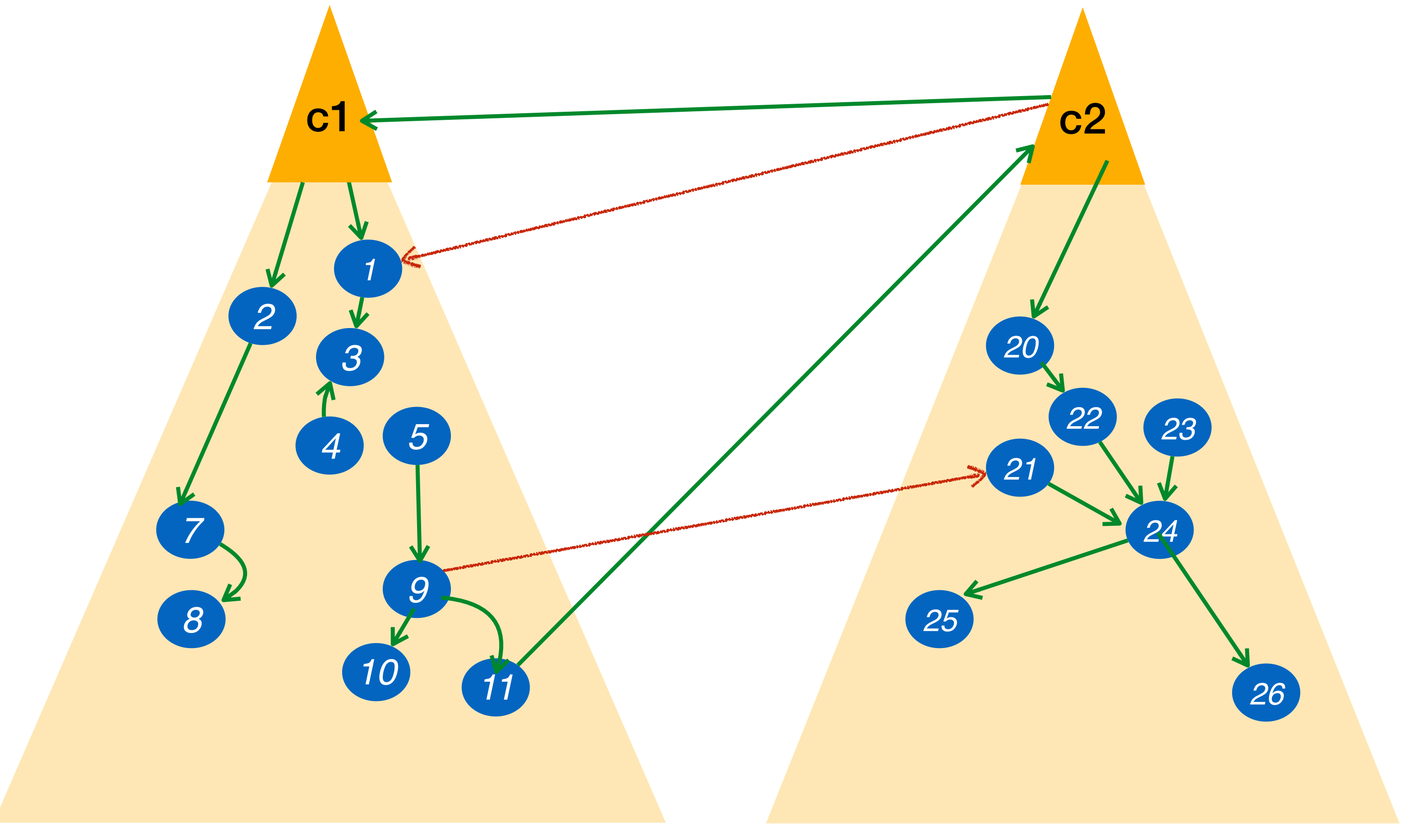

cown or actor
26
object
legal reference

Separation



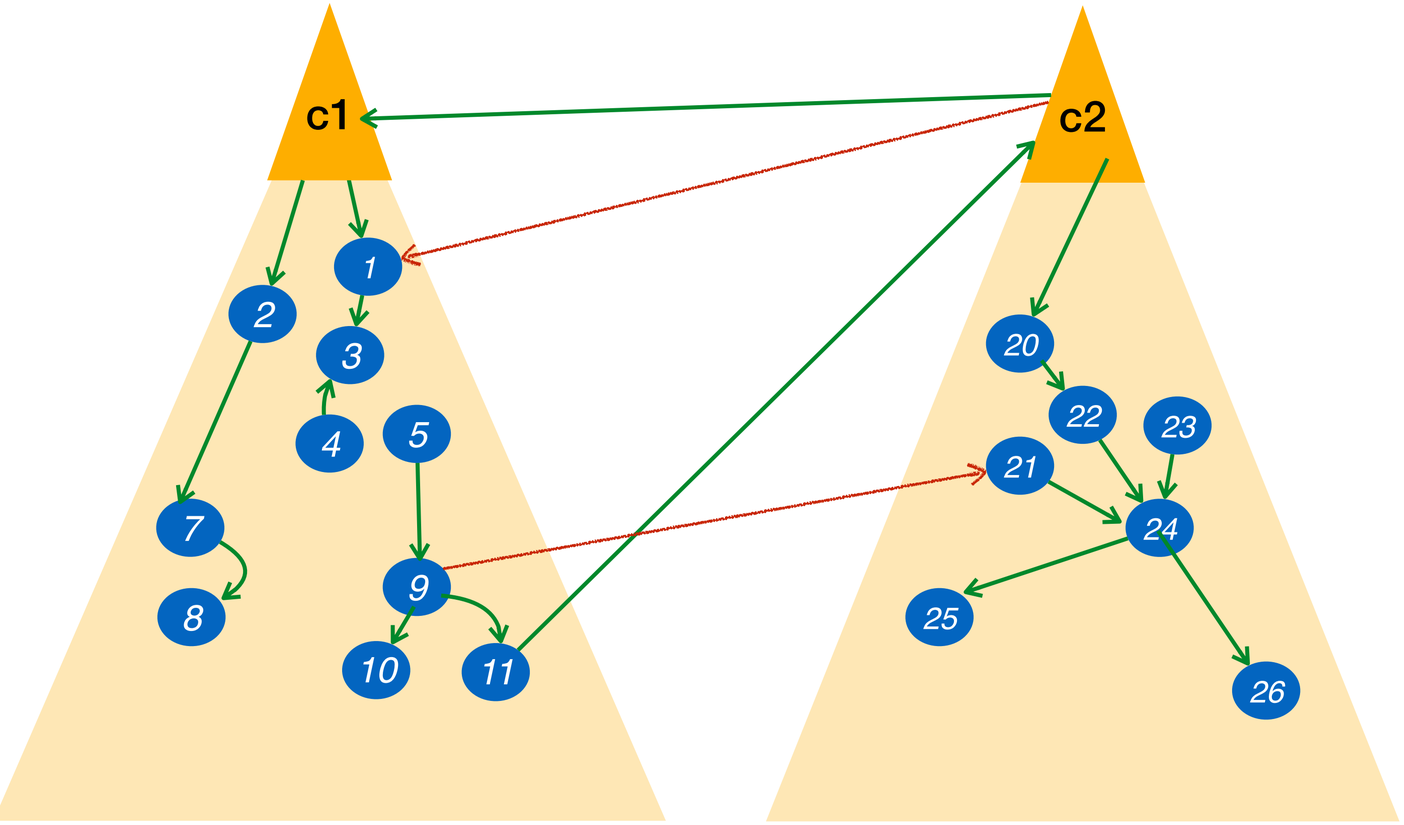

cown or actor

object

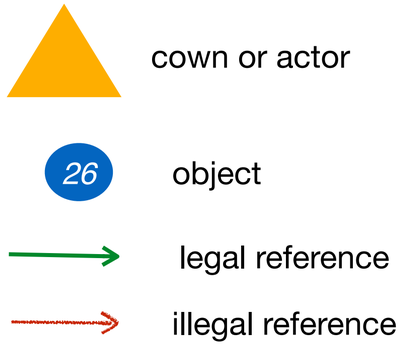

legal reference


illegal reference

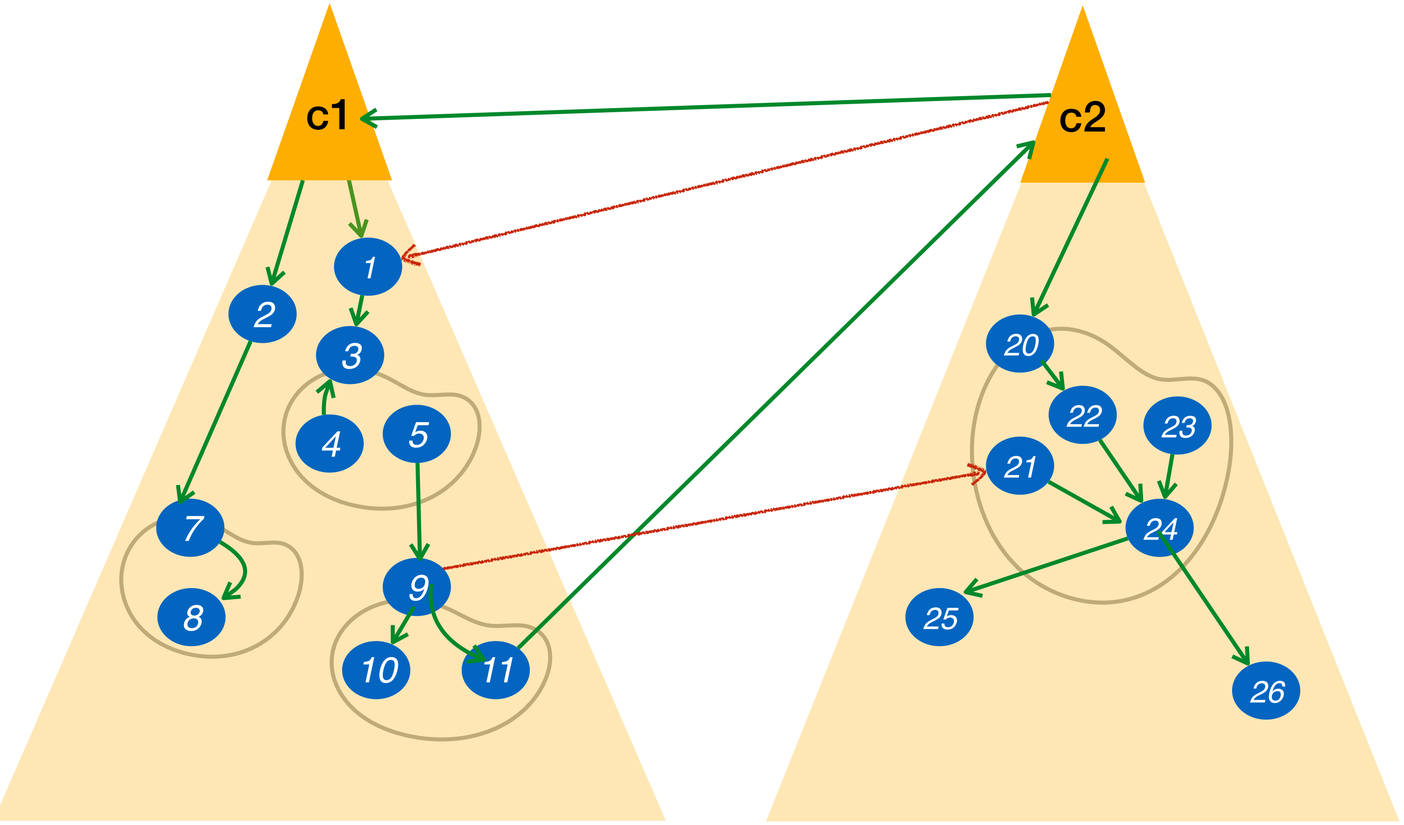
Separation ... and its remit



- Data-race freedom
- Share state safely without copy
- Garbage collection
- Causality



Finer-grained Separation — with Regions



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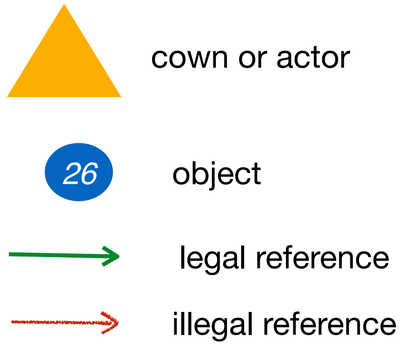

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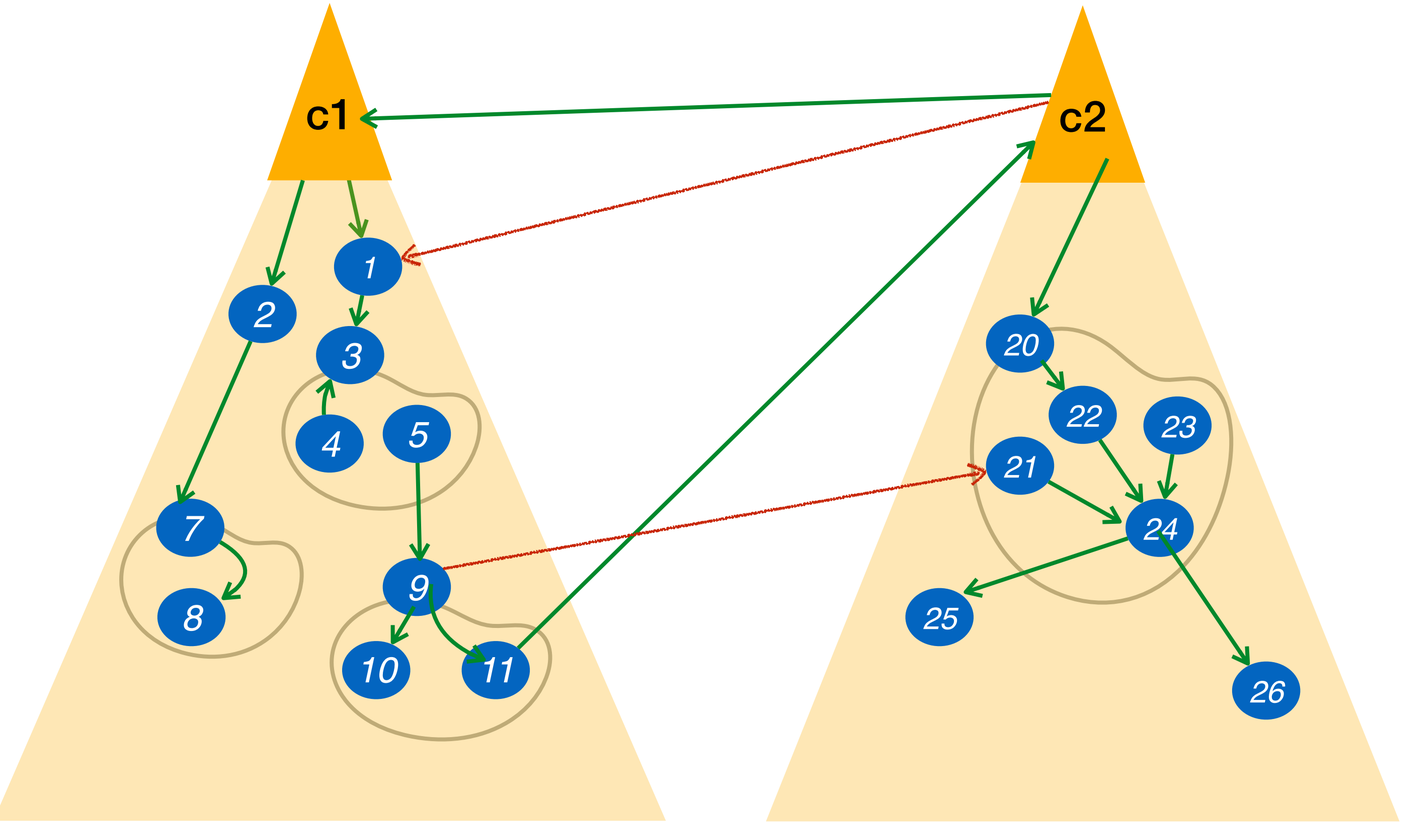

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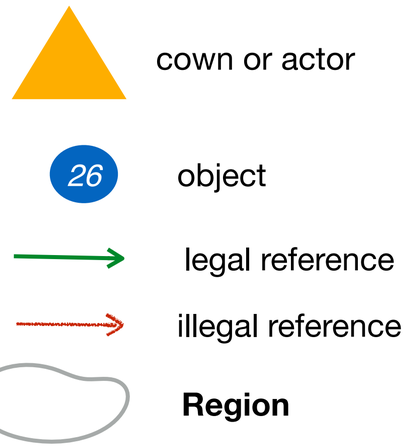

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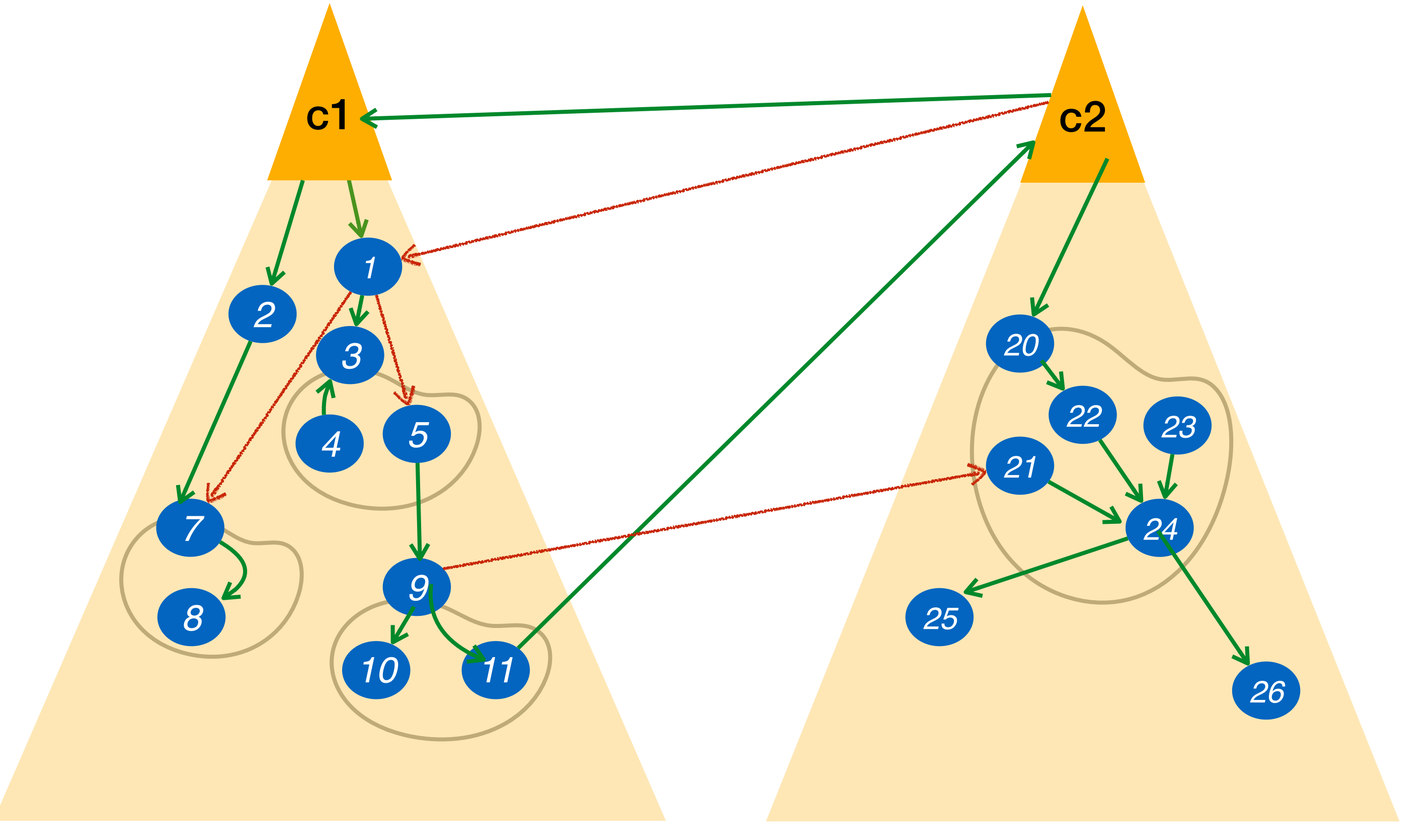

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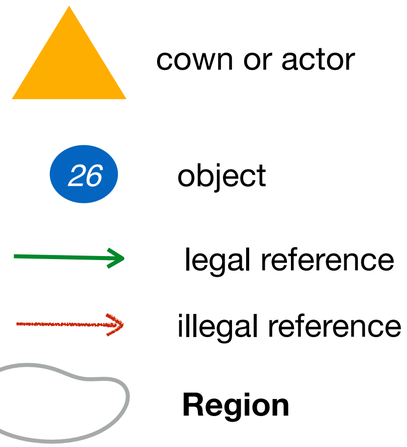

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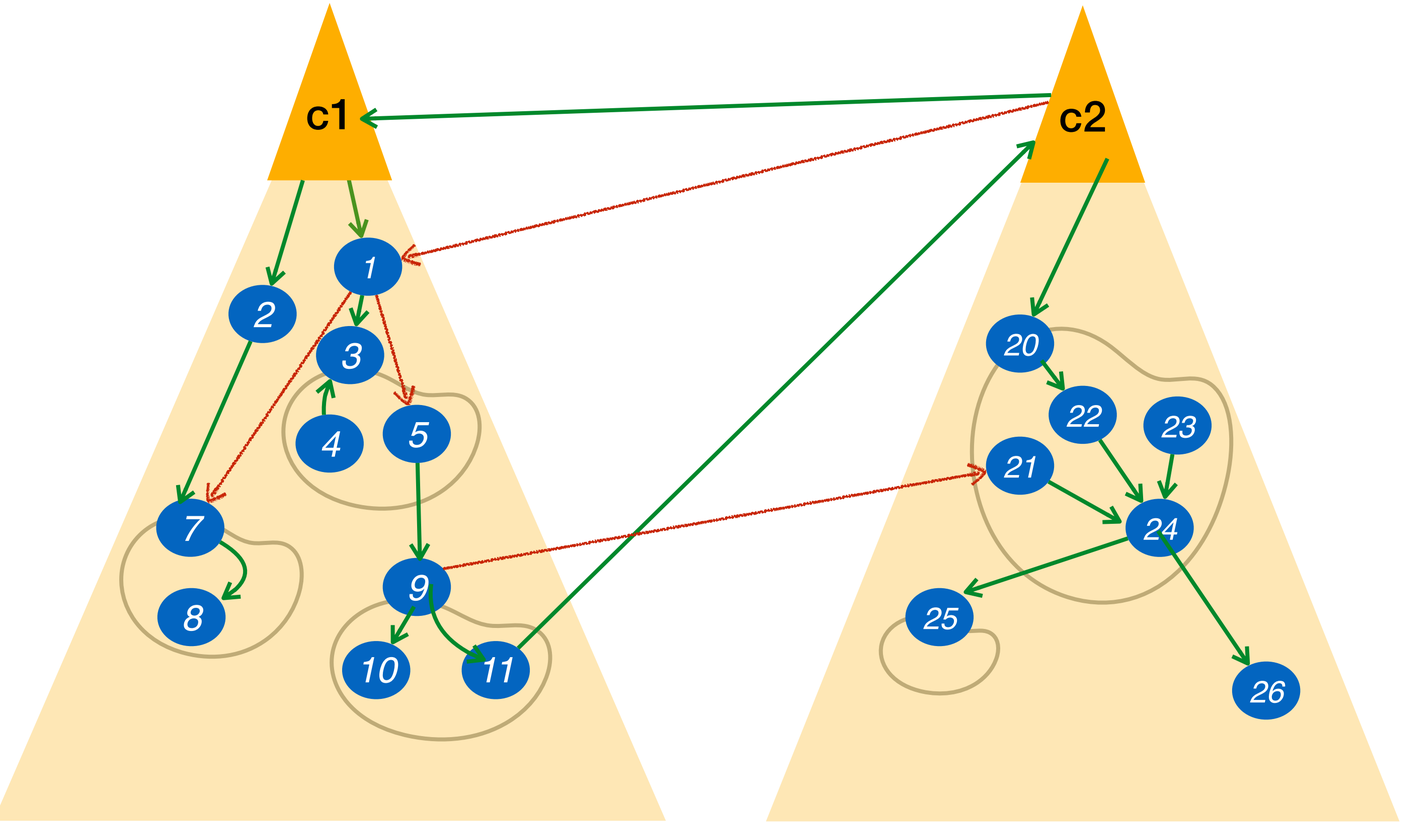

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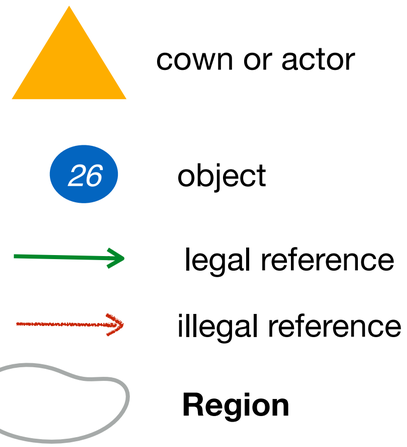

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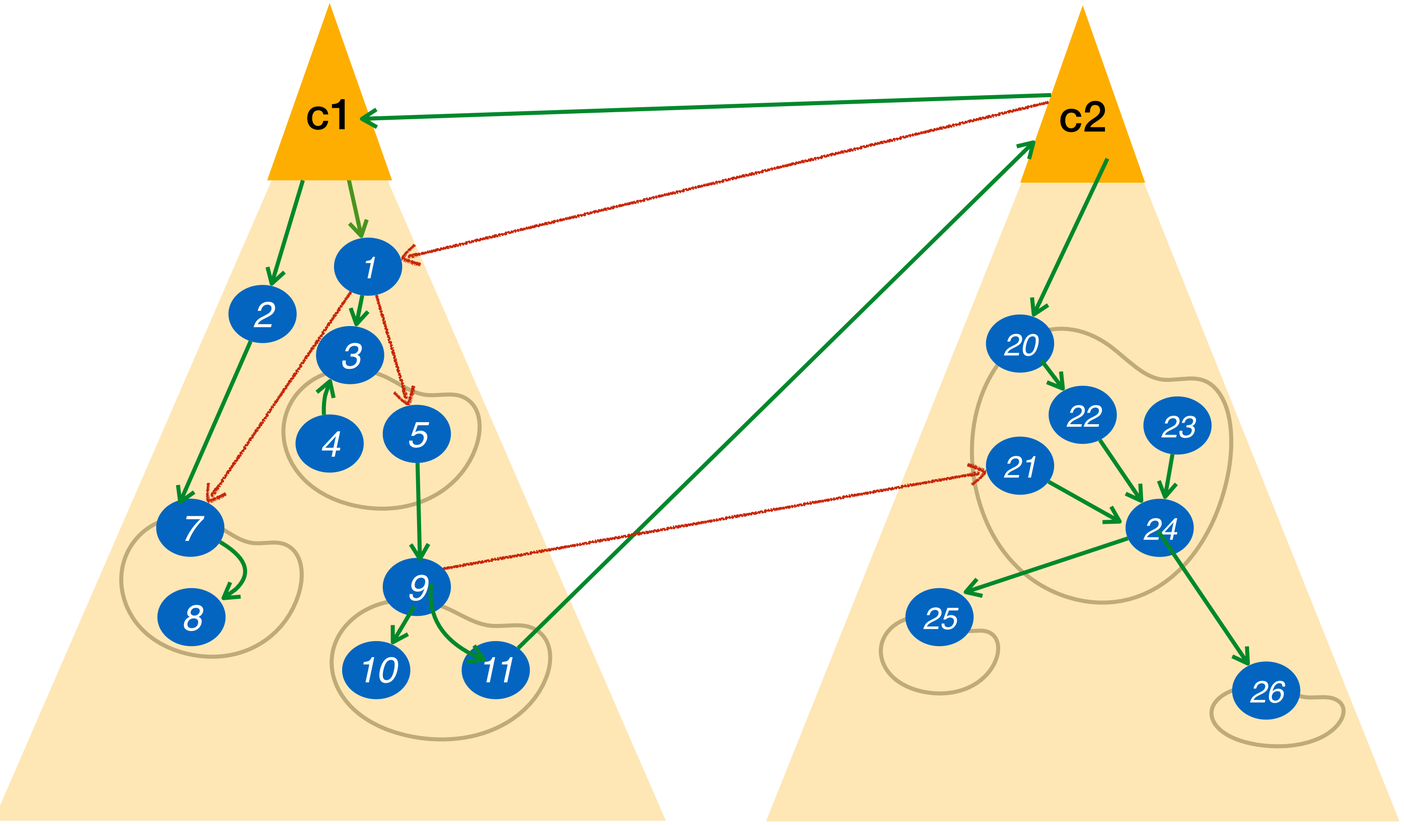

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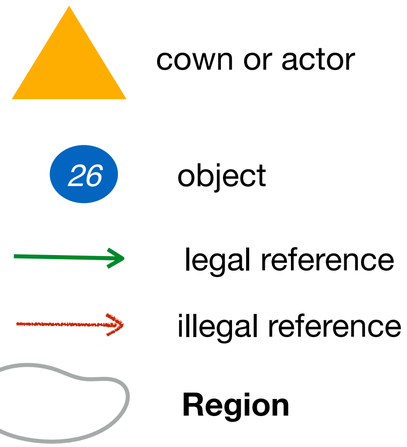

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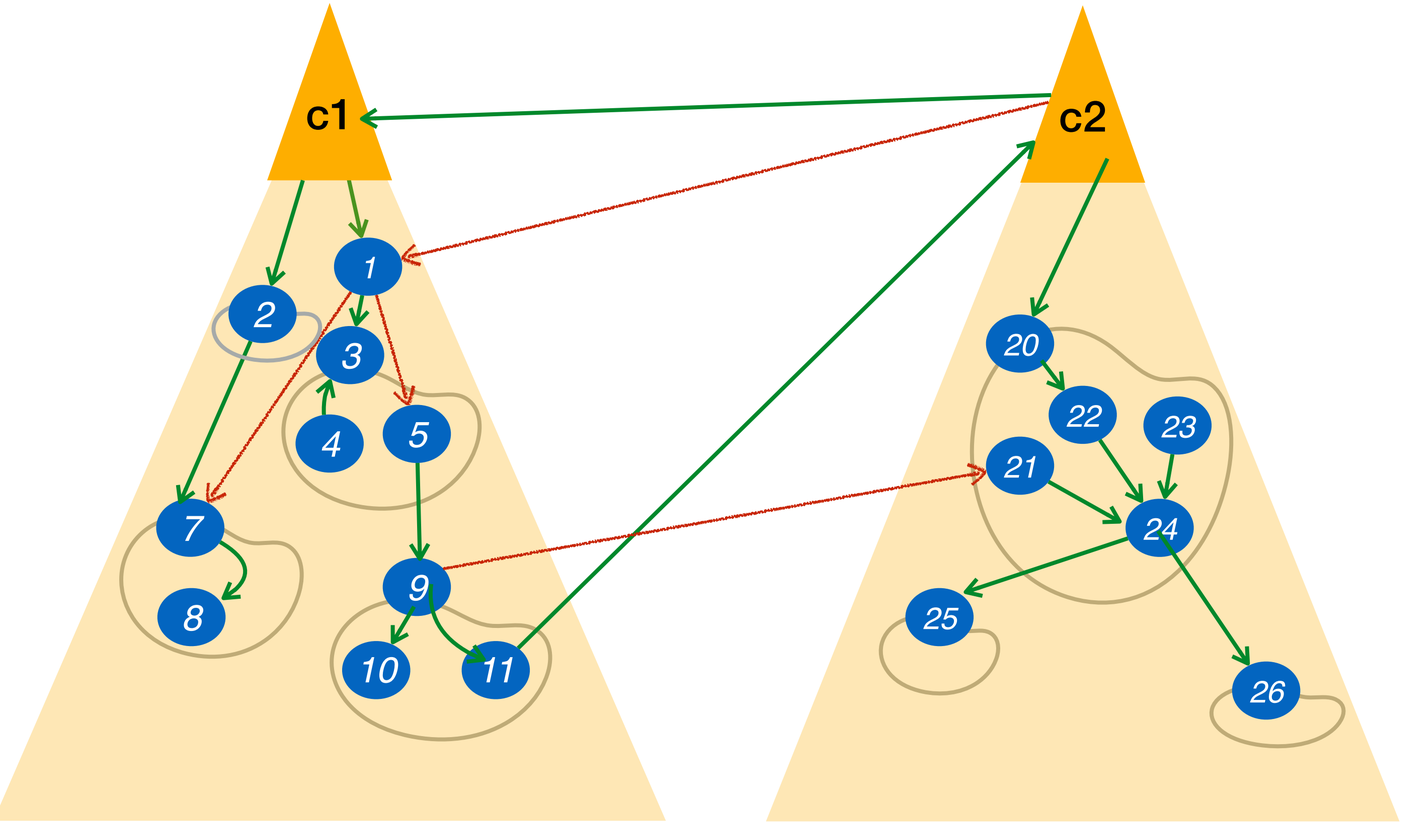

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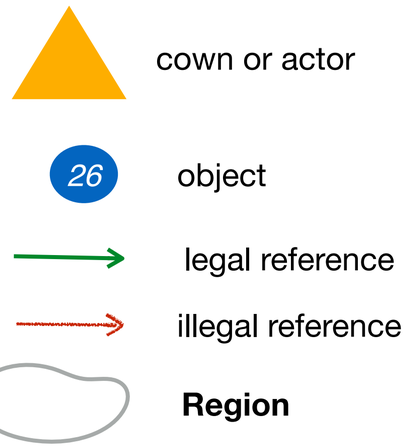

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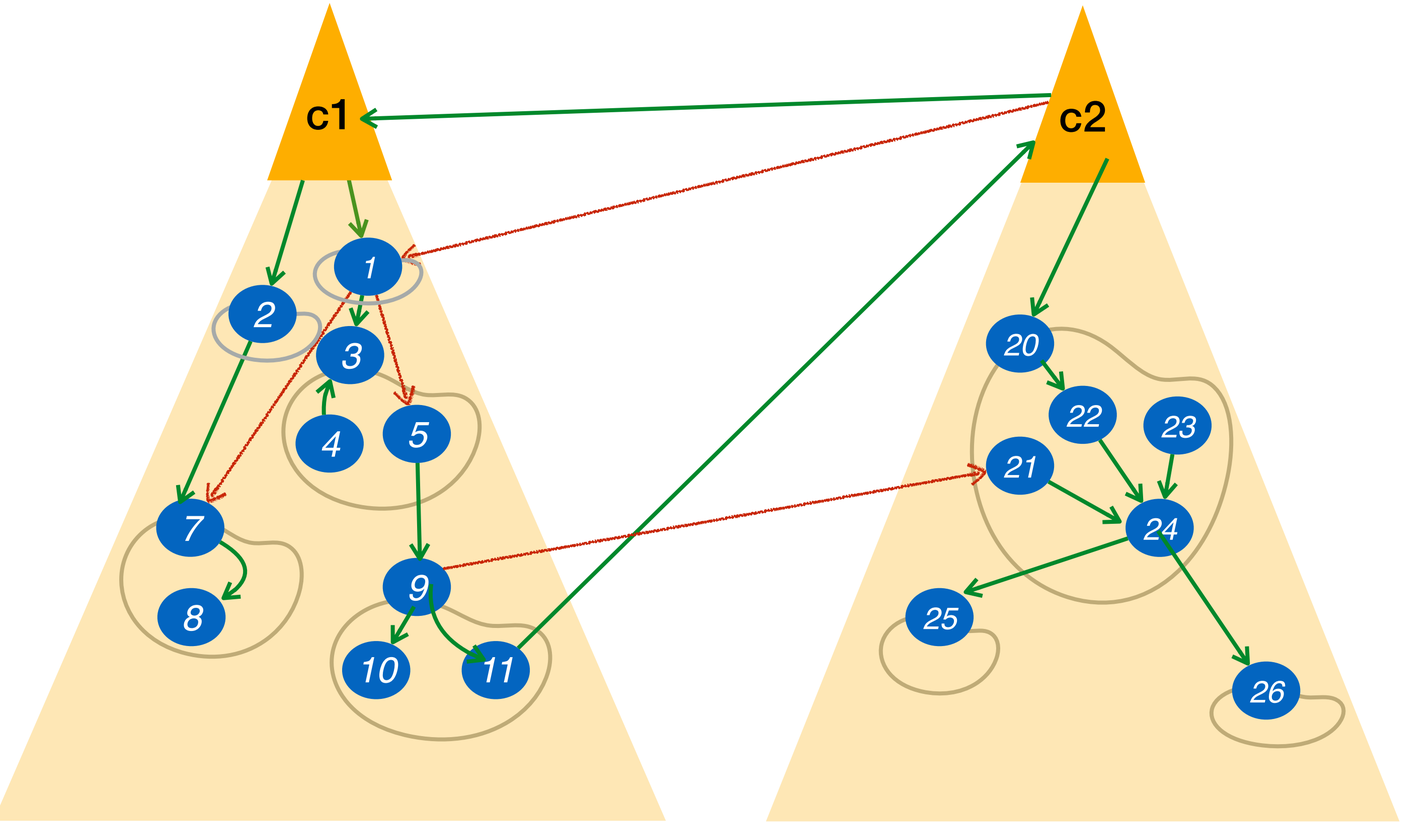

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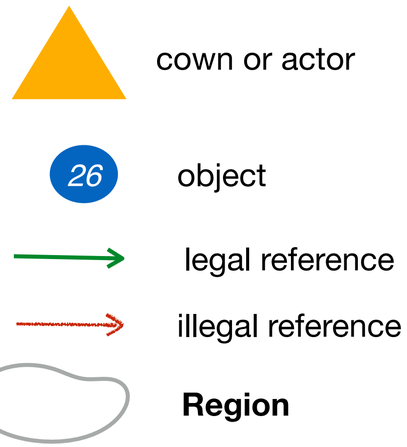


Actor-based programming (Pony)

Summary

- actor ~ active object (state)
- actors send asynchronous messages to other actors (**be**haviours)
- messages stored in queues; when scheduled, actor executes first behaviour from its message queue
- actors send synchronous messages to objects, or to themselves (**fun**ctions)

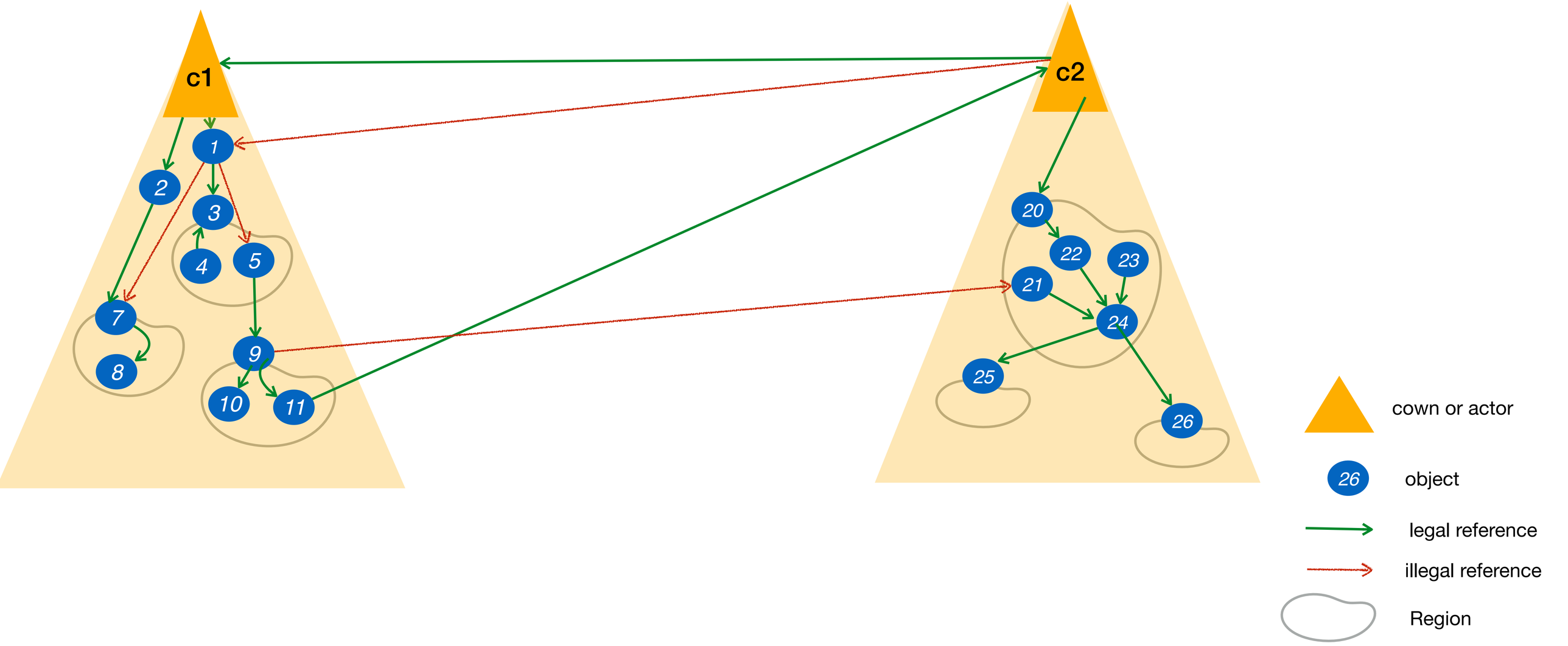
Behaviour oriented programming (Verona)

Summary

- Cowns protect separated state
- Behaviours require cowns;
  - acquire them atomically at the beginning of execution
  - release them atomically at the end of execution
- During its execution, behaviour has (unique) access to the state protected by the cowns it has acquired

Data race freedom

Data-race freedom Actors/Behaviours (and more later)



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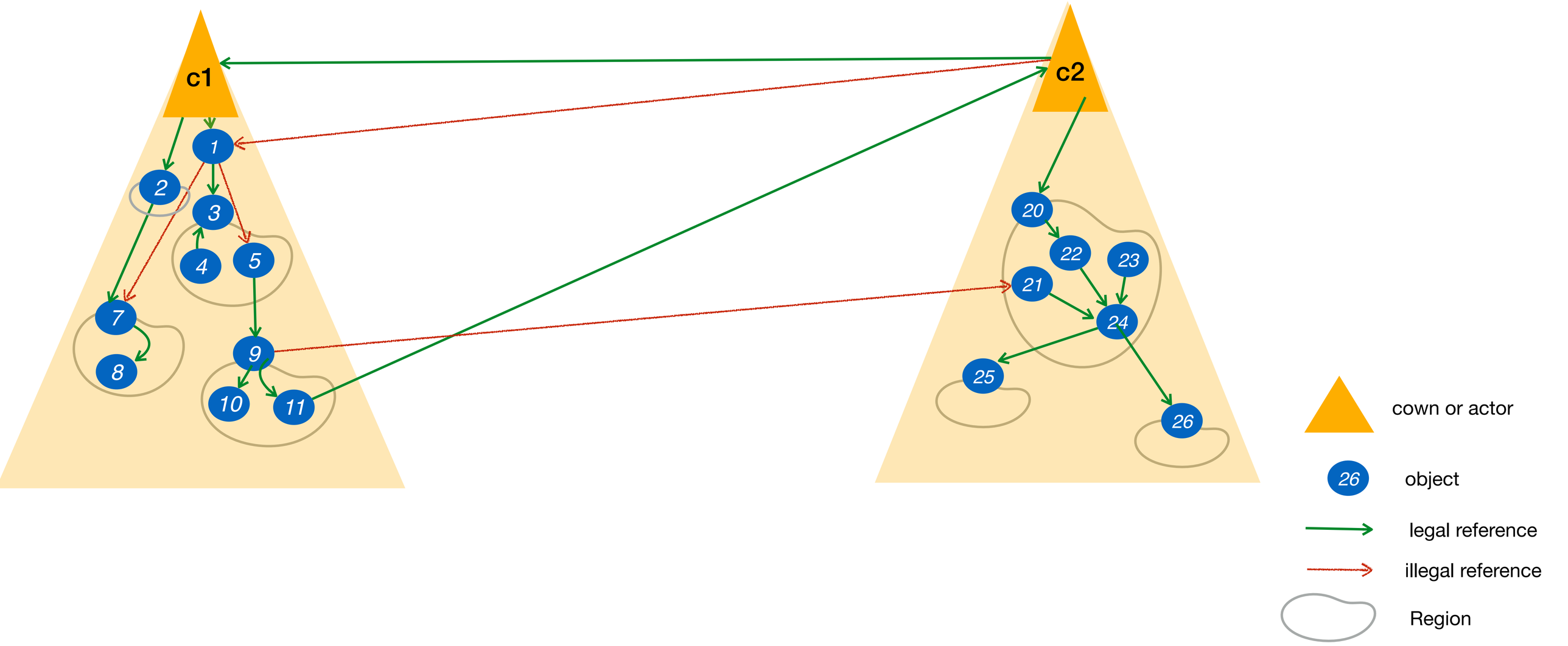
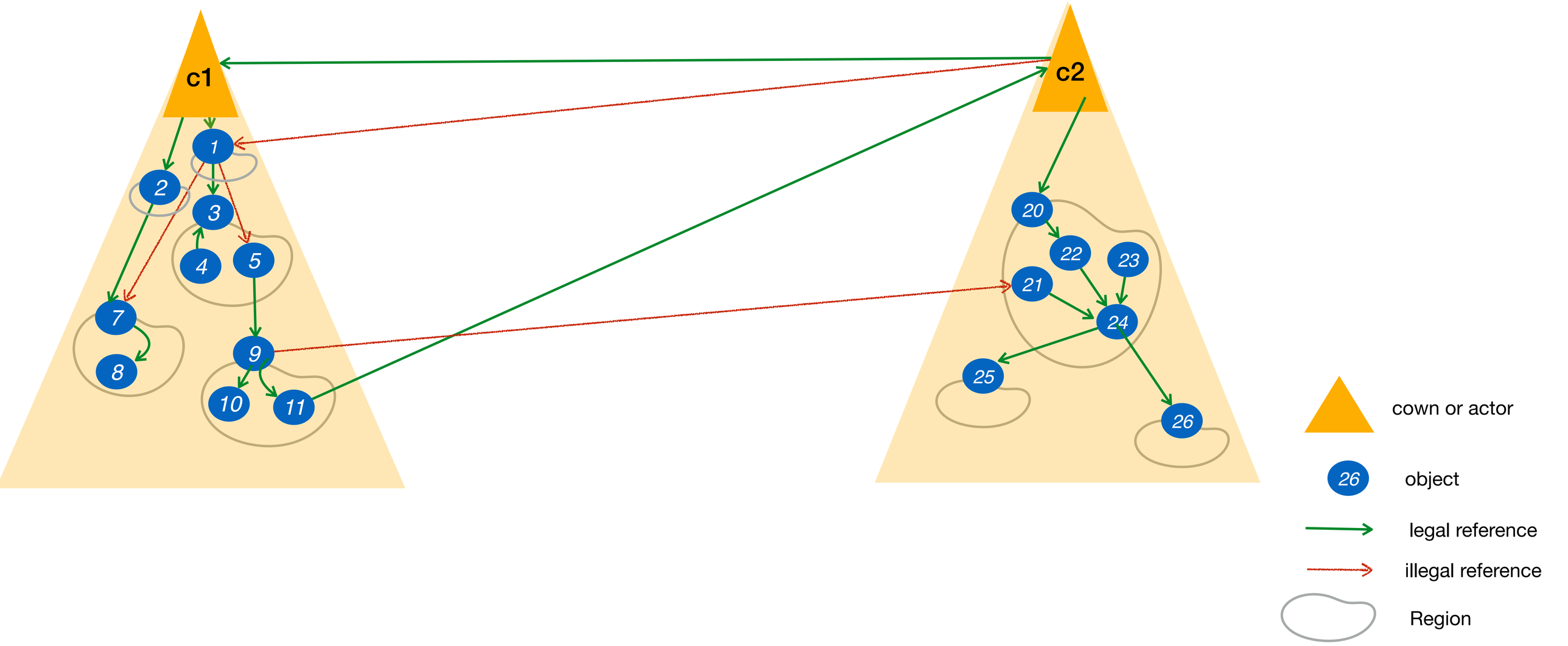
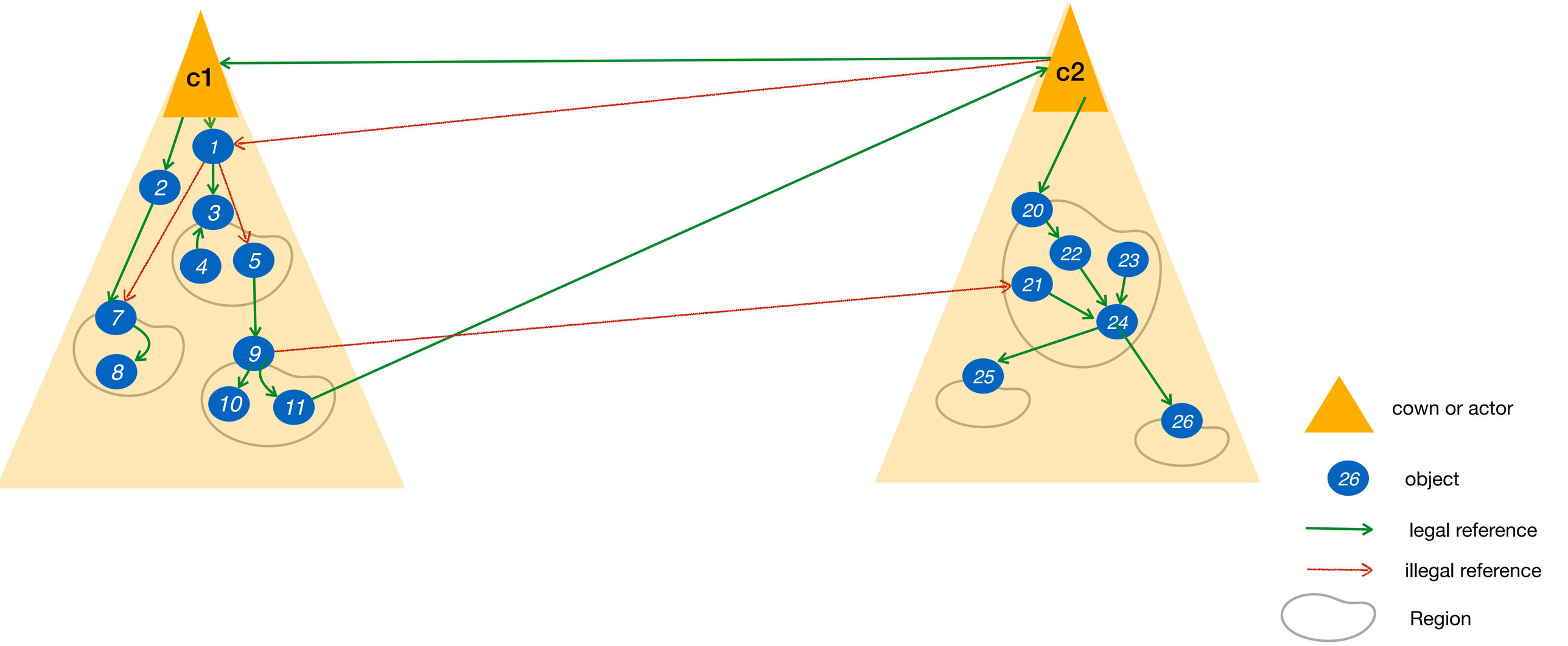


Data-race freedom Actors/Behaviours (and more later)



Safe share of state without copy

Pony actors share state safely - 1



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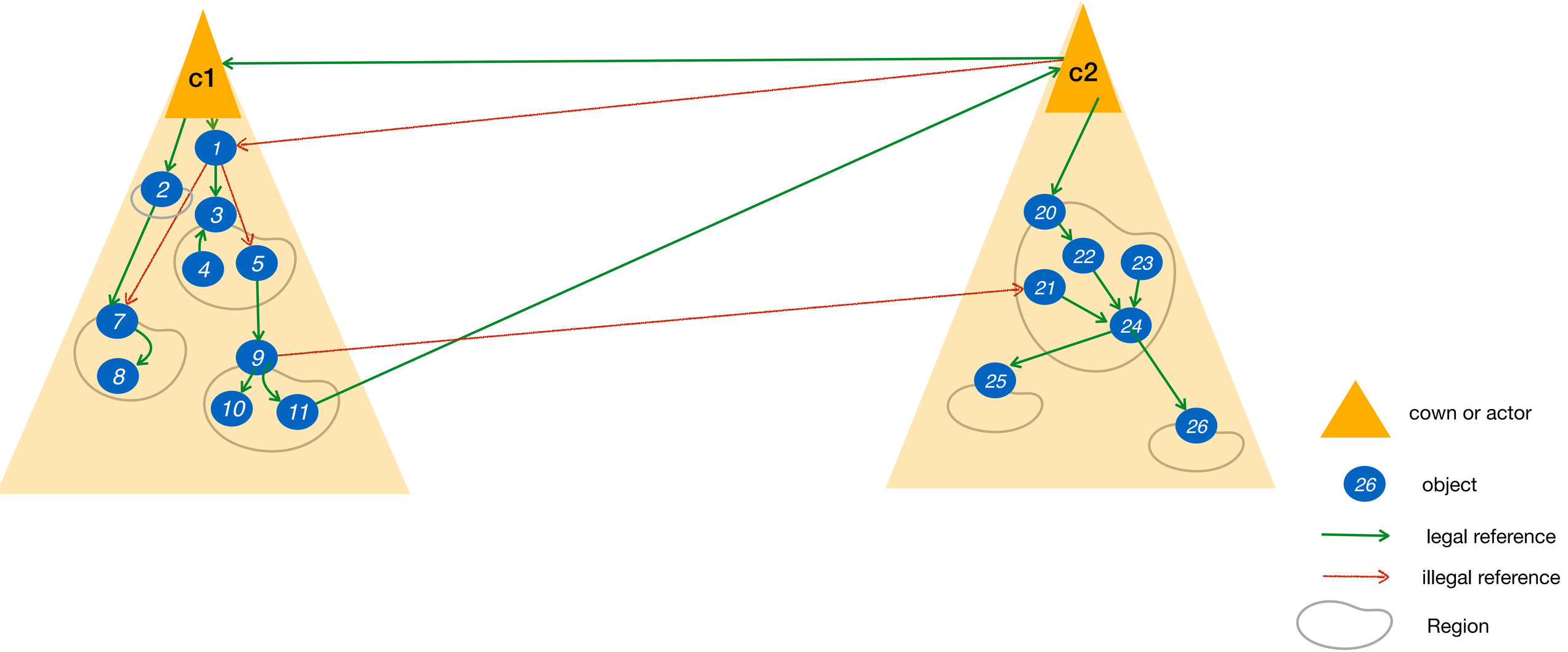

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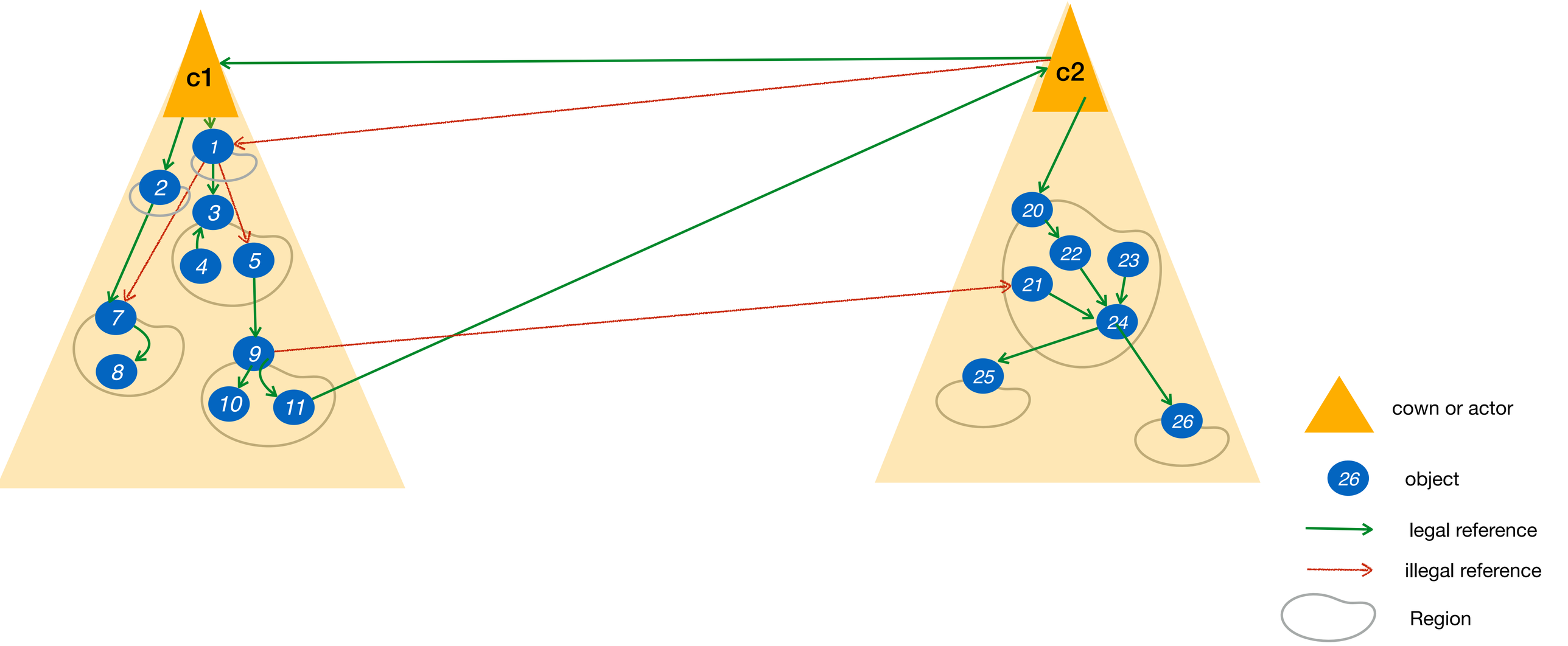
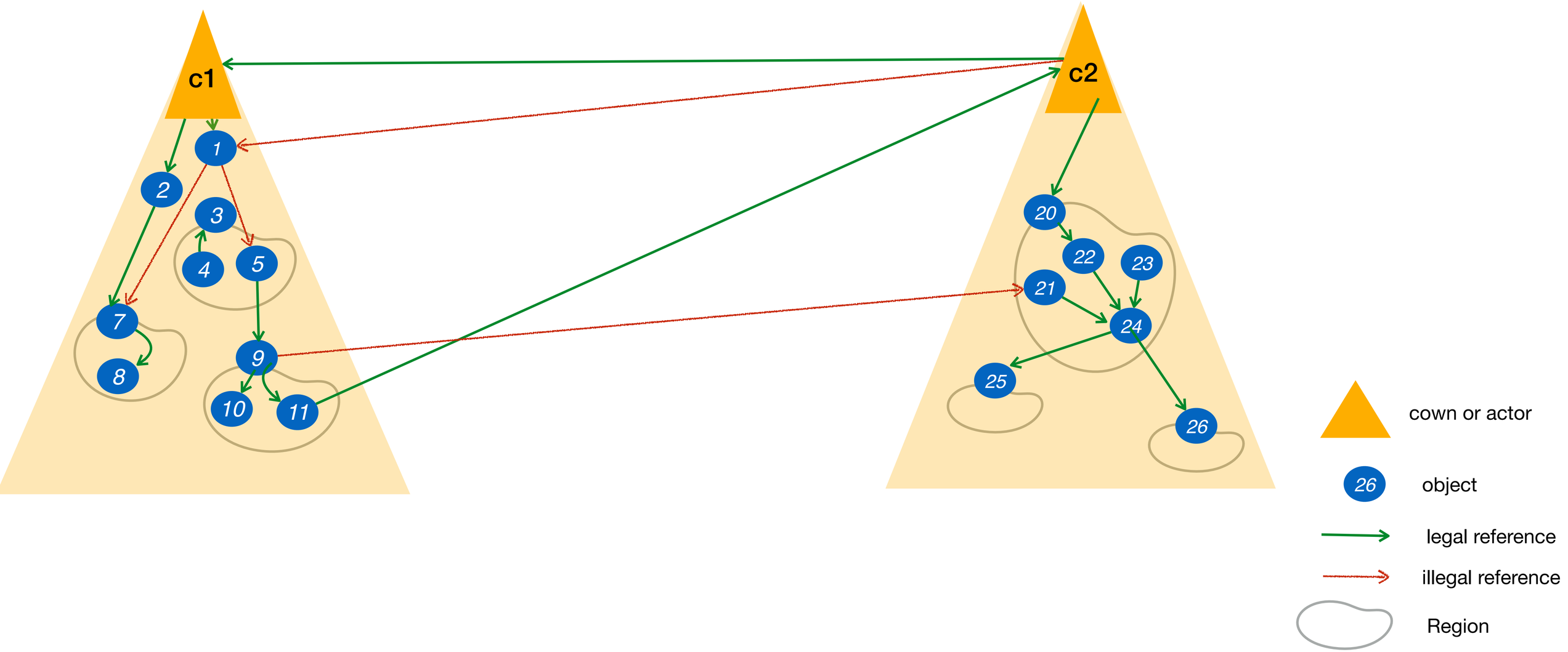


Pony actors share state safely - 2



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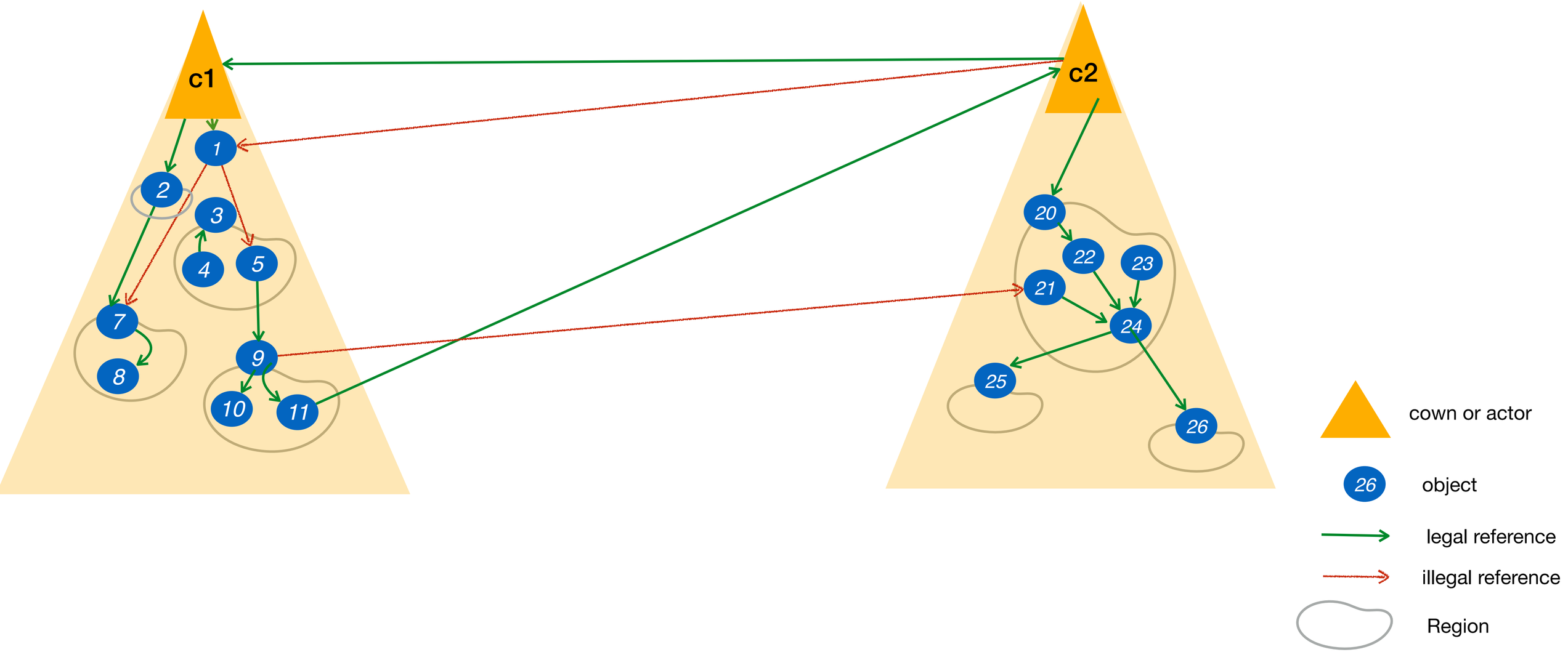

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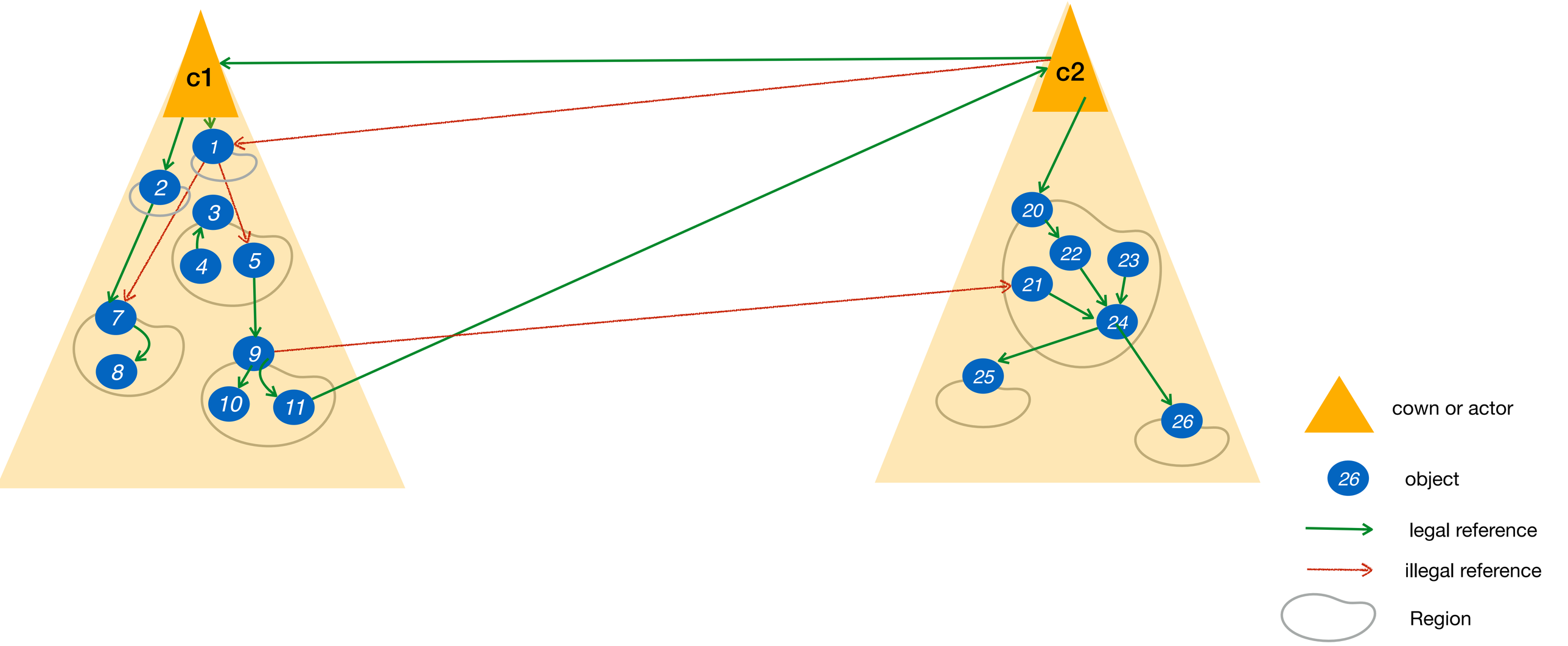
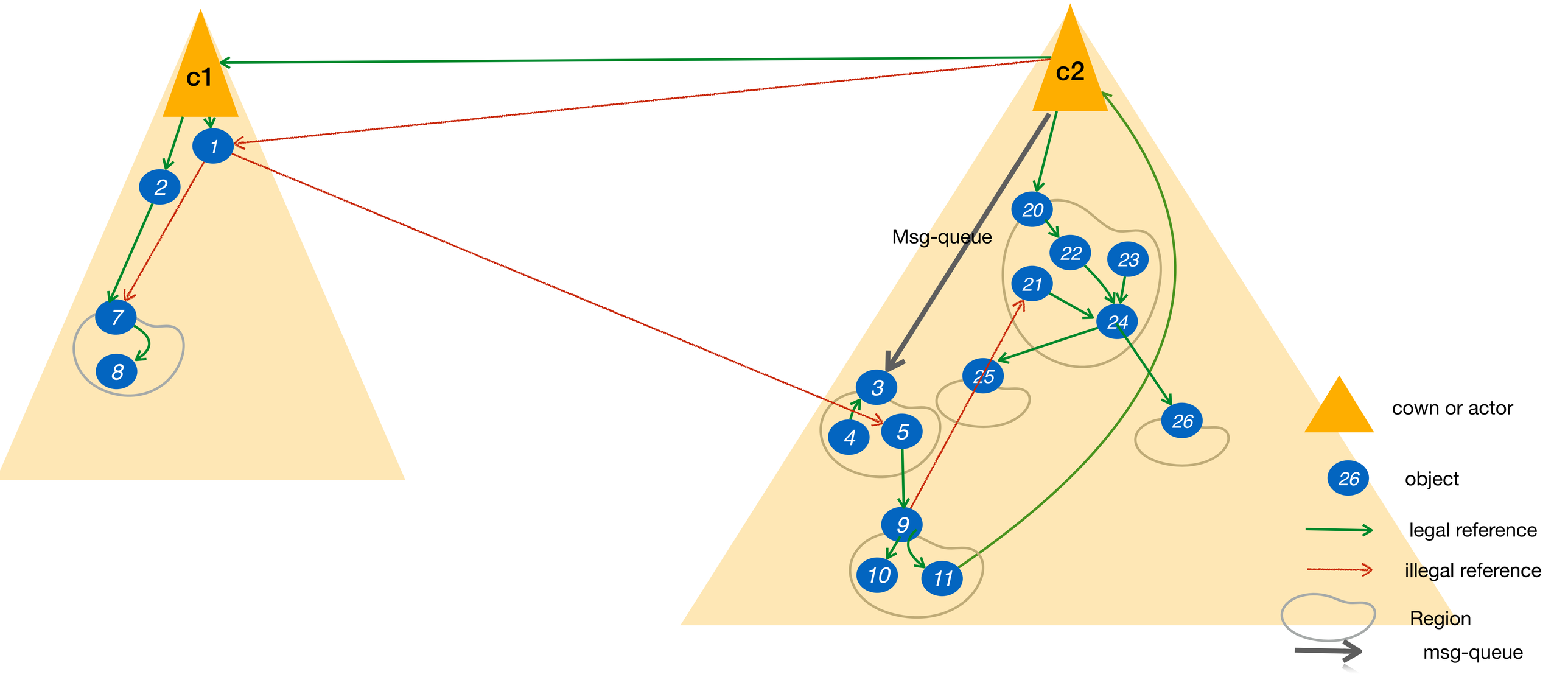


Pony actors share state safely - 3



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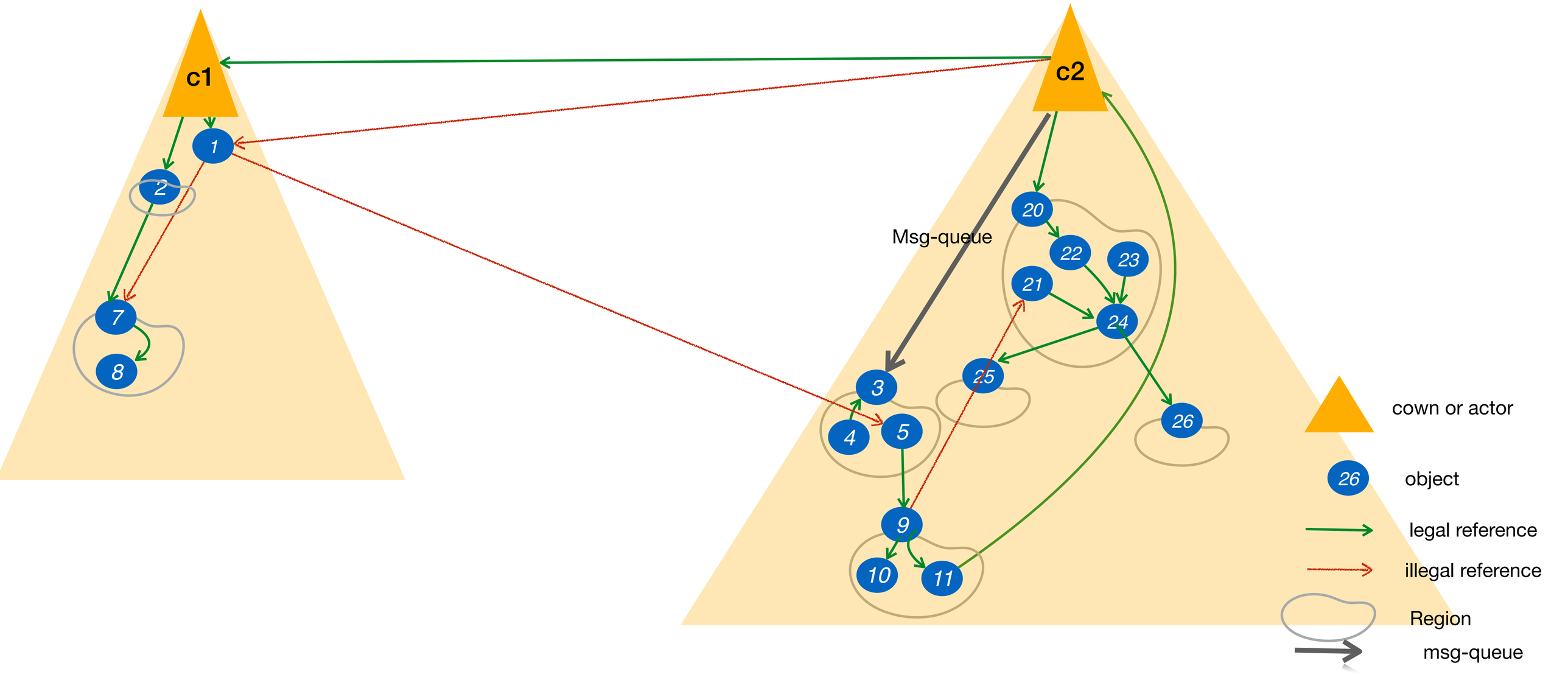

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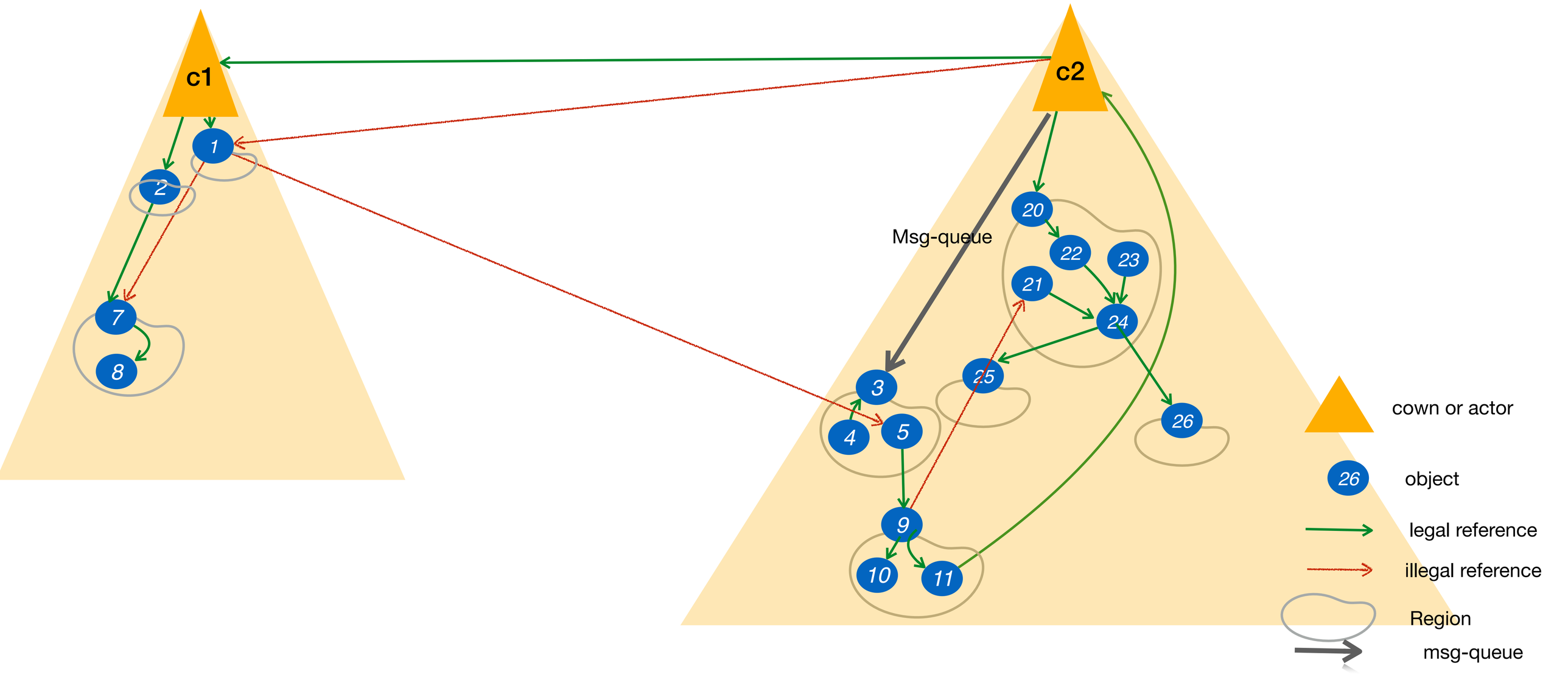
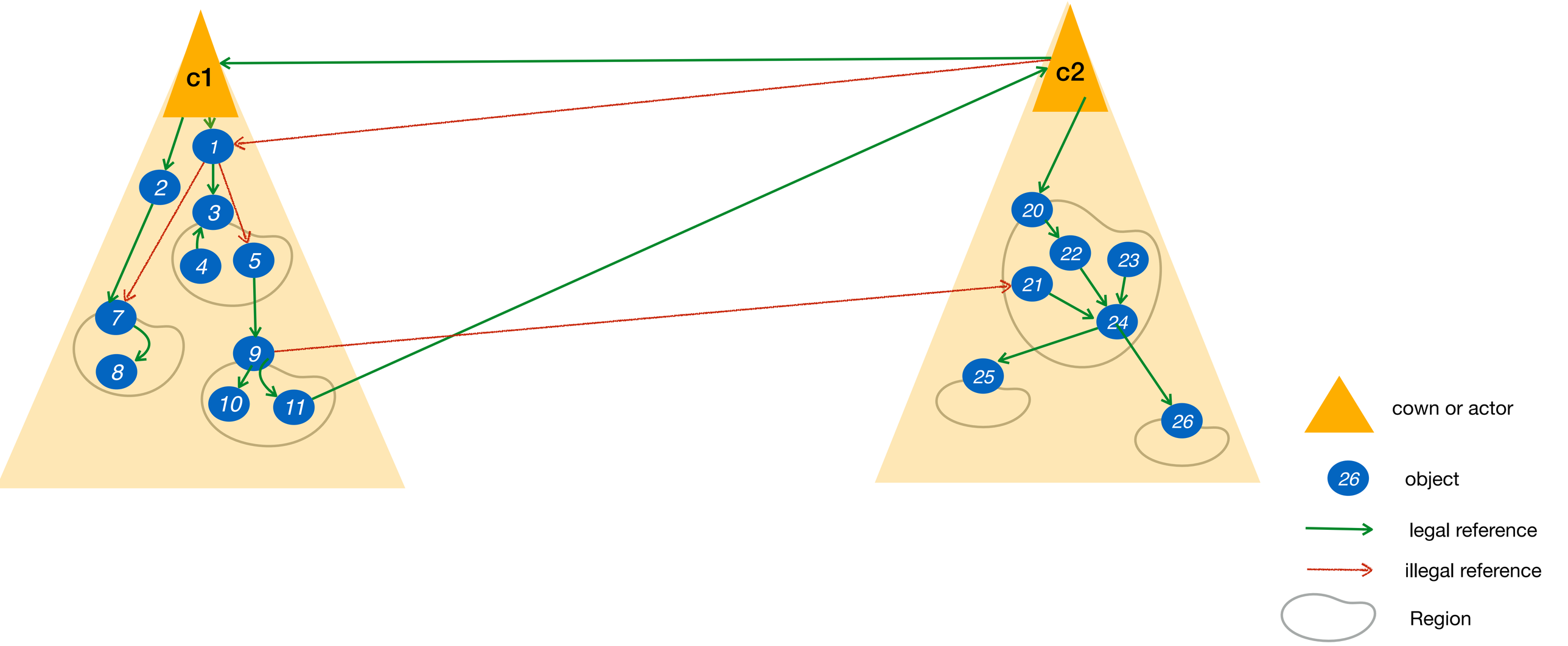


Cowns share state safely - 1



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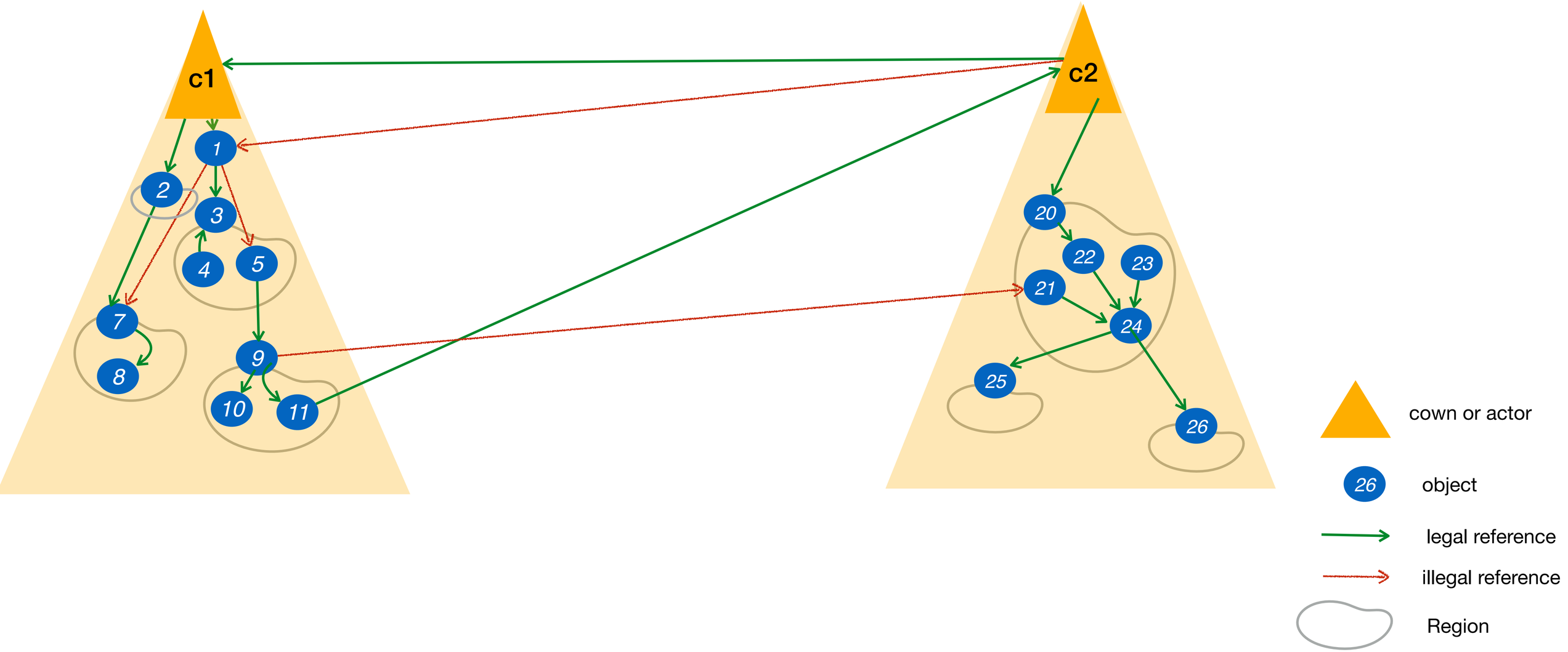

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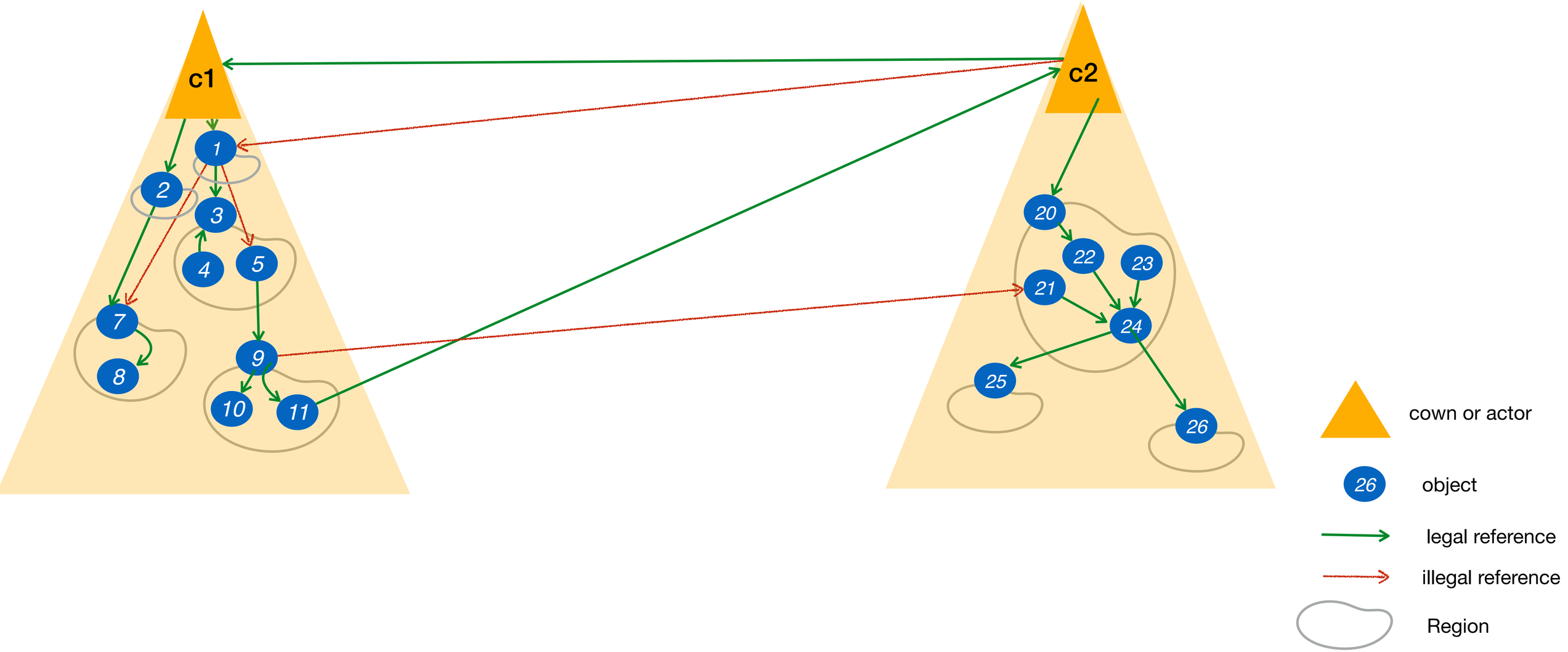

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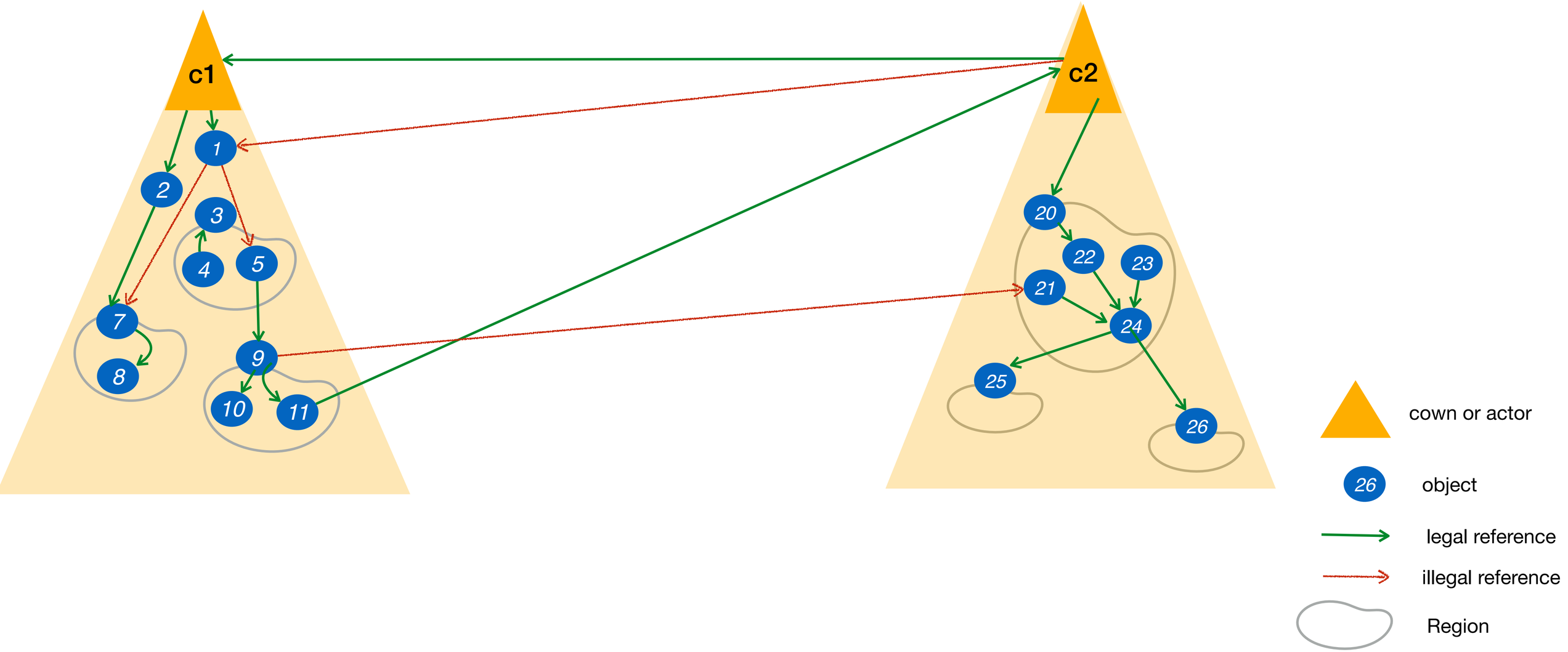

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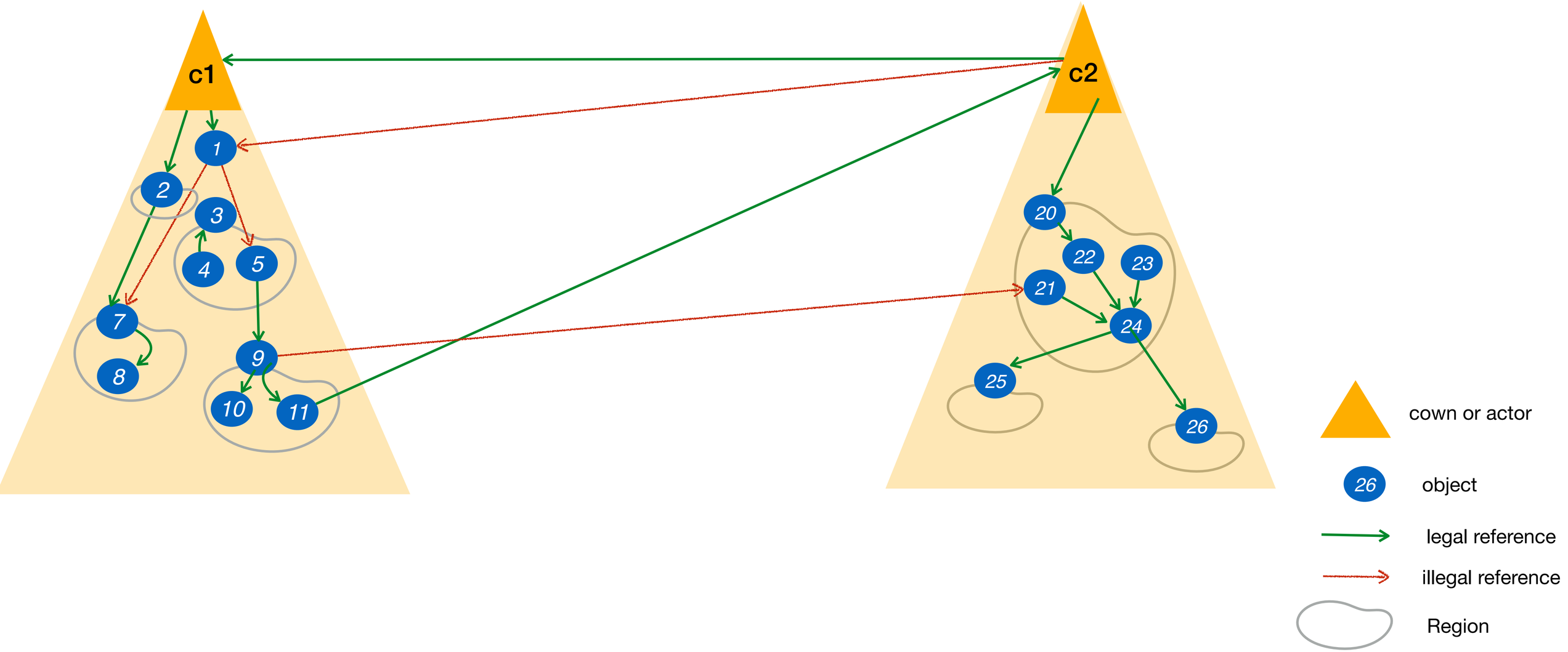

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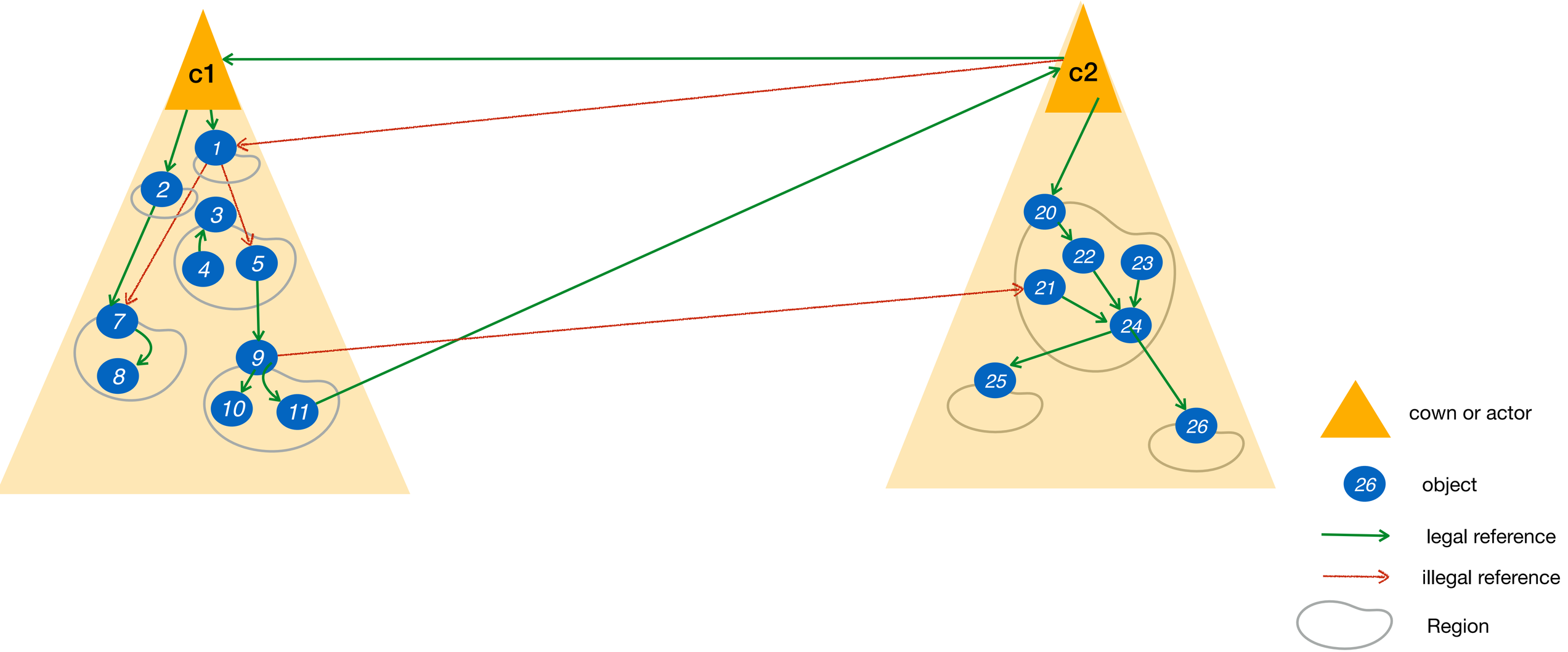

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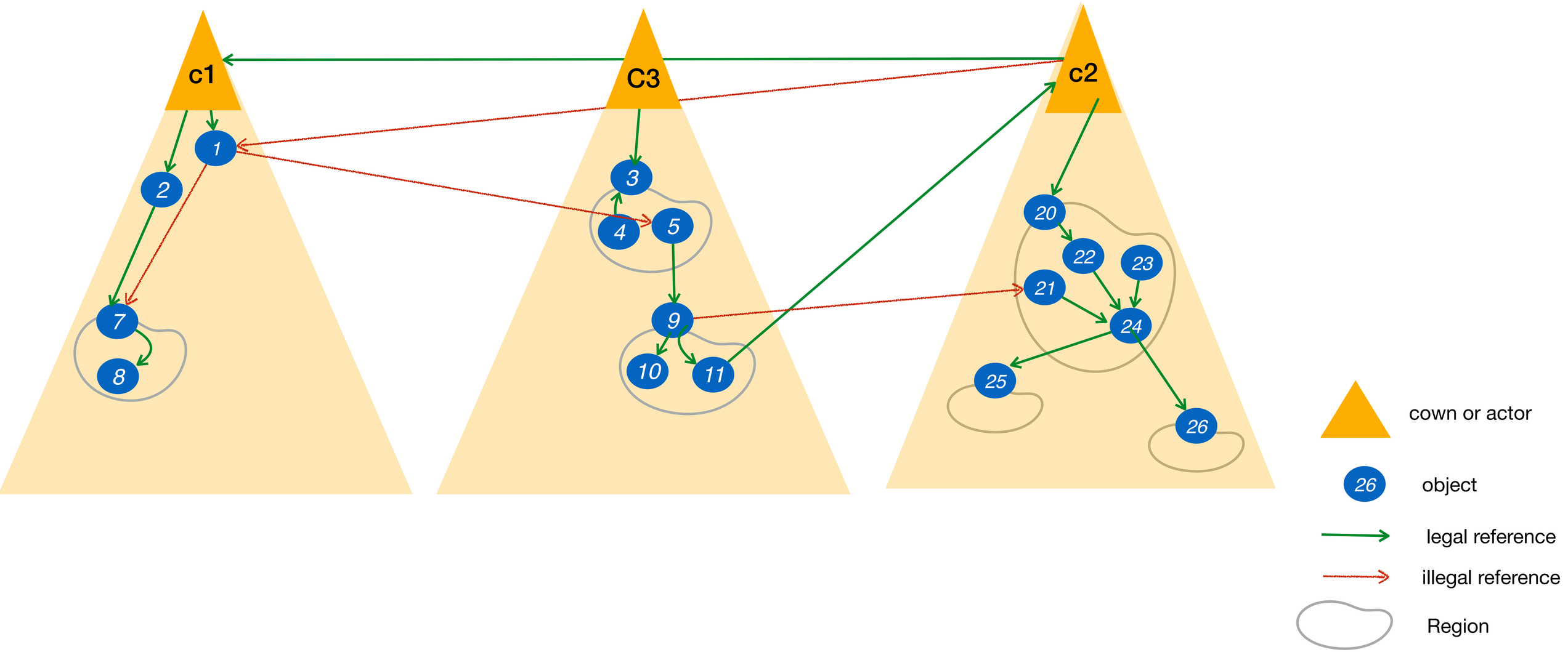

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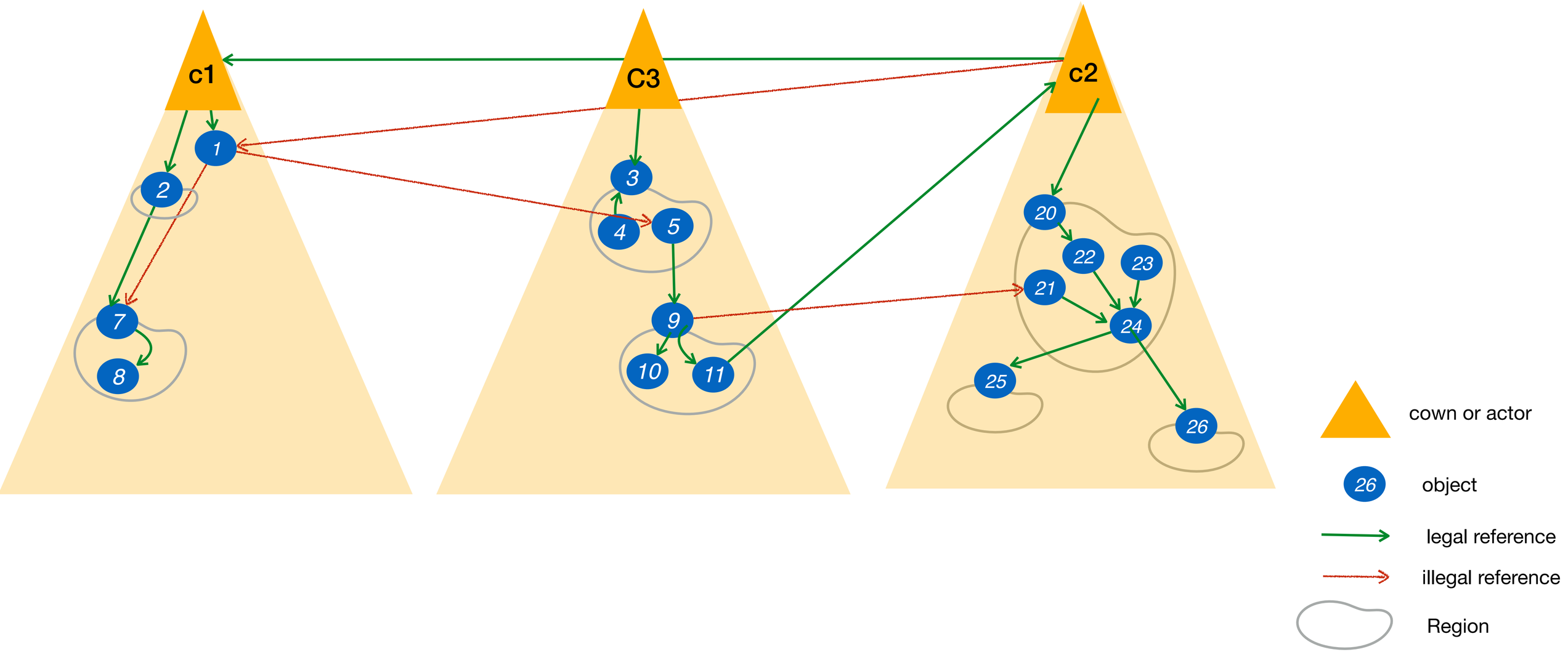

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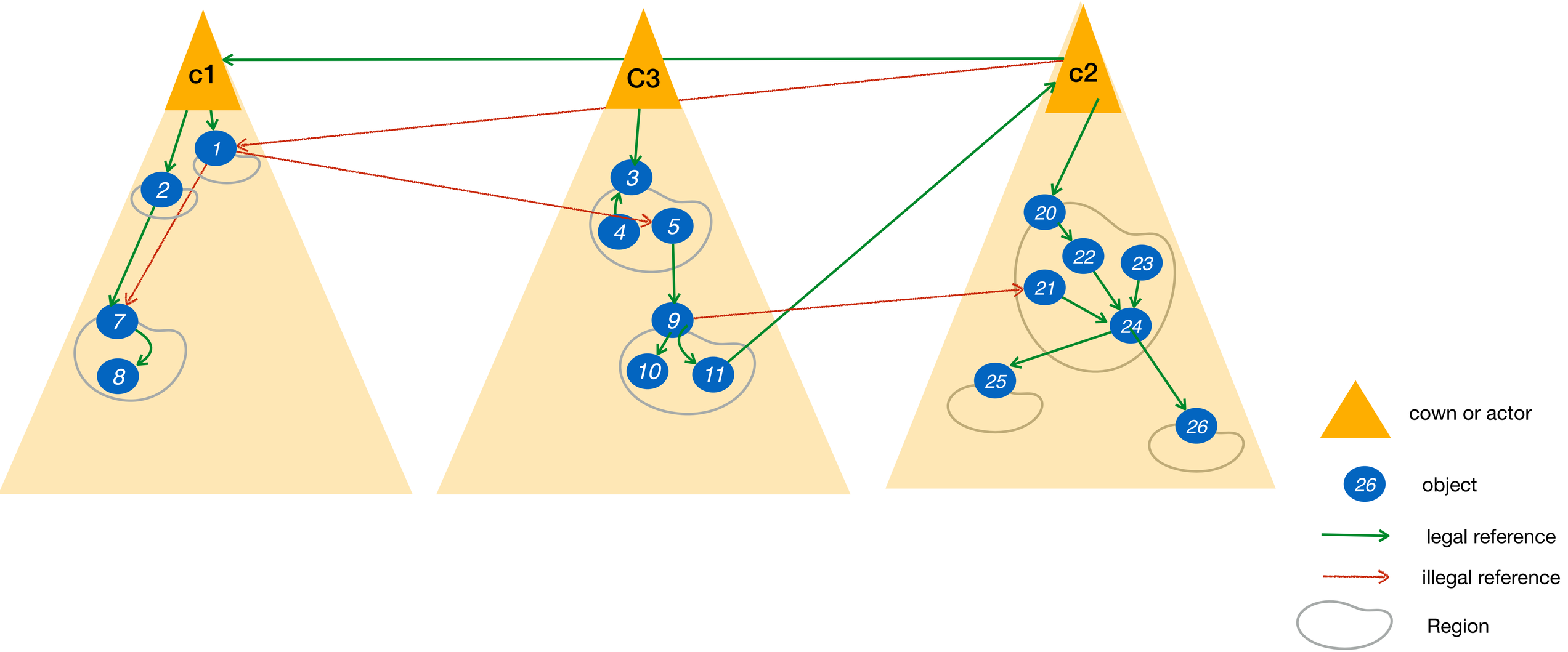

Garbage Collection

MAC: Multicore Actor Collector

GC for actors (Pony)

Fully Concurrent Garbage Collection of Actors on Many-Core Machines

Sylvan Clebsch and Sophia Drossopoulou
Department of Computing, Imperial College, London
{sc5511, scd}@doc.ic.ac.uk

What is a dead actor?

$$\text{Idle}(a) \quad \text{iff} \quad (\text{a is not executing a behaviour}) \ \wedge \ (\text{a.MsgQueue is empty})$$

$$\text{Dead}(a) \quad \text{iff} \quad \text{Idle}(a) \ \wedge \ \forall a'.[\, a \in a'.\text{heap} \implies \text{Dead}(a')\,] \ \wedge \ \forall a'.\,[\, a \notin a'.\text{MsgQueue}\,]$$

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not idle

Idle

Idle and Dead

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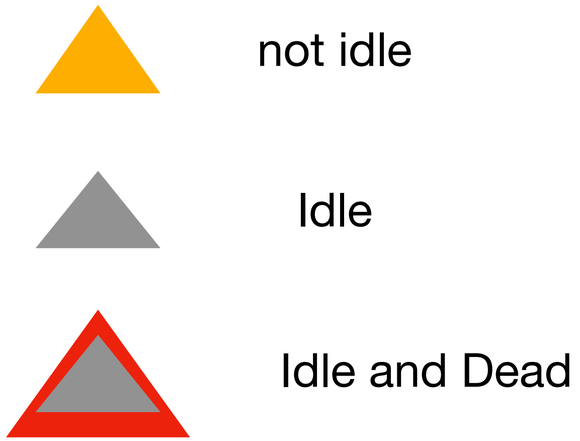

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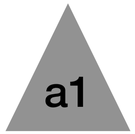

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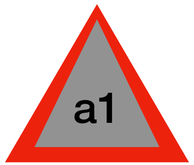

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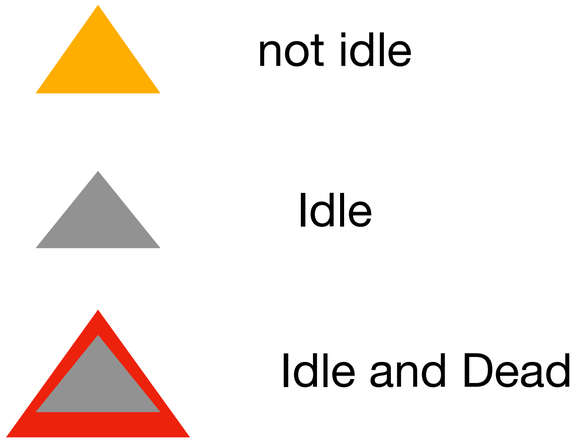

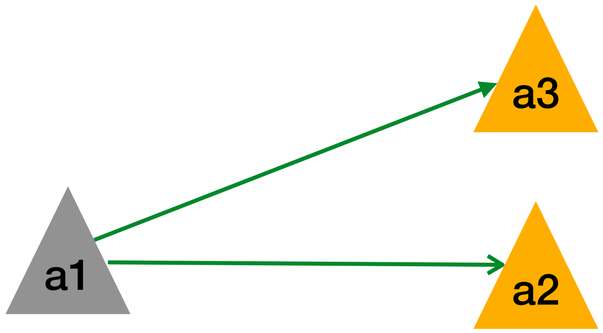

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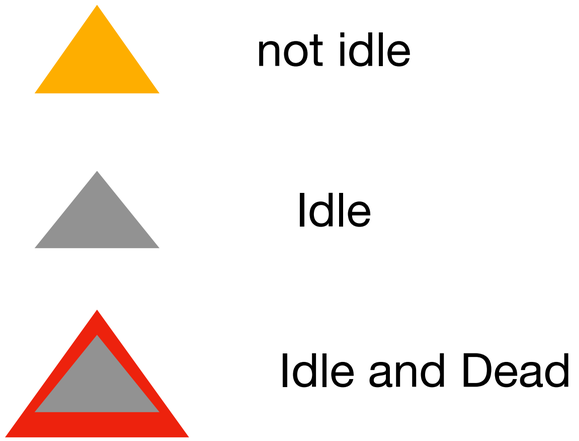

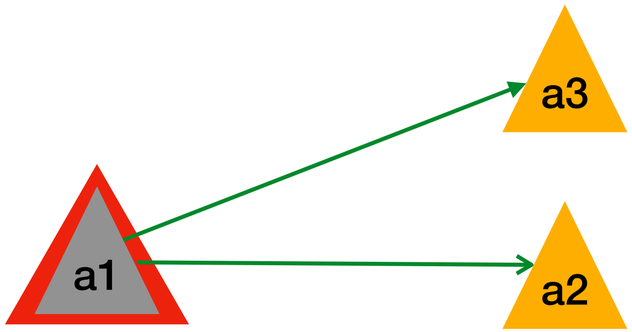

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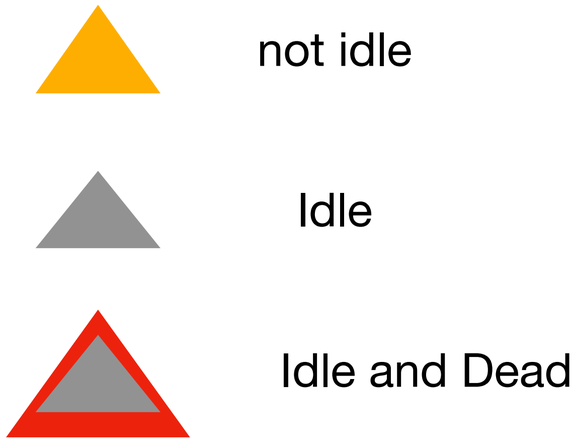

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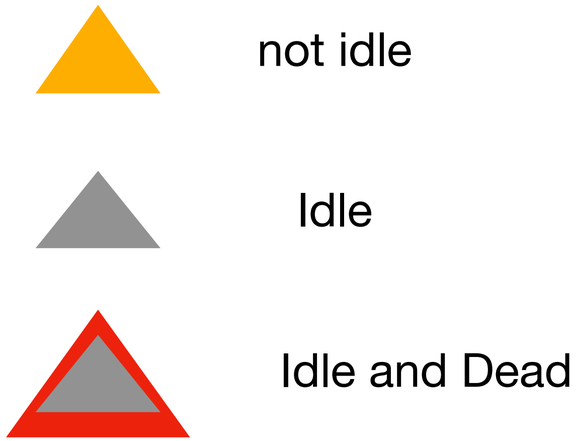

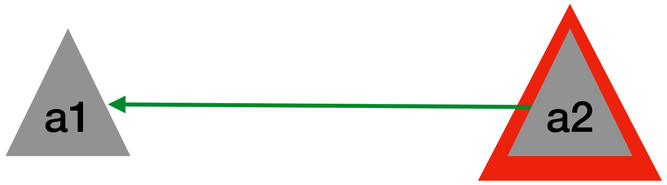

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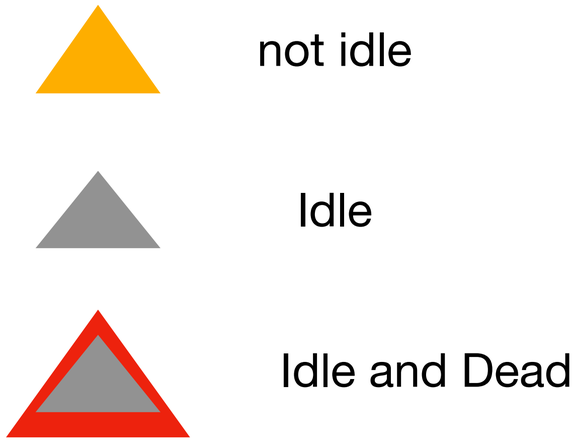

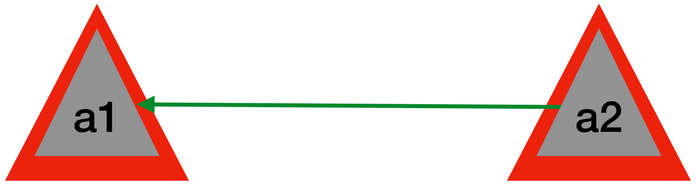

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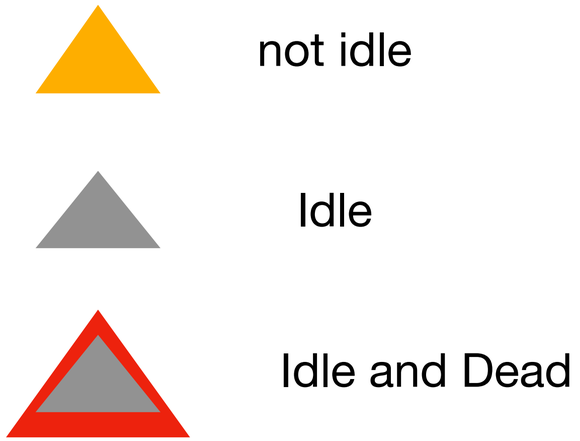

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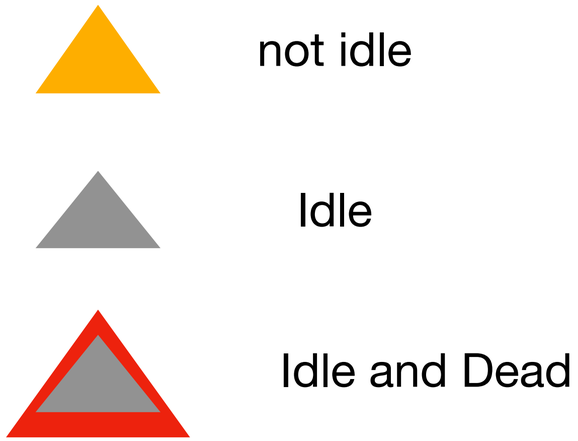

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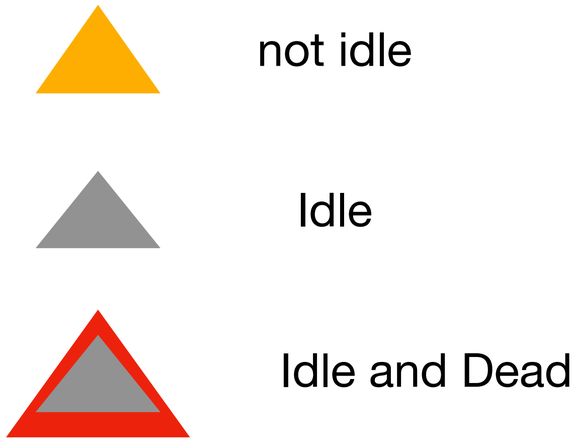

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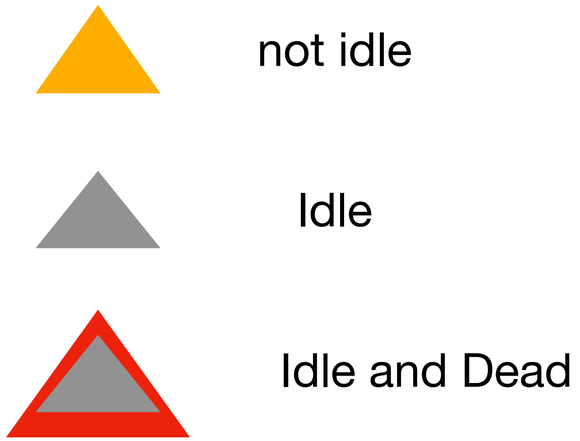

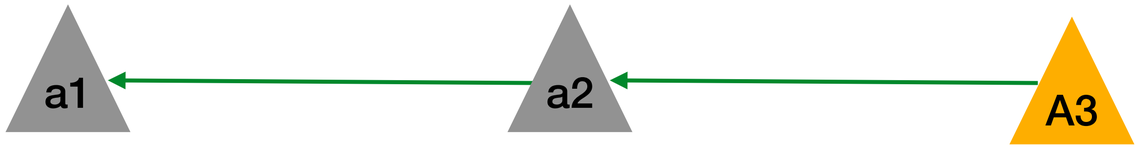

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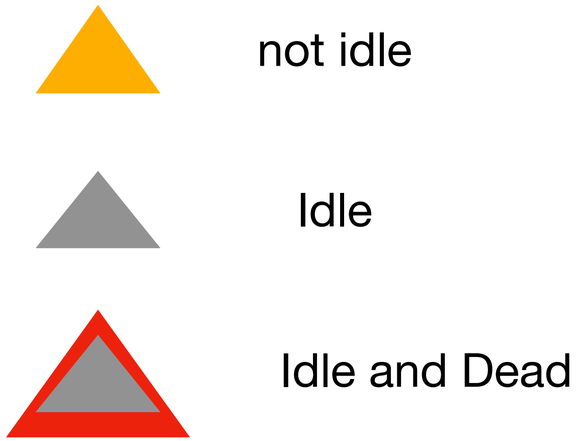

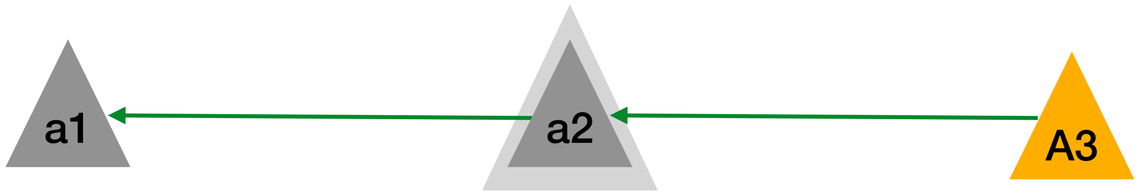

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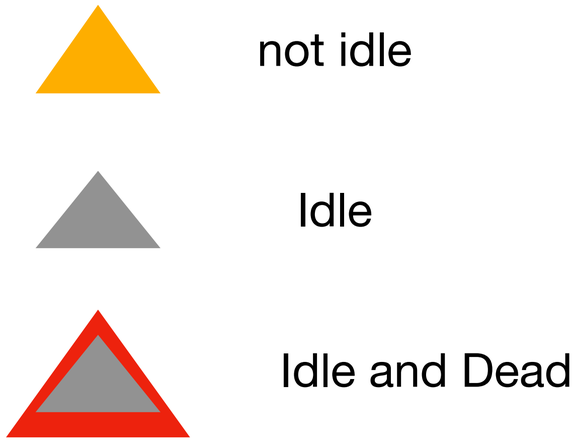

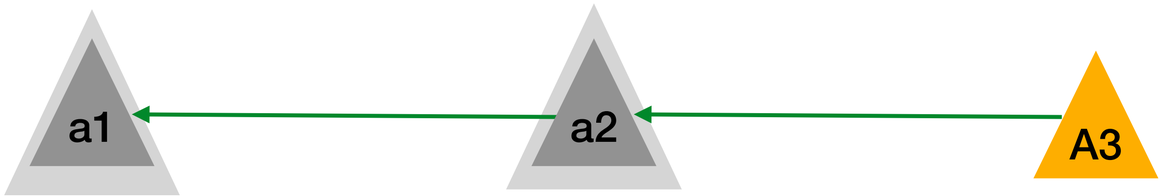

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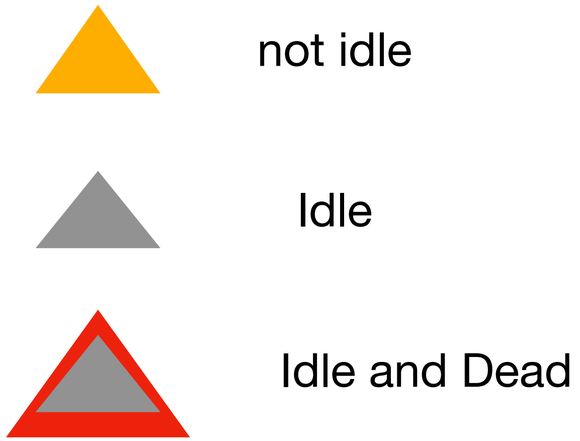

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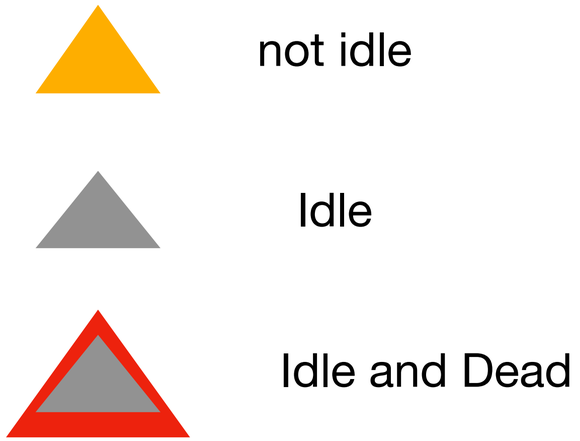

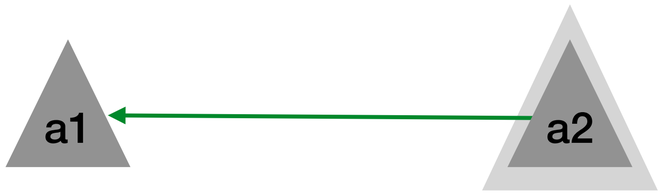

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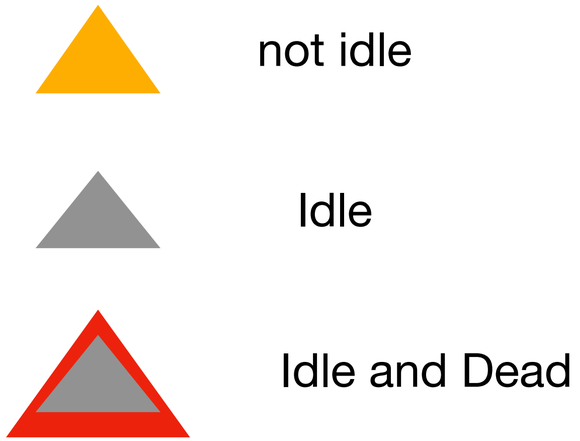

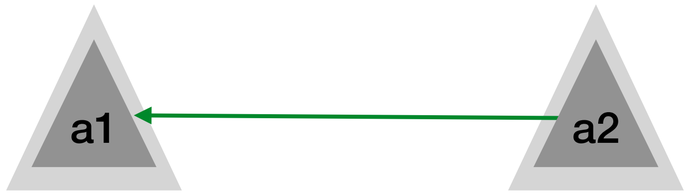

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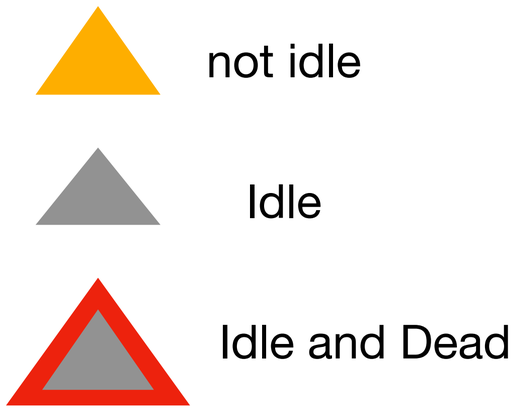

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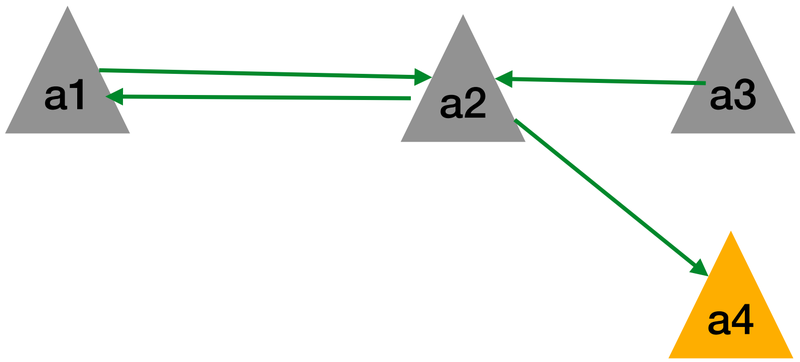

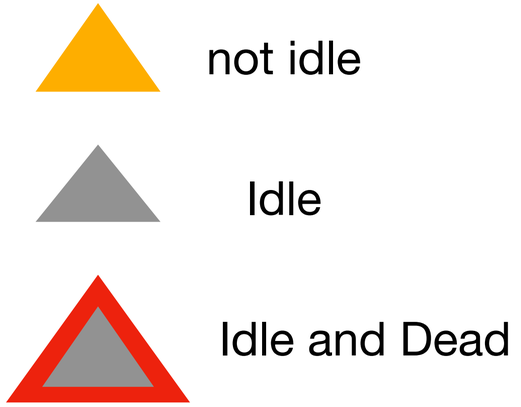

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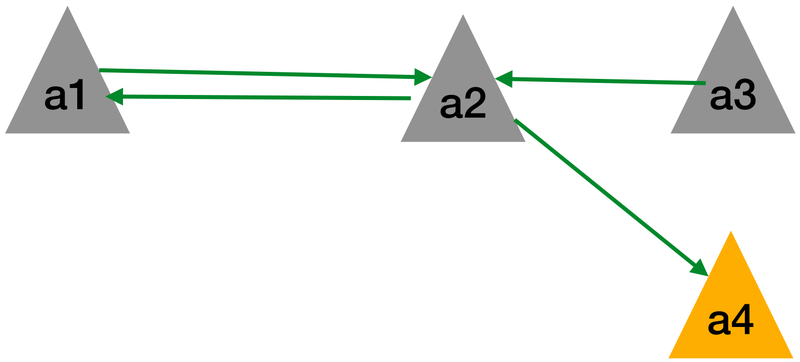

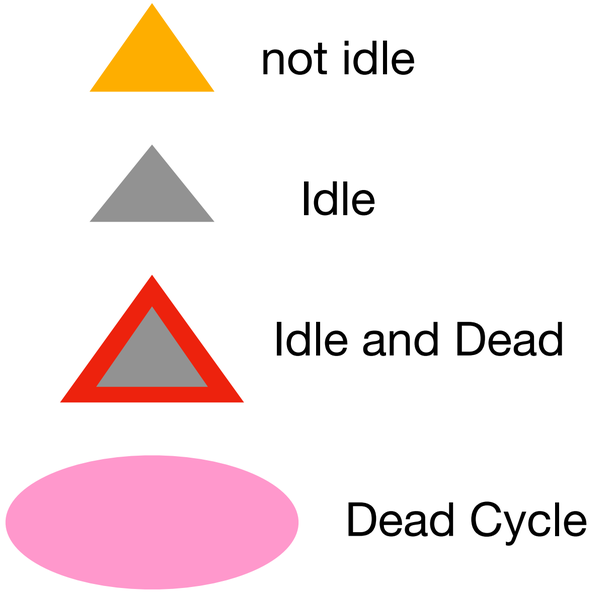

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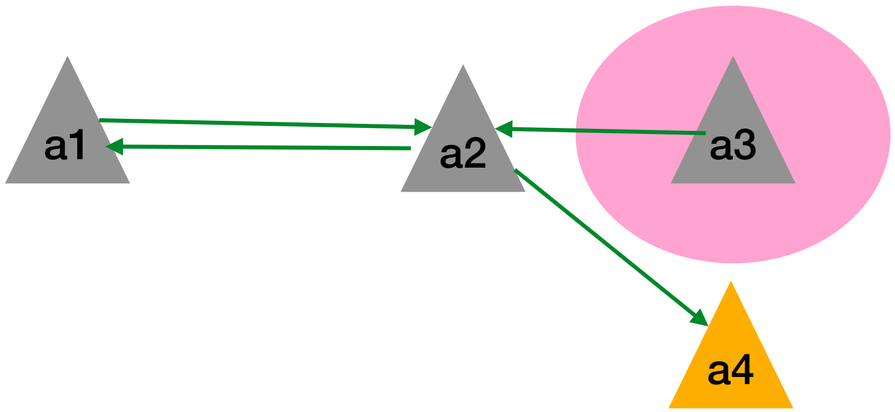

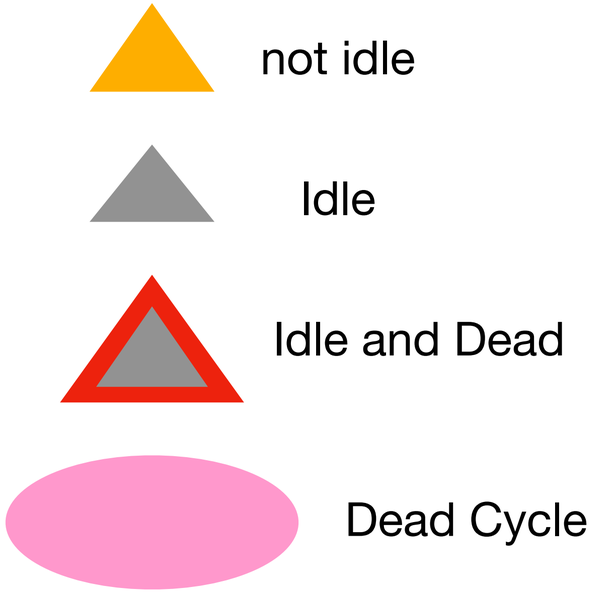

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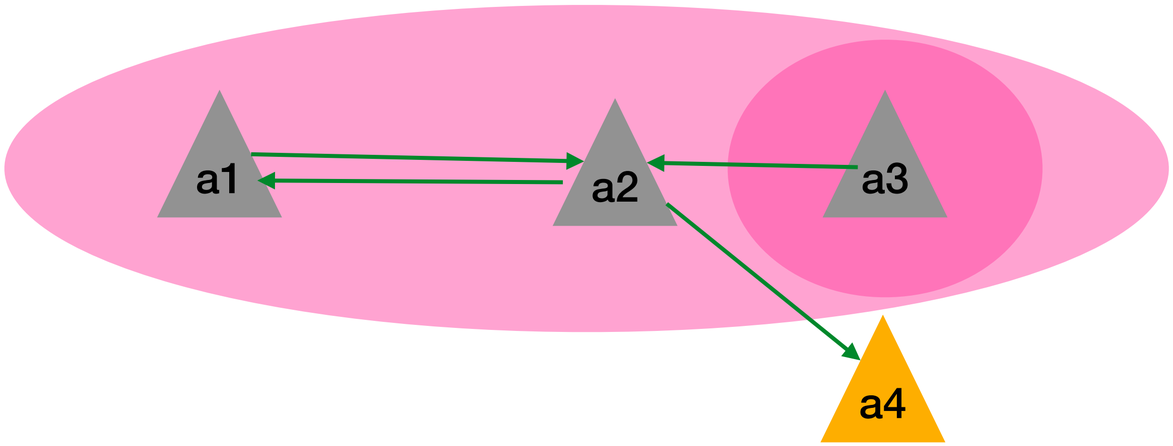

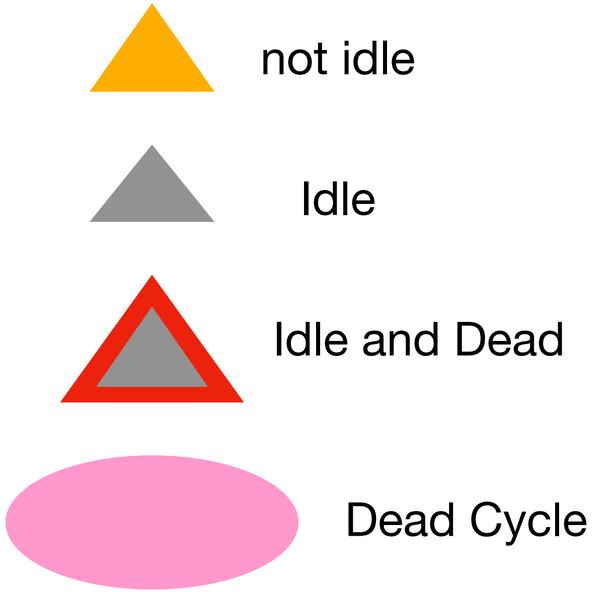

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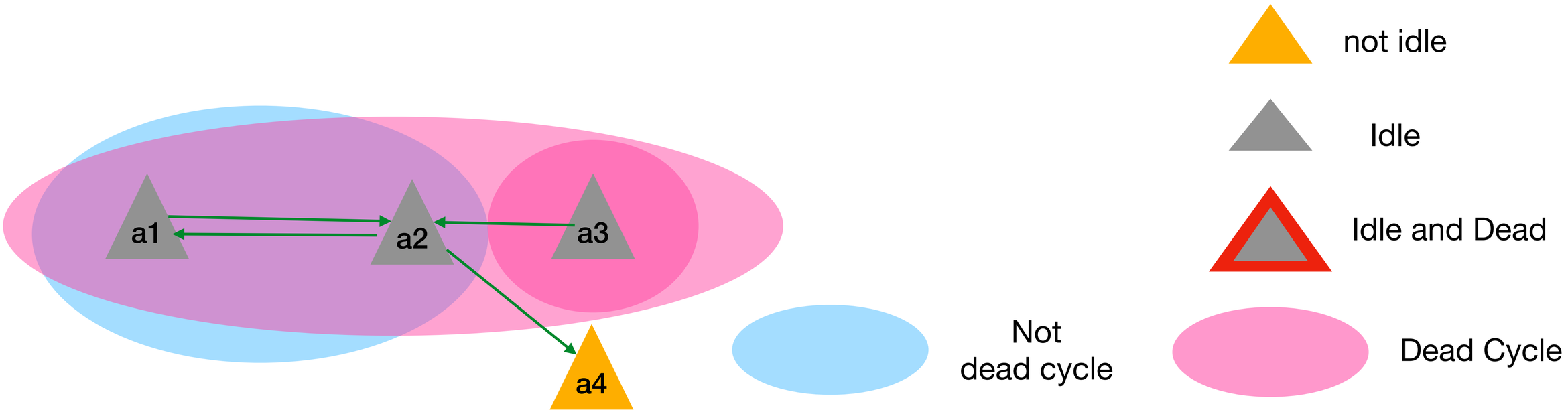

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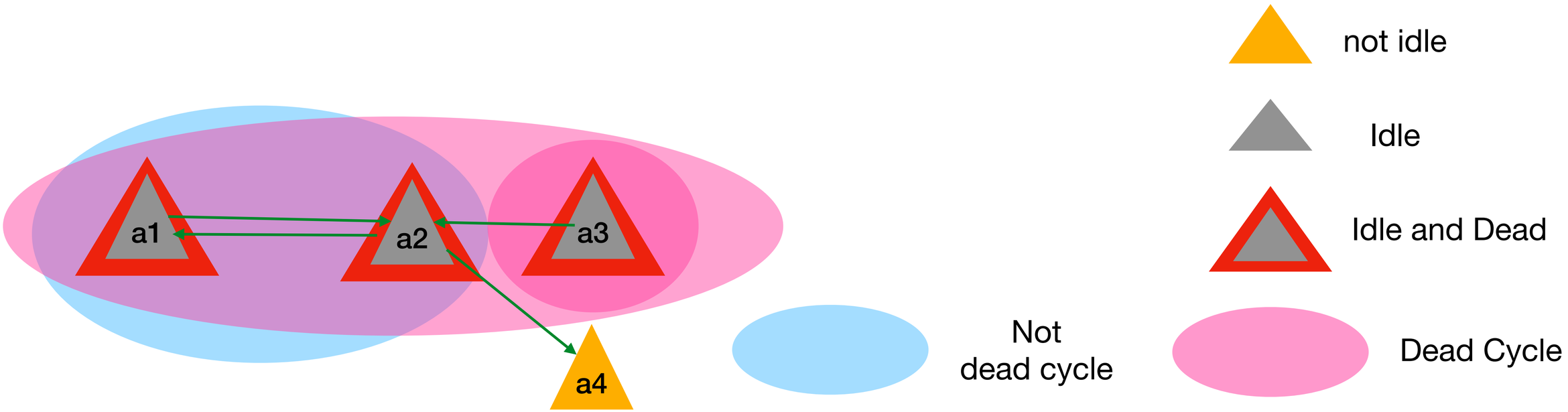

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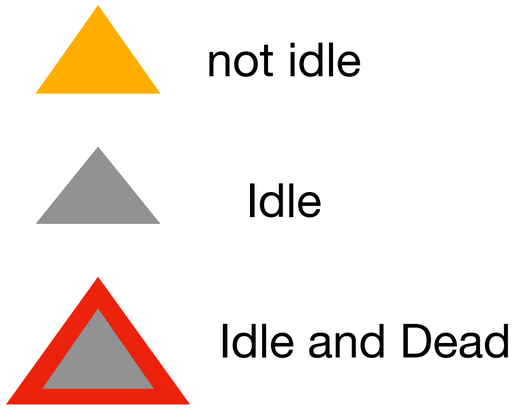
Lemma: $Dead(a) \implies \exists\ a_2,.. a_n.\ DeadCycle(a,a_2,.. a_n)$



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Idle(a) iff (a is not executing a behaviour) $\wedge$ (a.MsgQueue is empty)

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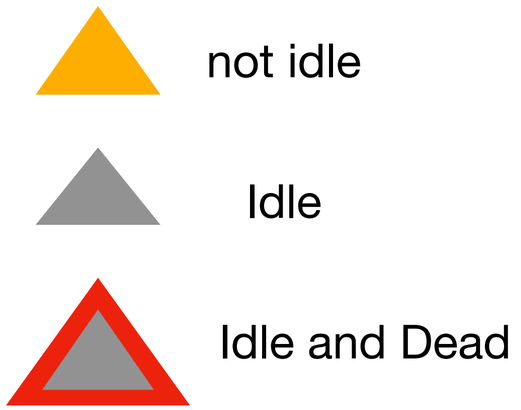
Lemma: Dead(a) $\Longrightarrow$ $\exists$ a_2,.. a_n. DeadCycle(a,a_2,.. a_n)



Therefore, we will be searching for dead cycles!

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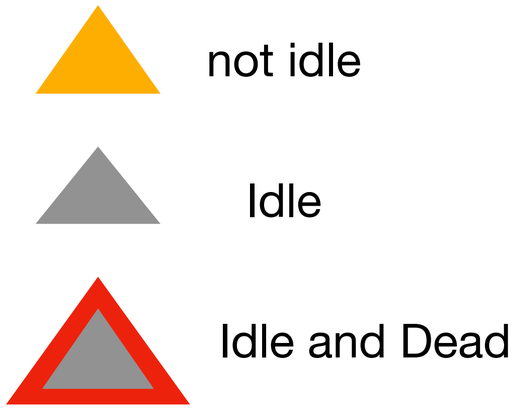

Therefore, we will be searching for dead cycles!

What is the challenge?

Searching for DeadCycle

$\text{Idle}(a)$ iff (a is not executing a behaviour) $\wedge$ (a.MsgQueue is empty)

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Lemma: DeadCycle(a_1,a_2,.. a_n) $\Longleftrightarrow$ DeadCycle'(a_1,a_2,.. a_n)

Searching for DeadCycle’

DeadCycle’$(a_1,.. a_n)$ iff $\forall j \in [1..n].$

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Actors carry a RC-field of type INT such that

(INV) $a.RC + \ldots\ldots = |\{ a' \mid a \in a'.heap \}| + |\{ (a',i) \mid a_j \in a'.MsgQueue[i] \}|$

Then, we have that

Lemma

$\forall j \in [1..n].\ [\ Idle(a_j) \wedge a_j.RC = |\{ k \mid k \in [1..n] \wedge a_j \in a_k.heap \}| \implies$ DeadCycle’(a_1,.. a_n)]

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Is it easier now?

Searching for DeadCycle’

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1) Complete … in INV
2) Preserve INV
3) Complete the protocol, using Lemma and INV
4) Take into account that topology / idleness changes concurrently with execution of protocol

Searching for DeadCycle’

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What remains to do?

1) Complete … in INV
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3) Complete the protocol, using Lemma and INV
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Preserve and Complete INV

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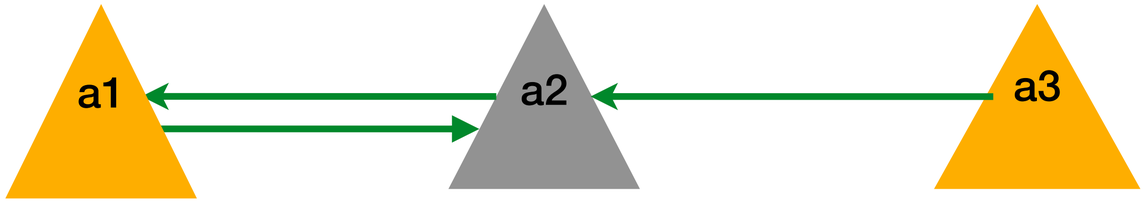

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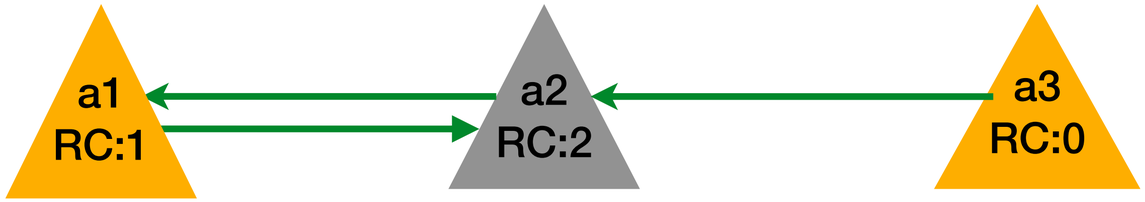

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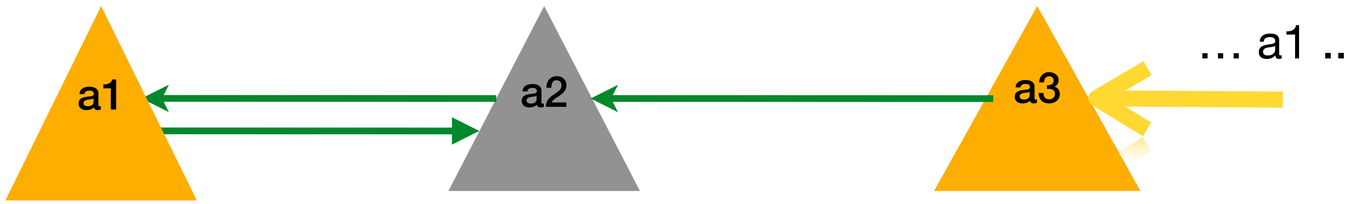

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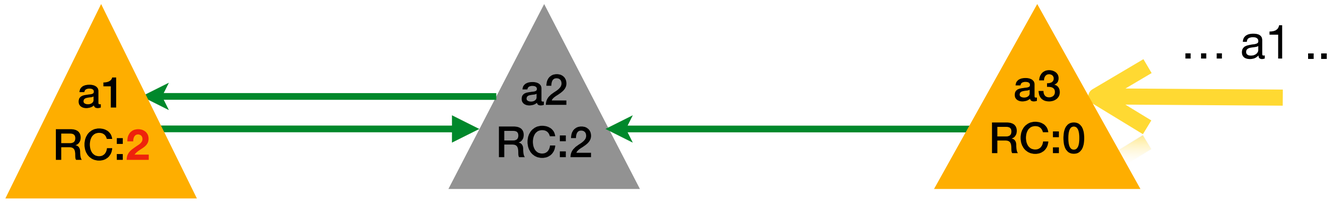

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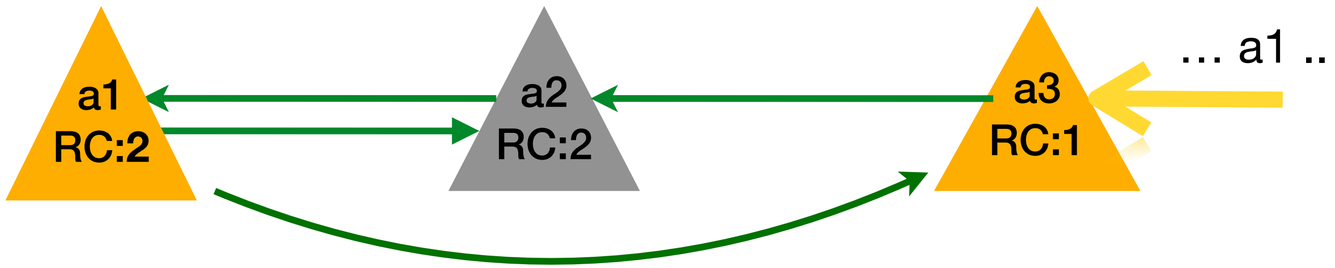

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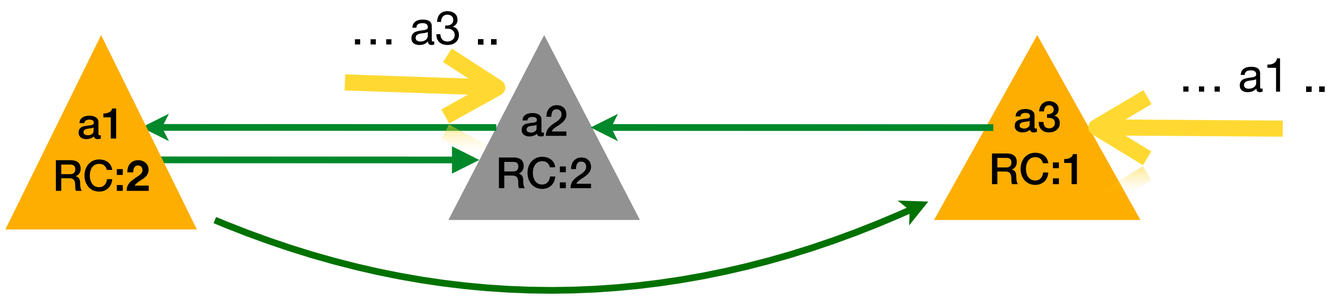

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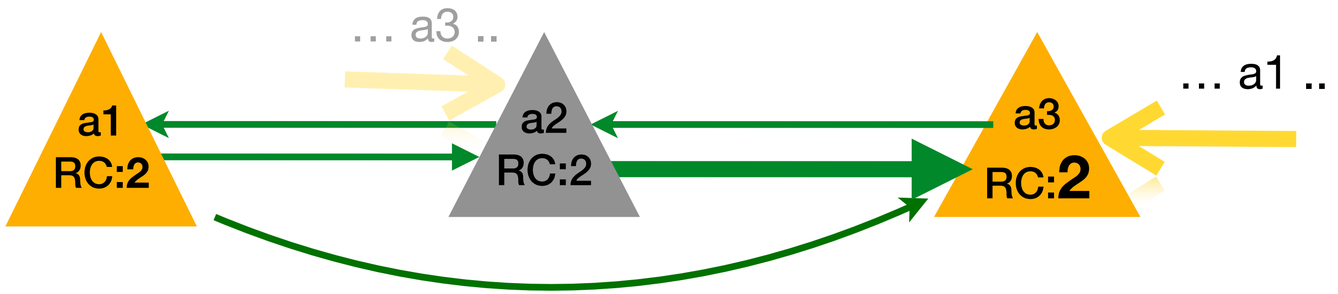

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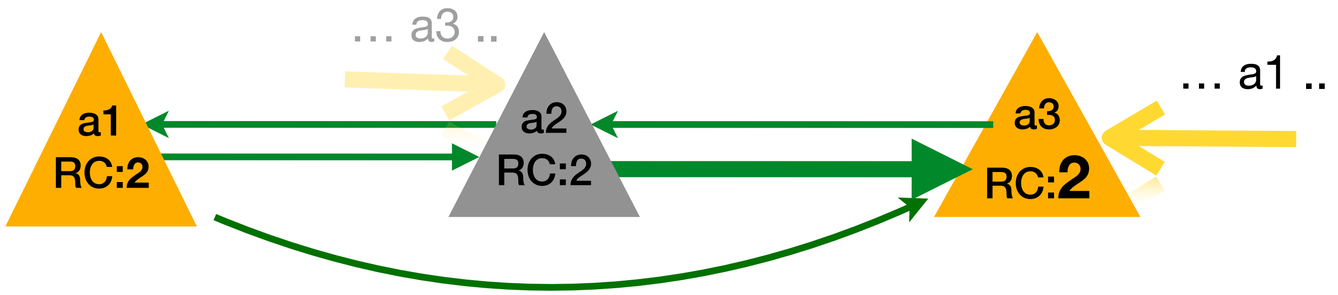

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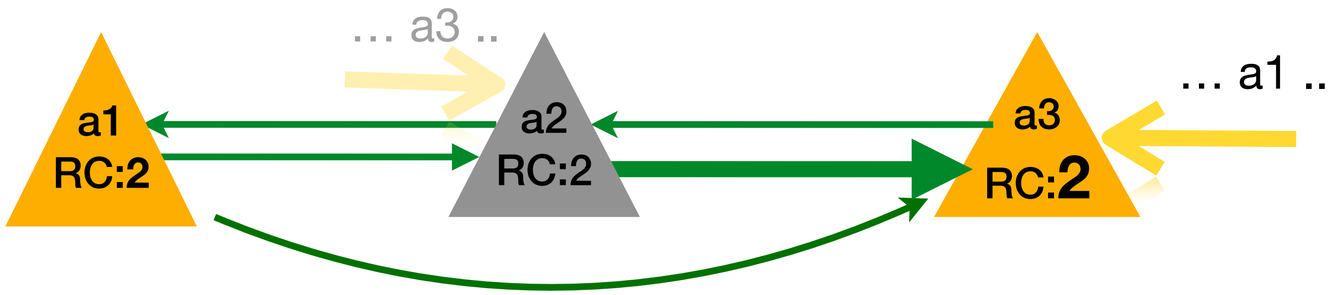

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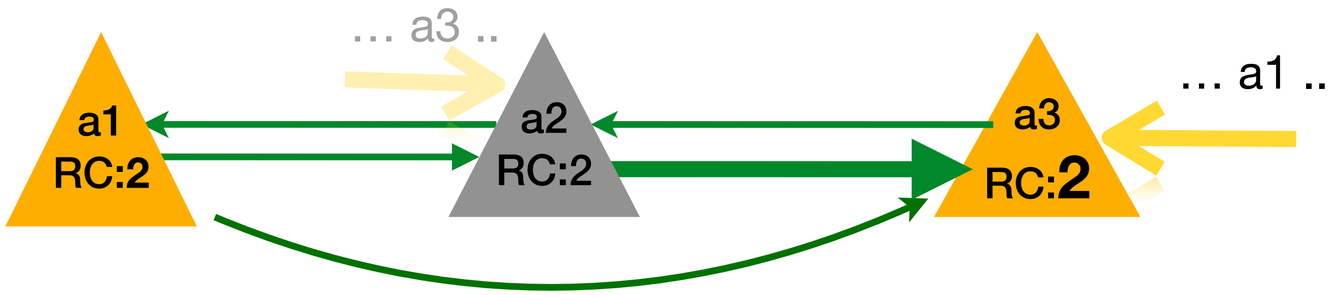

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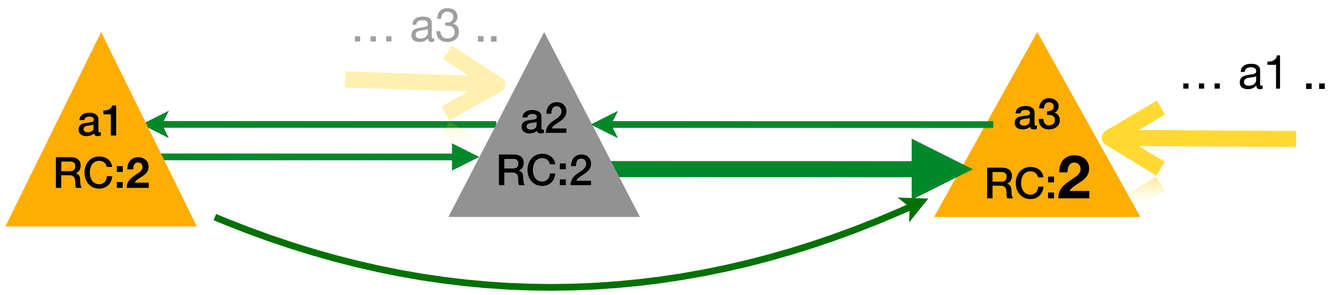

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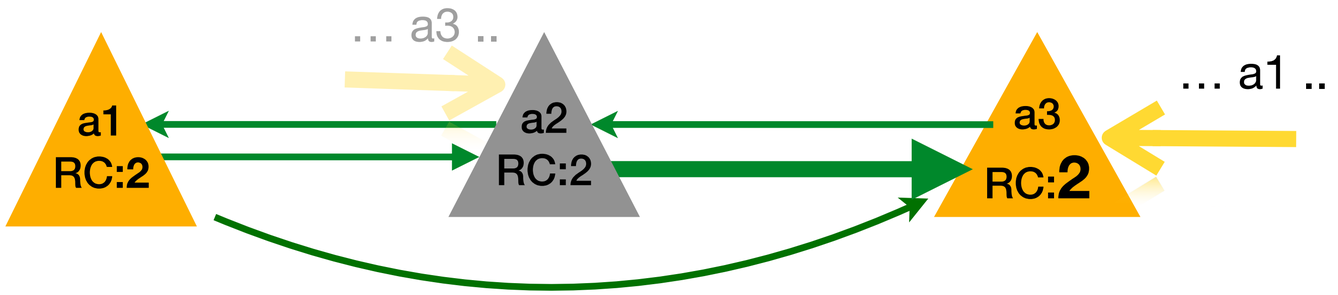

How will a3 know to increment its RC?

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How is INV preserved?

INV takes the INC (and DEC messages) into account

Preserve and Complete INV

(INV) a.RC + **a.INCDEC** = | { a’ | a∈a’.heap } | + | { (a’,i) | a_j∈a’.MsgQueue[i] } |

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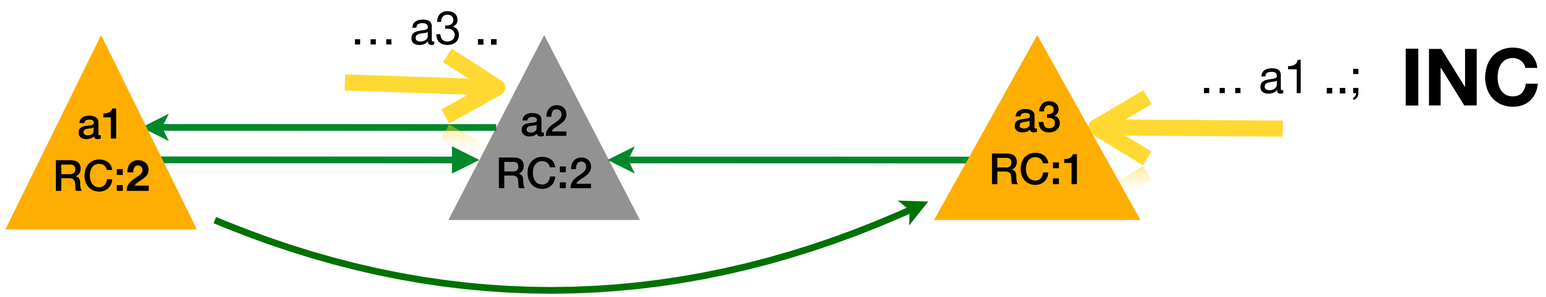
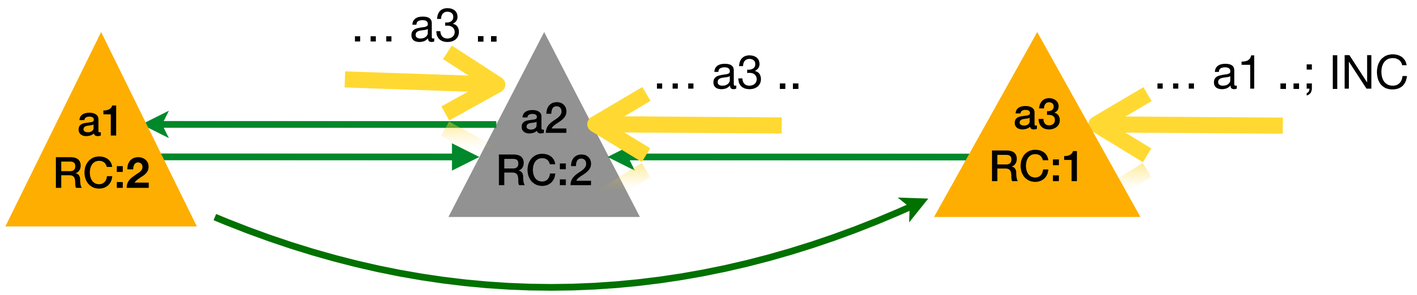


a.INCDEC = | { k | a.MsgQueue[k] = INC } | - { k | a.MsgQueue[k] = DEC } |

Preserving INV — sending message

(INV) $a.RC + a.INCDEC = |\{ a' \mid a \in a'.heap \}| + |\{ (a',i) \mid a_j \in a'.MsgQueue[i] \}|$

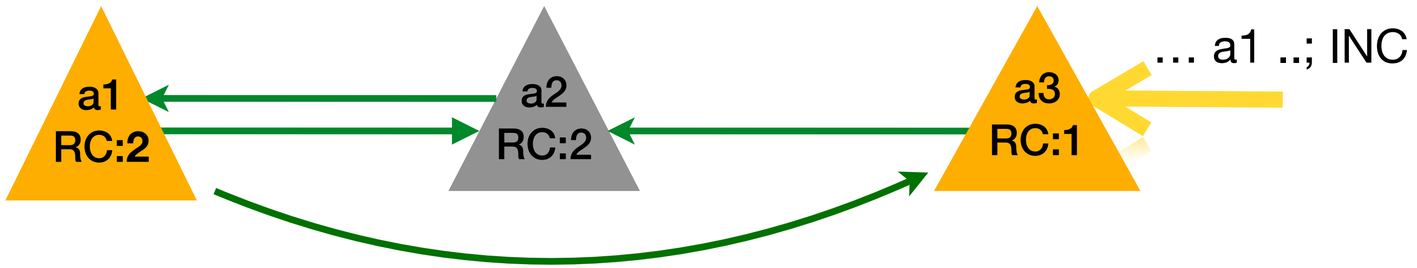
If a wants to send msg(a') to a"
then Append(a'.MsqQueue,INC)
Append(a".MsqQueue,msg(a"))



Preserving INV — receiving message

(INV) a.RC + a.INCDEC = | { a' | a∈a'.heap } | + | { (a',i) | a_j∈a'.MsgQueue[i] } |

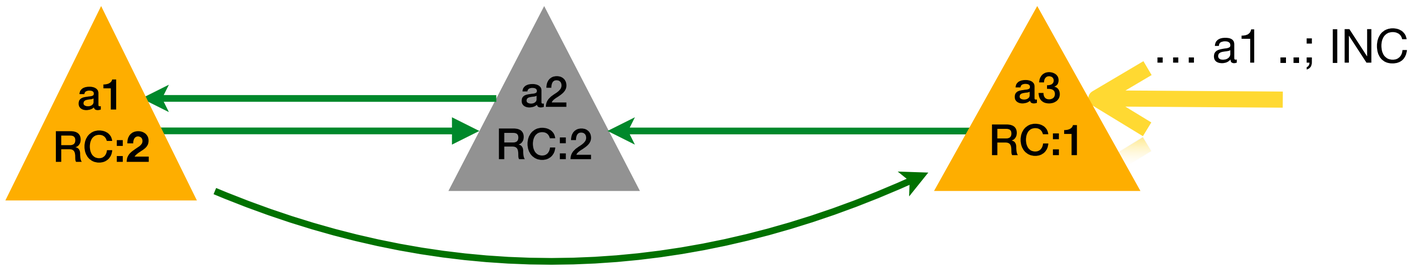
If Top(a.MsqQueue)=msg(a')
then Pop(a.MsgQueue);
if a'∈a.heap
then Append(a'.MsgQueue,DEC)



Preserving INV — receiving INC

(INV) a.RC + a.INCDEC = | { a' | a∈a'.heap } | + | { (a',i) | a_j∈a'.MsgQueue[i] } |

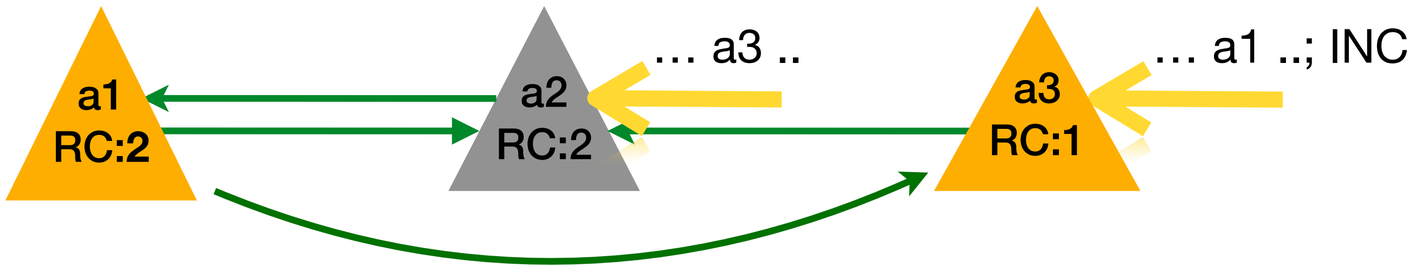
If Top(a.MsqQueue)=INC
then Pop(a.MsqQueue);
a.RC:=a.RC+1



Preserving INV — receiving DEC

(INV) $a.RC + a.INCDEC = |\{ a' \mid a \in a'.heap \}| + |\{ (a',i) \mid a_j \in a'.MsgQueue[i] \}|$

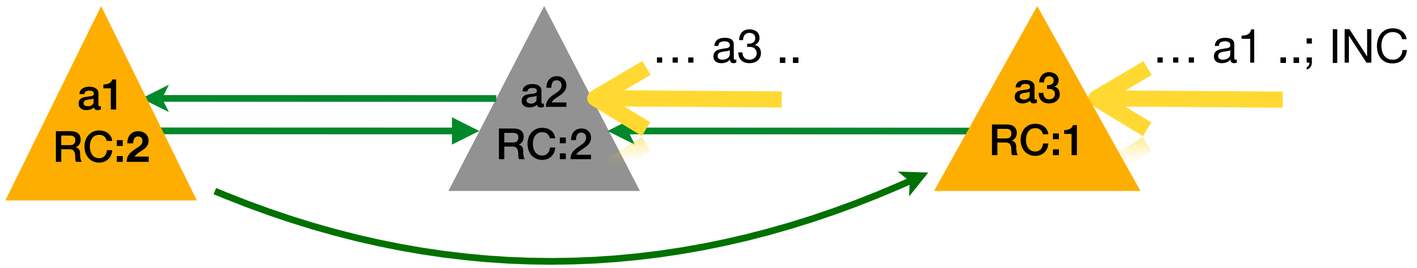
If Top(a.MsqQueue)=DEC
then Pop(a.MsqQueue);
a.RC:=a.RC-1



Preserving INV — local GC

(INV) a.RC + a.INCDEC = | { a’ | a∈a’.heap } | + | { (a’,i) | a_j∈a’.MsgQueue[i] } |

If a.heap drops reference to a’
then Append(a’.MsgQueue,DEC)



Searching for DeadCycle’

Lemma

$\forall j \in [1..n].\ [\quad Idle(a_j) \ \wedge\ a_j.RC = |\{ k \mid k \in [1..n] \wedge\ a_j \in a_k.heap \}| \quad \Longrightarrow\quad DeadCycle'(a_1,.. a_n)\quad]$

And where

(INV) $a.RC + a.INCDEC = |\{ a' \mid a \in a'.heap \}| + |\{ (a',i) \mid a_j \in a'.MsgQueue[i] \}|$

1) ~~Complete … in INV~~
2) ~~Preserve INV~~
3) Complete the protocol using Lemma
4) Take into account that topology / idleness changes concurrently with execution of protocol

Searching for DeadCycle’

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$\forall j \in [1..n].\ [\quad Idle(a_j) \ \wedge \ a_j.RC = |\{ k \mid k \in [1..n] \wedge a_j \in a_k.heap \}| \quad \Longrightarrow \quad DeadCycle'(a_1,.. a_n) \quad]$

And where

(INV) $a.RC + a.INCDEC = |\{ a' \mid a \in a'.heap \}| + |\{ (a',i) \mid a_j \in a'.MsgQueue[i] \}|$

What remains to do?

1) ~~Complete … in INV~~
2) ~~Preserve INV~~
3) Complete the protocol using Lemma
4) Take into account that topology / idleness changes concurrently with execution of protocol

Searching for DeadCycle’

Lemma

$\forall j \in [1..n].\ [\quad Idle(a_j)\ \wedge\ a_j.RC = |\{\, k \mid k \in [1..n] \wedge\ a_j \in a_k.heap \,\}|\quad \Longrightarrow\quad DeadCycle'(a_1,..\ a_n)\quad]$

Searching for DeadCycle’

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We introduce a global cycle detector (CD). When an actor becomes idle, it sends to CD a BLK-message with

a) a.RC

b) { a’ | a’ ∈a.heap }

Searching for DeadCycle’

Lemma

$\forall j \in [1..n].\ [\quad Idle(a_j)\ \wedge\ a_j.RC = |\{\ k \mid k \in [1..n] \wedge\ a_j \in a_k.heap\ \}|\quad \Longrightarrow\quad DeadCycle'(a_1,..\ a_n)\quad]$

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Based on the collected information, the CD can determine whether a set forms a DeadCycle’.

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Based on the collected information, the CD can determine whether a set forms a DeadCycle’.

What if the topology/idleness changed after the actor sent BLK-msg to CD?

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If an actor receives a INC/DEC/application message after having sent BLK, it sends UNBLK to CD, who discards this actor’s entry.

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We introduce a global cycle detector (CD). When an actor becomes idle, it sends to CD a BLK-message with

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If an actor receives a INC/DEC/application message after having sent BLK, it sends UNBLK to CD, who discards this actor’s entry.

When the CD has found a DeadCycle’(a_1,.. a_n), then it creates a fresh token t, and sends a CONF(t) request to all wh respond with ACK(t). When it receives ACK from all the actors, it collects a_1,.. a_n

Reflections on MAC

Is that the whole story?

Is it useful?

Is it sound?

Is it complete?

Does separation play any role?

What are its drawbacks?

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CD is a bottleneck.

CD performs a complex search on a large data structure.

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What are its drawbacks?

CD is a bottleneck.

CD performs a complex search on a large data structure.

We need to “scan” every application message upon send/receive.

Reflections on MAC

Is that the whole story? **No**, some more clever ideas used.

Is it useful? Yes

Is it sound? **YES** — and we have two latex proofs.

Is it complete? **YES** — and we have one latex proof.

Does separation play any role? **YES** — when scanning messages, and own heap.

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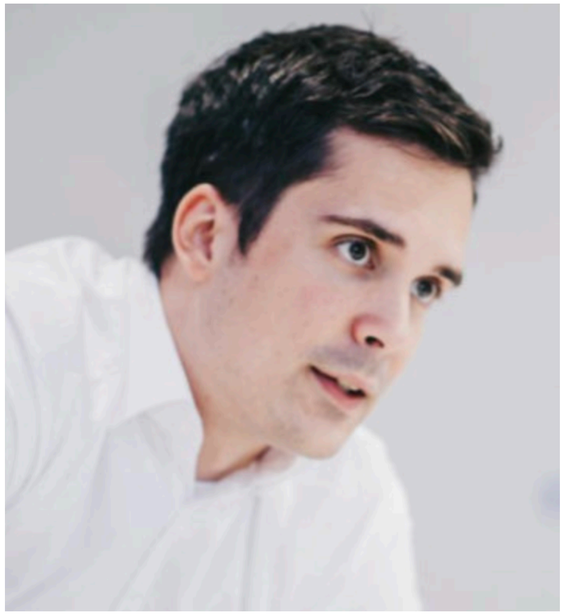
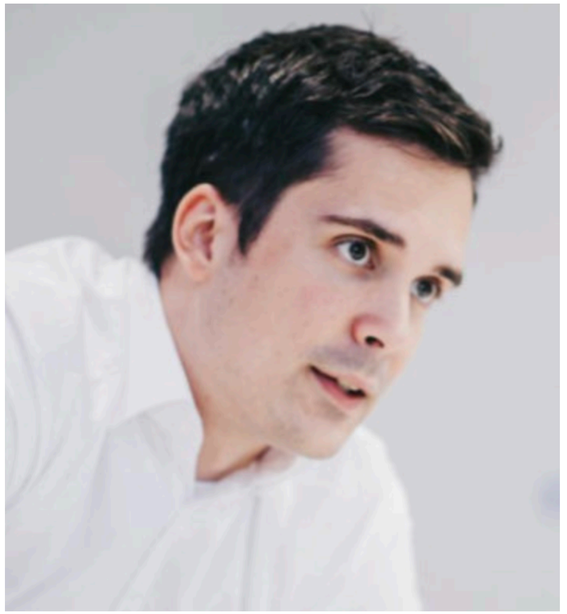
We need to “scan” every application message upon send/receive.

Enter eMAC - Sebastian Blessing



Enter eMAC - Sebastian Blessing



As of last Friday:

- MAC outperforms eMAC when there are a few very large cylces, and
- eMAC outperforms MAC when there are a lot of small cycles.

eMAC - basic idea

Perception: (ActorId, Number)
(A,k) : k out of A's direct predecessors are of unknown status

Perceptions: Perception*

Perceptions: Each actor keeps perception in its state
Actors notify their successors when their perception "improves"

eMAC - basic idea

Notice: ActorId × Number

A : k actor A has notified that a.RC-k of its immediate predecessors have reported idle

Notification: ActorId × Notice*

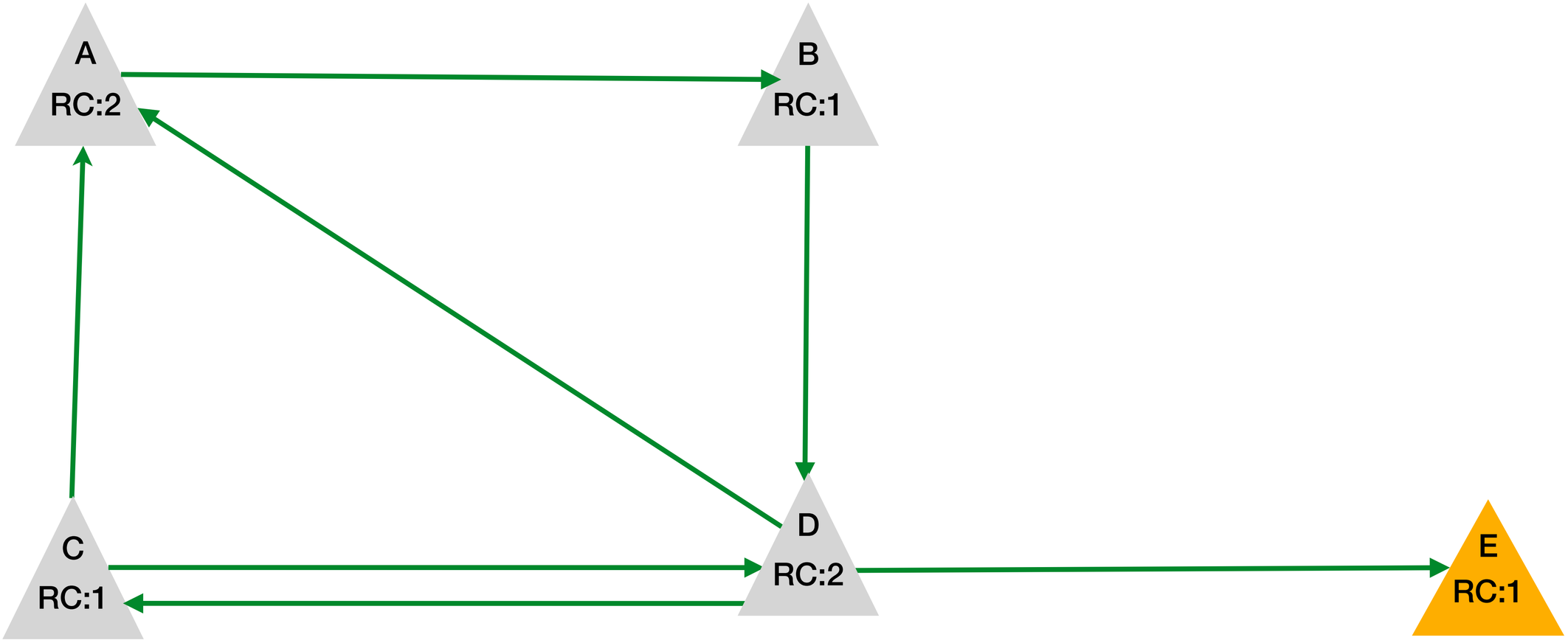
A, A_1:k_1…. A_n:k_n : A sends notices A_1:k_1 …. A_n:k_n

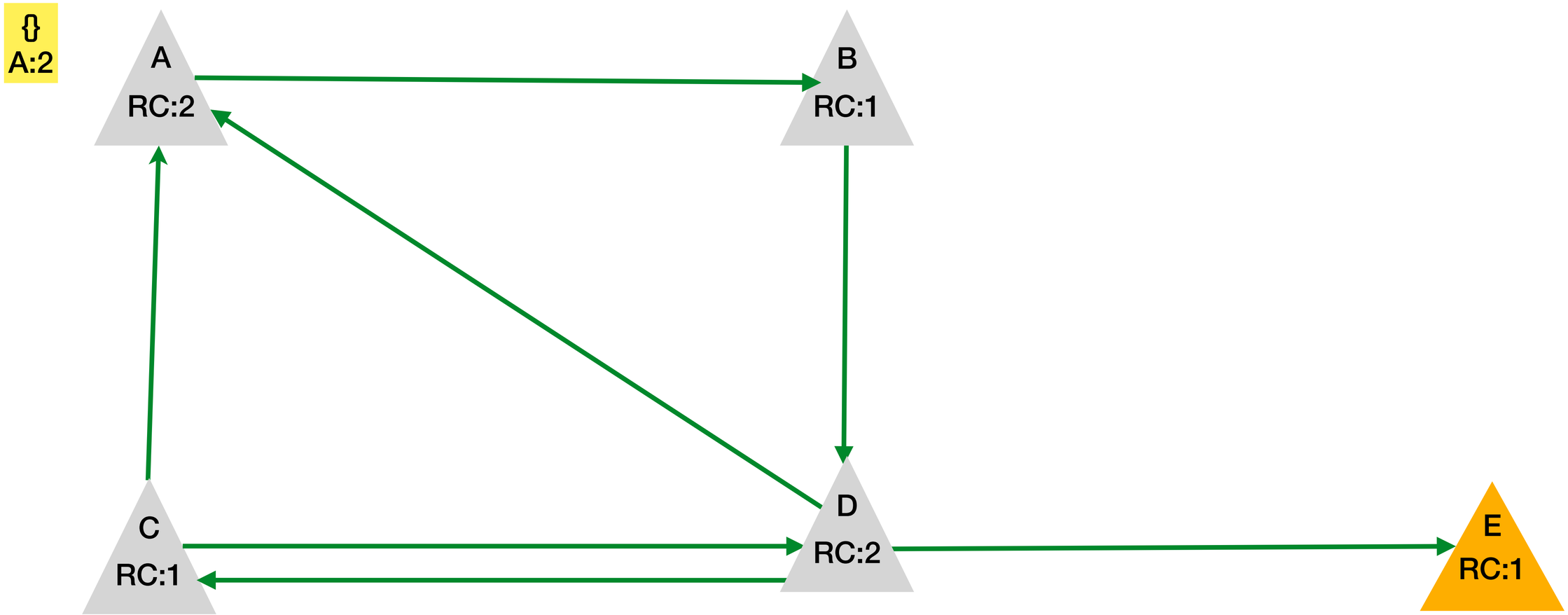
Perception: ActorId* × Notice*

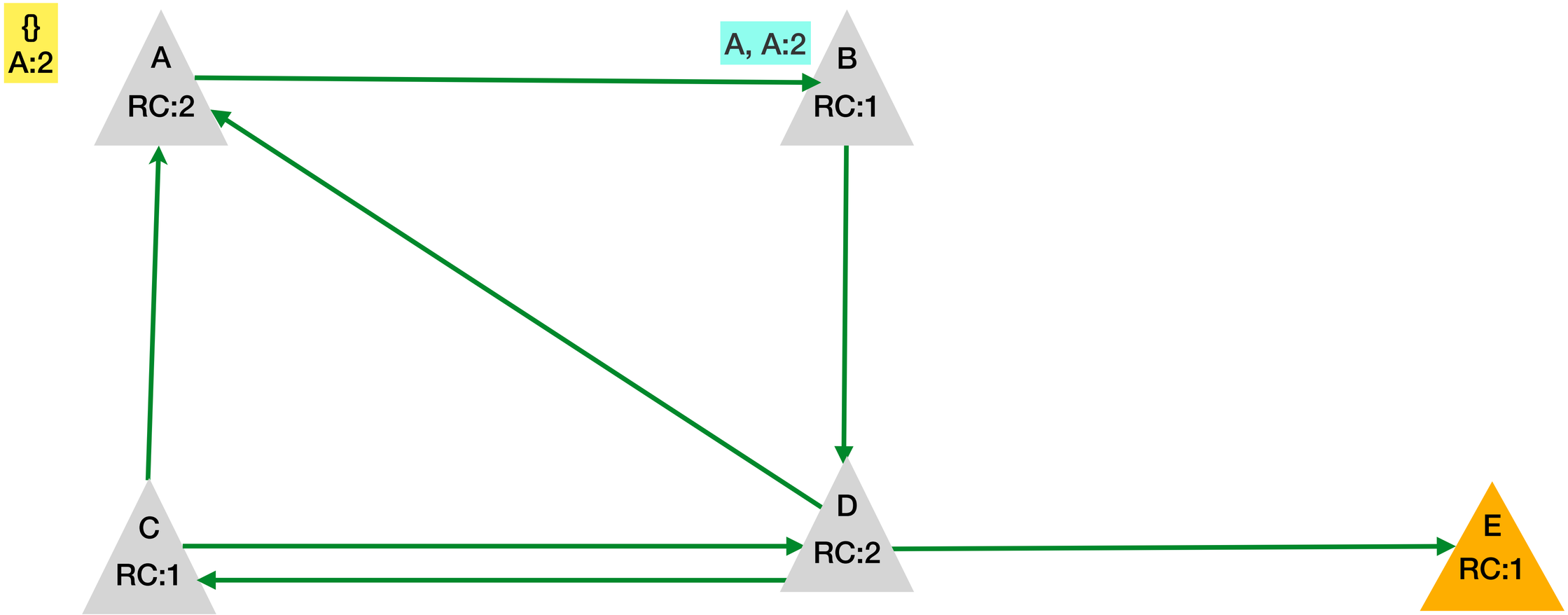
{ A_1, … A_n }, A'_1:k_1…. A'_m:k_m

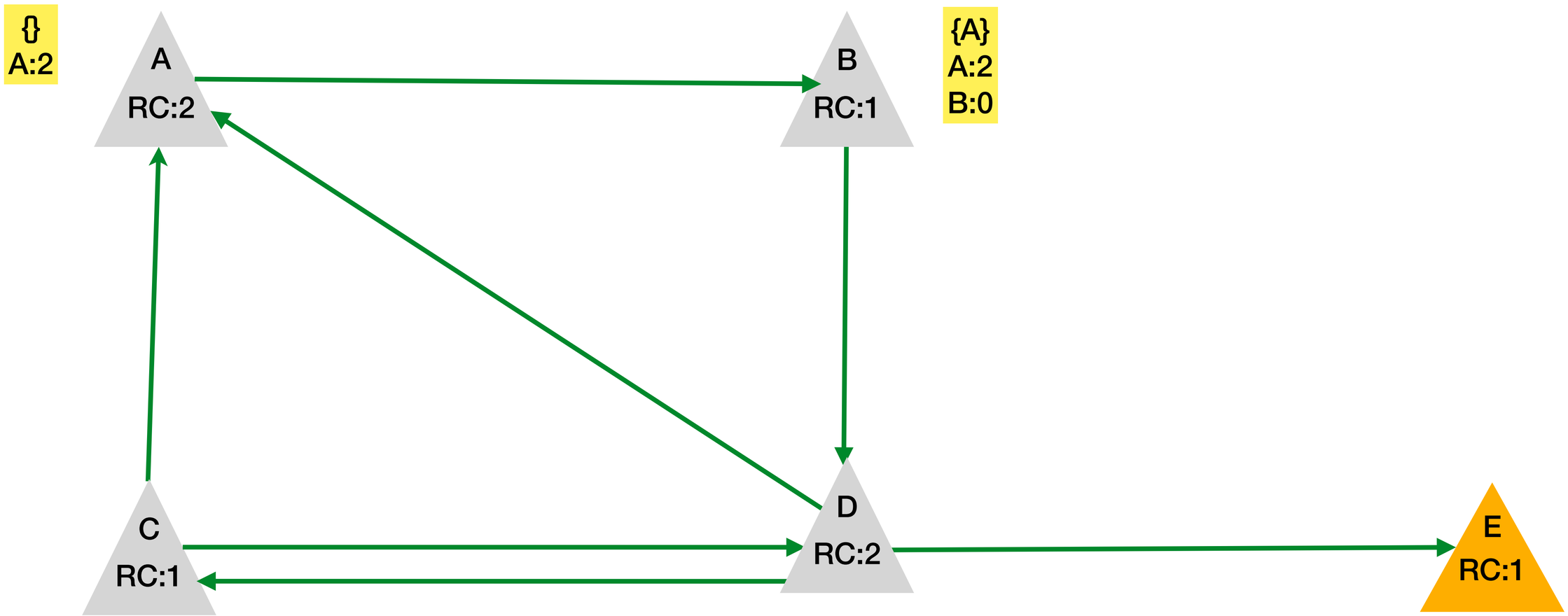
A_1, … A_n are some of the receiver's direct predecessors, and have sent notices to receiver
A'_1, … A'_m are some of the receiver's indirect predecessors, and have each sent notice A'_j:k_j

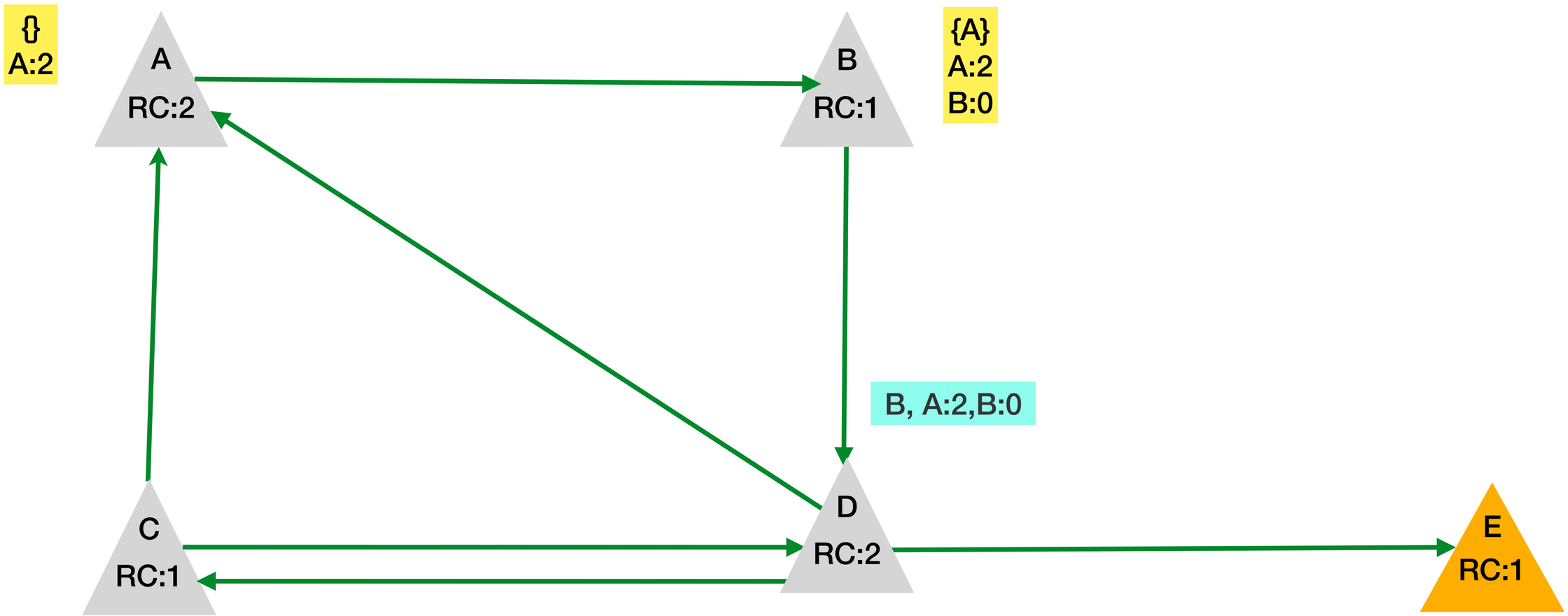
Protocol: Actors keep perception in their state
Actors notifies their immediate successors when they block, or their perception "improves"
Upon receipt of a notification, actors improve their perception
…..
…

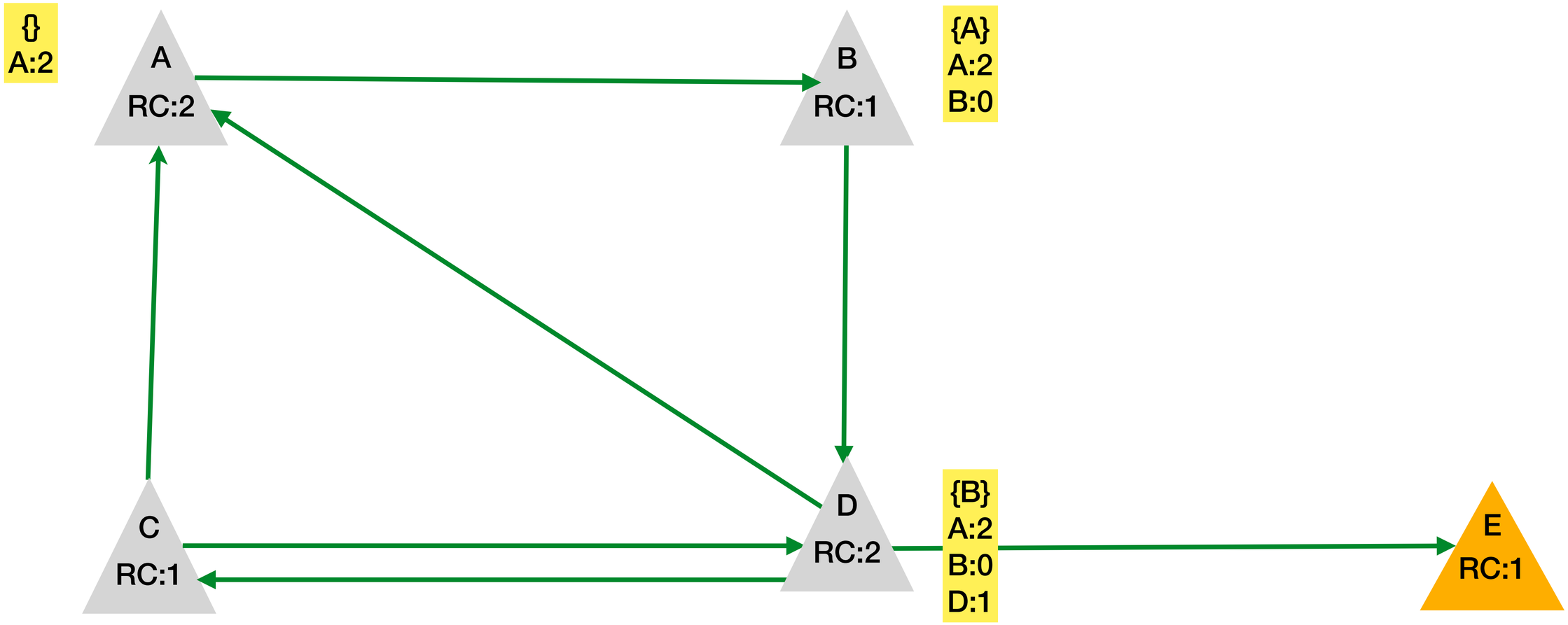

A
RC:2
B
RC:1
C
RC:1
D
RC:2
E
RC:1

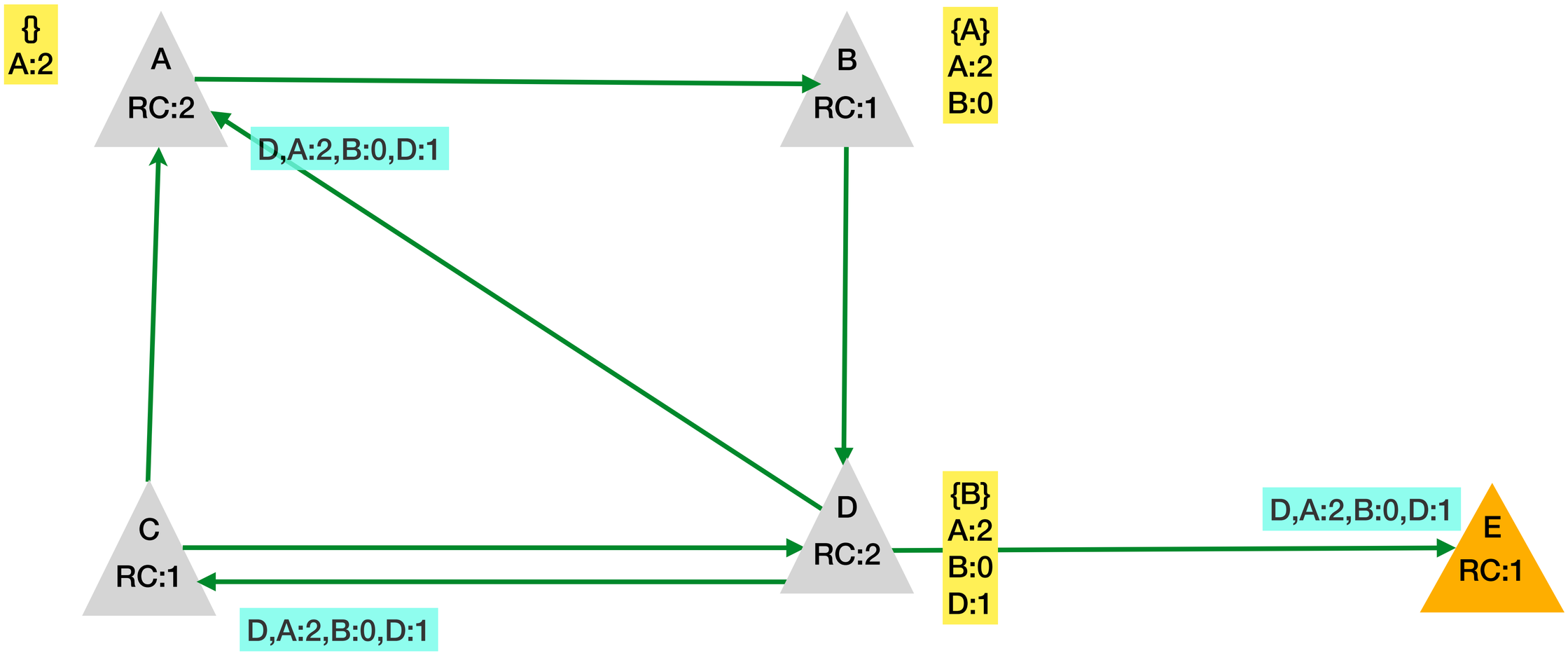

{}
A:2
A
RC:2
B
RC:1
C
RC:1
D
RC:2
E
RC:1


{}
A:2
A
RC:2
A, A:2
B
RC:1
C
RC:1
D
RC:2
E
RC:1


{}
A:2
A
RC:2
B
RC:1
{A}
A:2
B:0
C
RC:1
D
RC:2
E
RC:1


{}
A:2
A
RC:2
B
RC:1
{A}
A:2
B:0
B, A:2,B:0
C
RC:1
D
RC:2
E
RC:1


{}
A:2
A
RC:2
B
RC:1
{A}
A:2
B:0
C
RC:1
D
RC:2
{B}
A:2
B:0
D:1
E
RC:1


{}
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RC:2
B
RC:1
{A}
A:2
B:0
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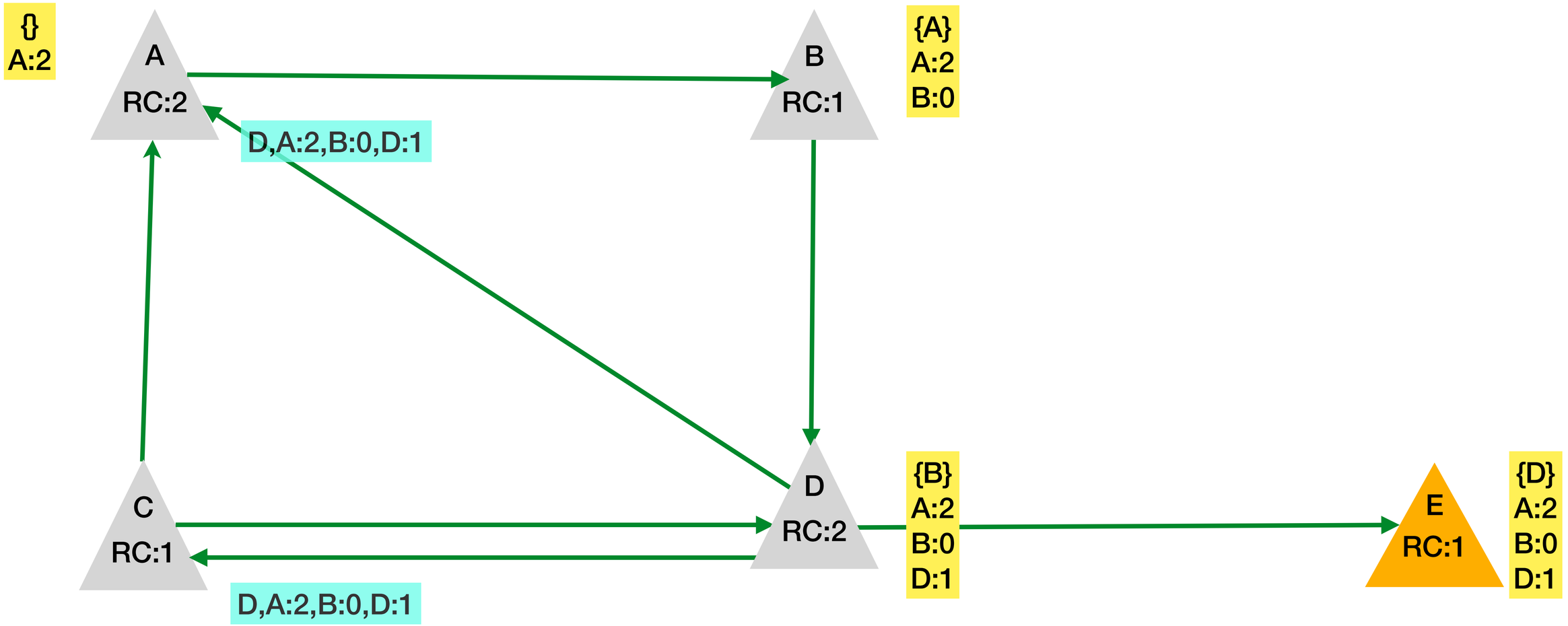
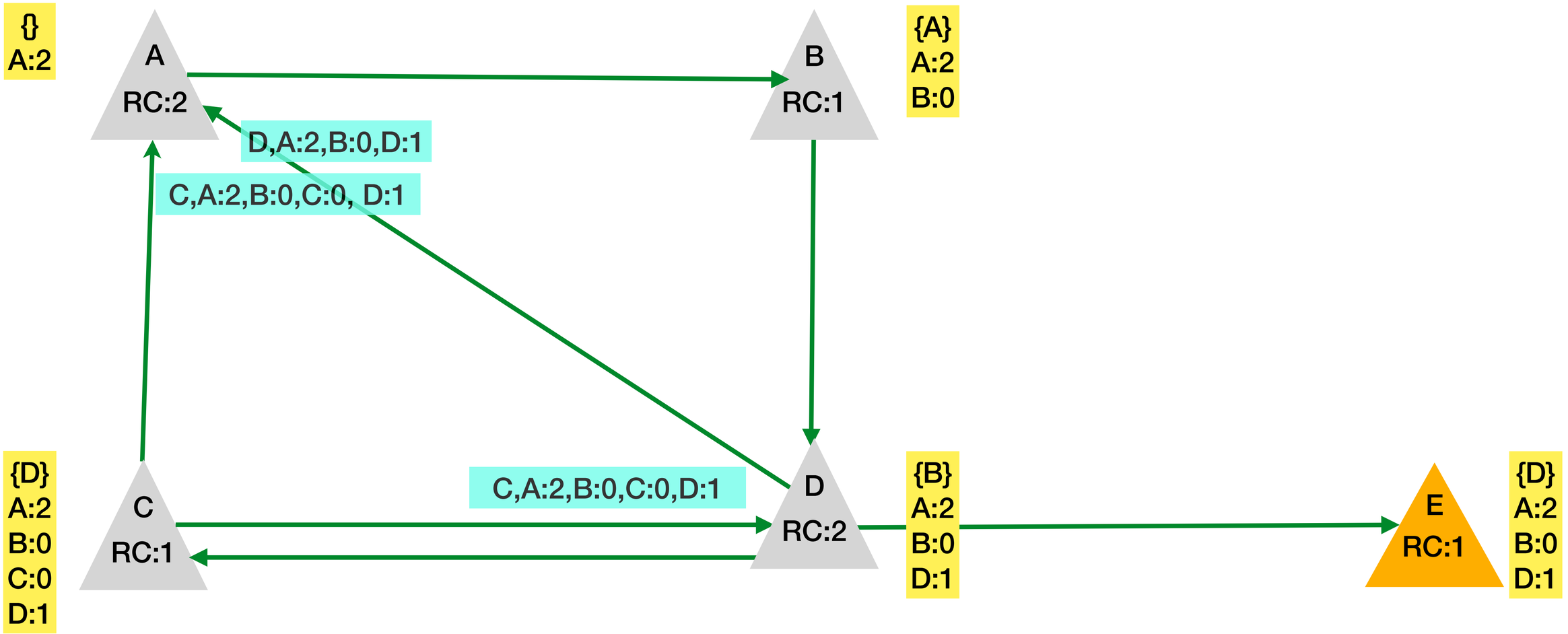
C
RC:1
D
RC:2
{B}
A:2
B:0
D:1
D,A:2,B:0,D:1
E
RC:1
D,A:2,B:0,D:1


{}
A:2
A
RC:2
B
RC:1
{A}
A:2
B:0
D,A:2,B:0,D:1
C
RC:1
D
RC:2
{B}
A:2
B:0
D:1
E
RC:1
{D}
A:2
B:0
D:1
D,A:2,B:0,D:1


{}
A:2
A
RC:2
B
RC:1
{A}
A:2
B:0
D,A:2,B:0,D:1
C,A:2,B:0,C:0, D:1
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D:1
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RC:1
C,A:2,B:0,C:0,D:1
D
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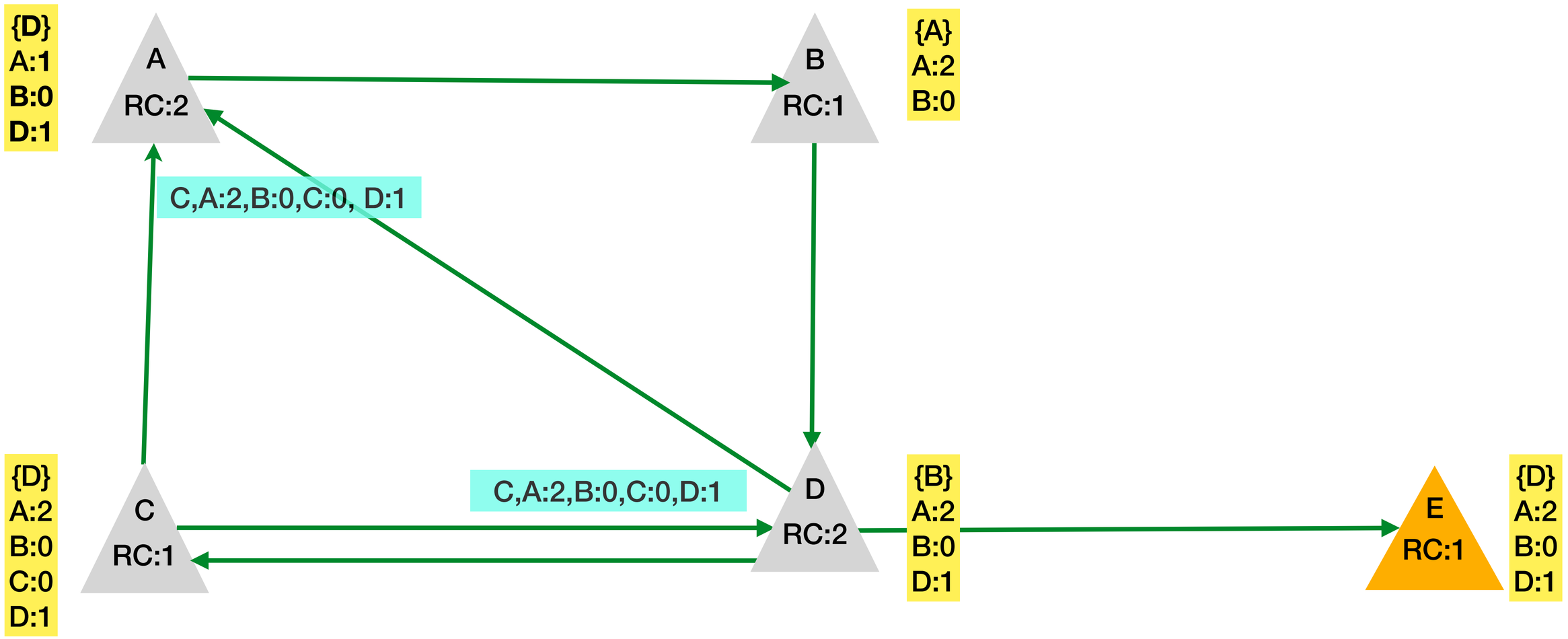
D:1


{D}
A:1
B:0
D:1
A
RC:2
B
RC:1
{A}
A:2
B:0
C,A:2,B:0,C:0, D:1
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B:0
C:0
D:1
C
RC:1
C,A:2,B:0,C:0,D:1
D
RC:2
{B}
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B:0
D:1
E
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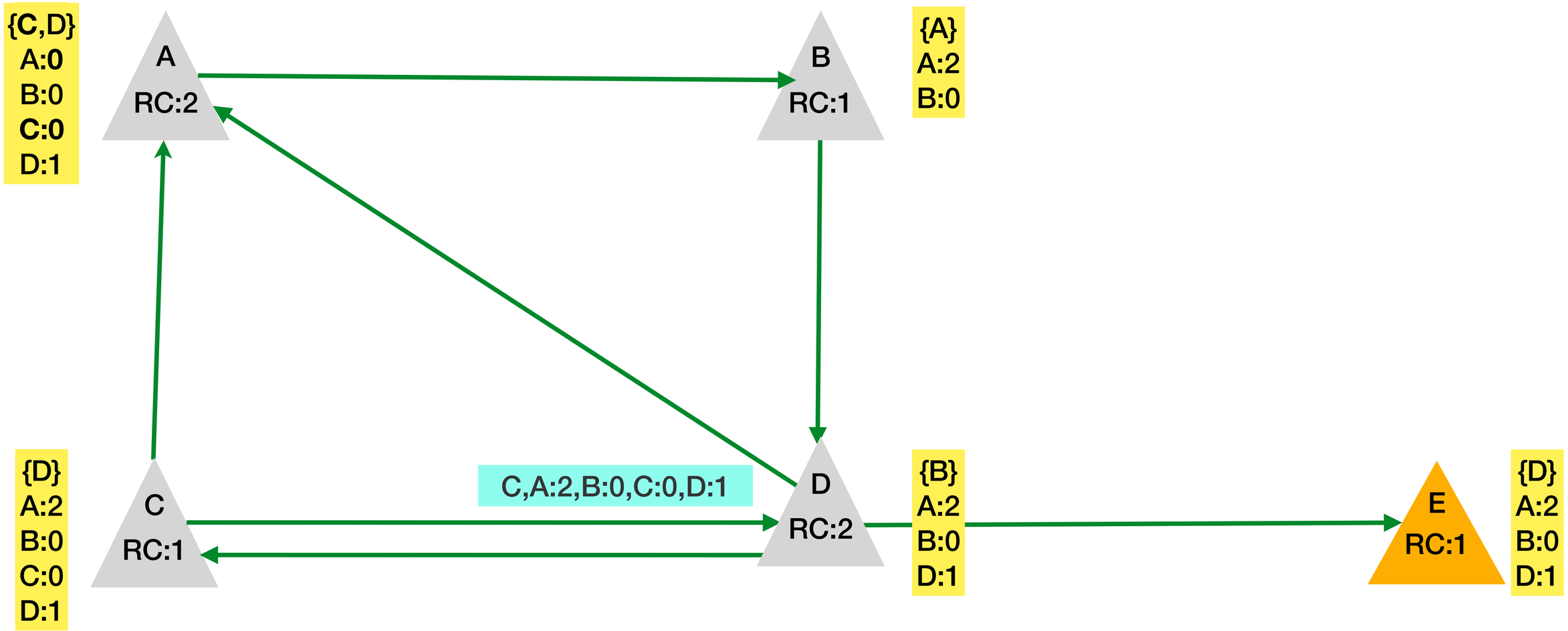
{D}
A:2
B:0
D:1


{C,D}
A:0
B:0
C:0
D:1
A
RC:2
B
RC:1
{A}
A:2
B:0
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B:0
C:0
D:1
C
RC:1
C,A:2,B:0,C:0,D:1
D
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B:0
D:1
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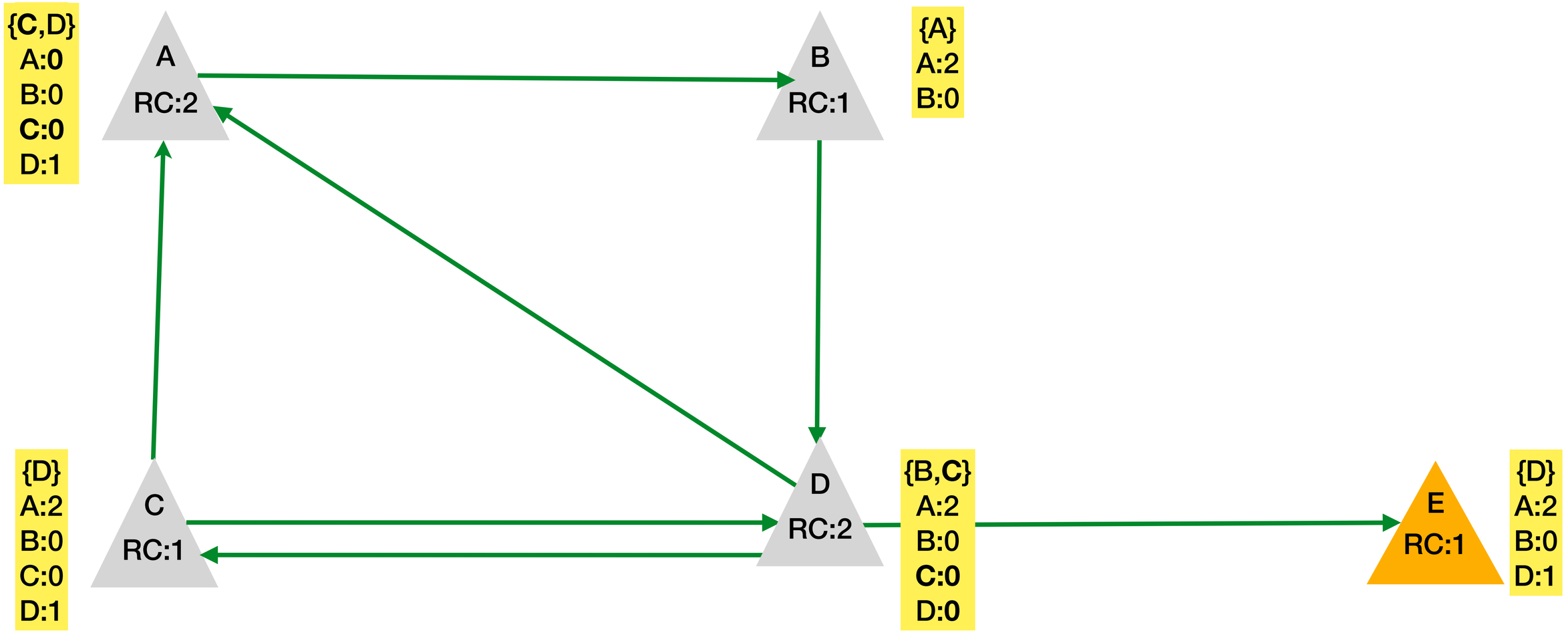
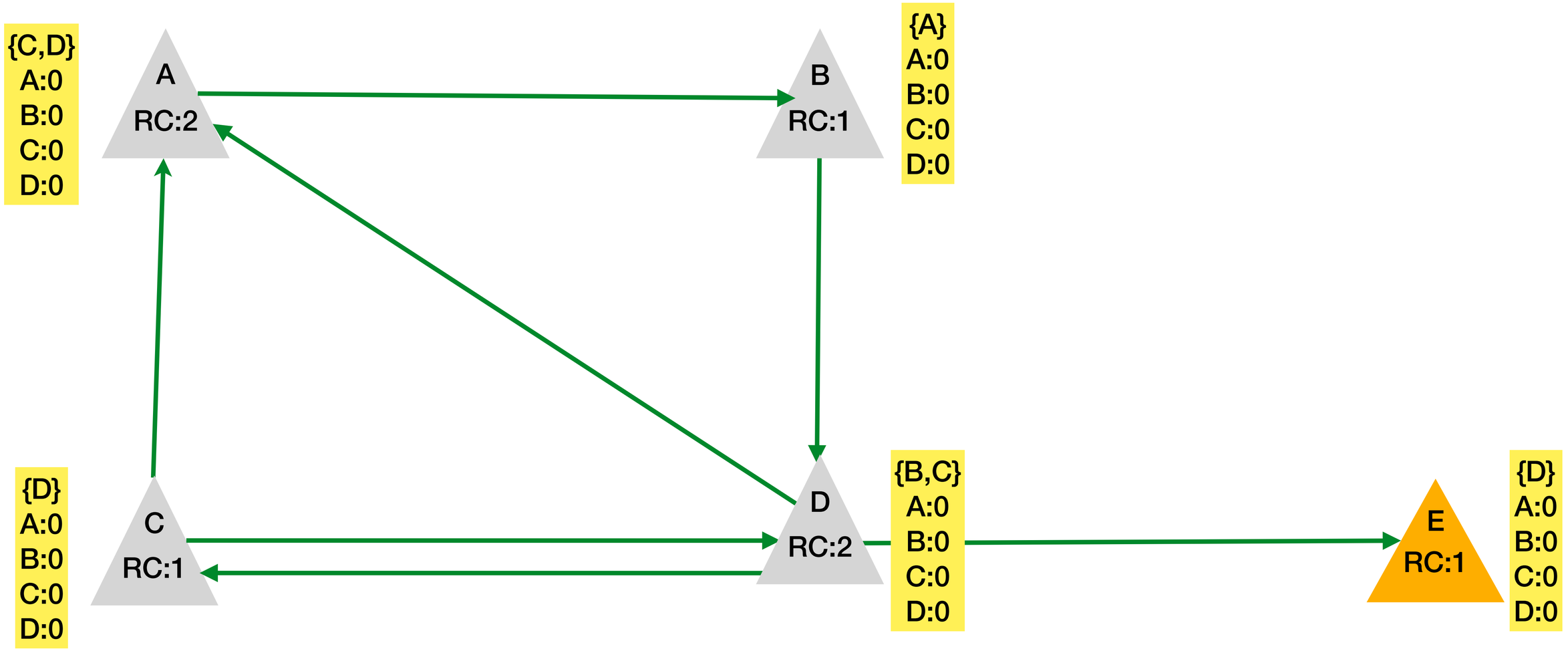
D:1


{C,D}
A:0
B:0
C:0
D:1
A
RC:2
B
RC:1
{A}
A:2
B:0
{D}
A:2
B:0
C:0
D:1
C
RC:1
D
RC:2
{B,C}
A:2
B:0
C:0
D:0
E
RC:1
{D}
A:2
B:0
D:1

eventually ….


{C,D}
A:0
B:0
C:0
D:0
A
RC:2
B
RC:1
{A}
A:0
B:0
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D:0
{D}
A:0
B:0
C:0
D:0
C
RC:1
D
RC:2
{B,C}
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B:0
C:0
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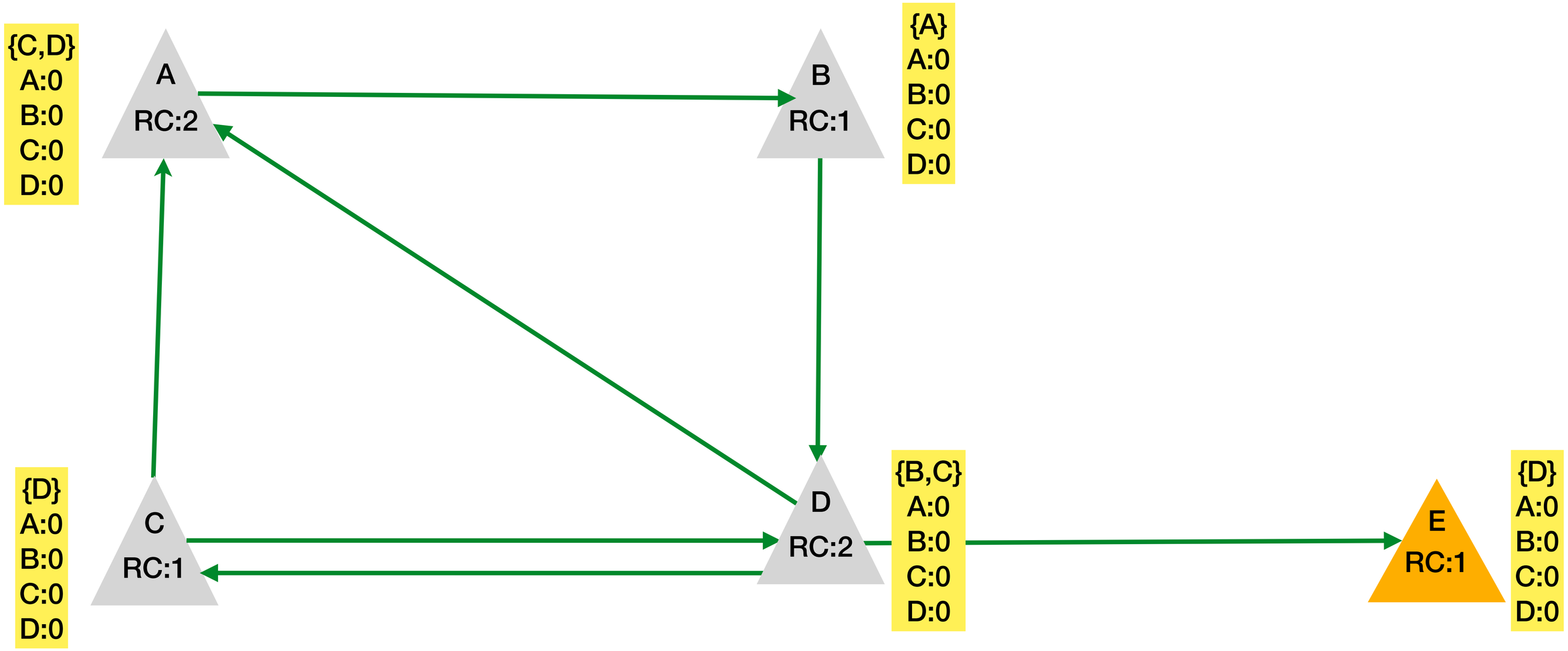
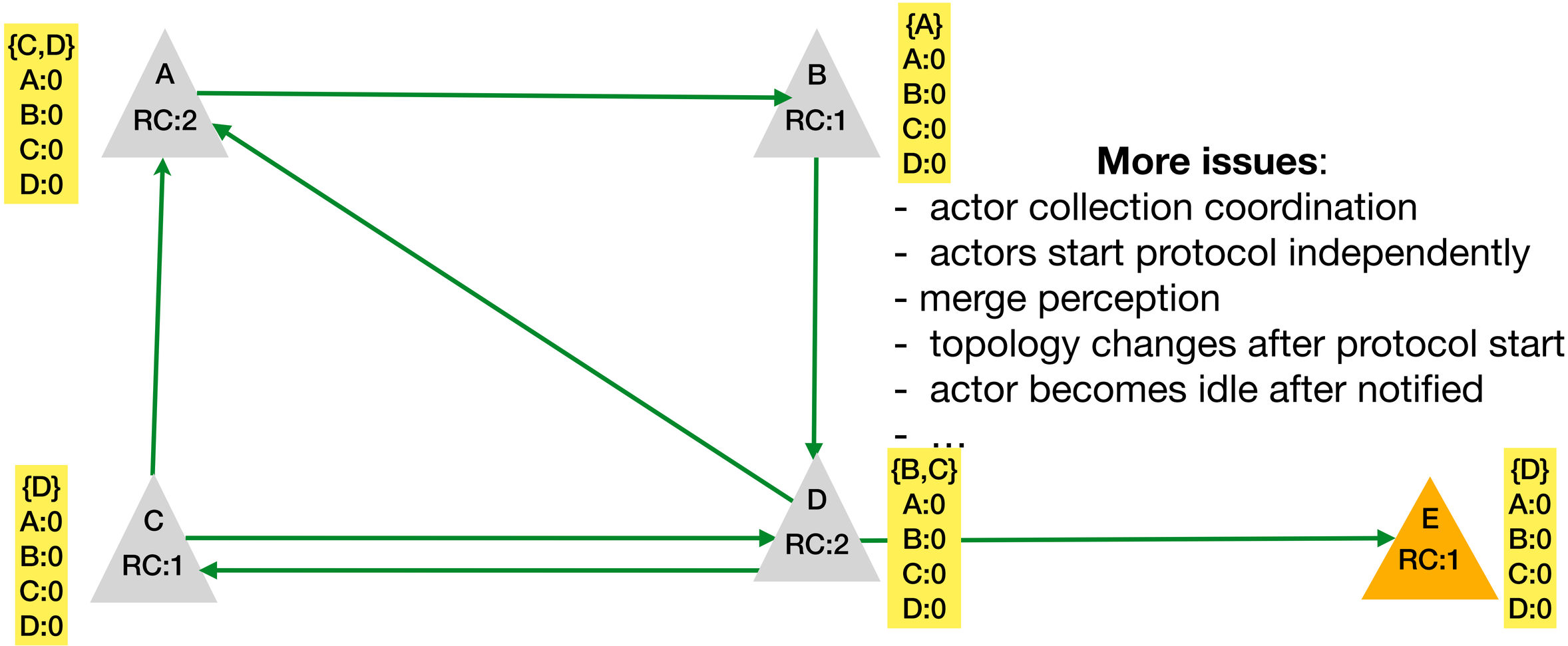
E
RC:1
{D}
A:0
B:0
C:0
D:0

eventually ….



… and now A, B, C, D can be collected

eventually ….



More issues:

- actor collection coordination
- actors start protocol independently
- merge perception
- topology changes after protocol start
- actor becomes idle after notified
- …

… and now A, B, C, D can be collected

Reflections on eMAC

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Is it sound?

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We need to “scan” every application message upon send/receive.

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~~CD performs a complex search on a large data structure.~~

We need to “scan” every application message upon send/receive.

More and longer messages

Garbage Collection
for objects (Pony)

Soundness of a Concurrent Collector for Actors

Juliana Franco[1] Sylvan Clebsch[2]
Sophia Drossopoulou[1] Jan Vitek[3] Tobias Wrigstad[4]

[1] Imperial College, London [2] Microsoft Research Cambridge
[3] Northeastern University & CVUT [4] Uppsala University, Uppsala

Abstract ORCA is a garbage collection protocol for actor-based programs. Multiple actors may mutate the heap while the collector is run

ESOP'18

Orca: GC and Type System Co-Design for Actor Languages

SYLVAN CLEBSCH, Microsoft Research Cambridge, United Kingdom
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Orca is a concurrent and parallel garbage collector for actor programs, which does not require any stop-the-world steps, or synchronisation mechanisms, and which has been designed to support zero-copy message passing and sharing of mutable data. Orca is part of the runtime of the actor-based language Pony. Pony's runtime was co-designed with the Pony language. This co-design allowed us to exploit certain language

OOPSLA'17

Garbage Collection
for objects (Pony)

ORCA:
Ownership and
Reference Counting based
Garbage Collection in the
Actor World

Soundness of a Concurrent Collector for Actors

Juliana Franco[1] Sylvan Clebsch[2]
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[1] Imperial College, London [2] Microsoft Research Cambridge
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ESOP'18

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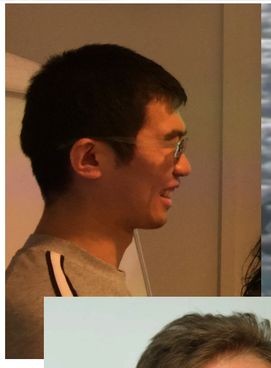

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Abstract ORCA is a garbage collection protocol for actor-based programs. Multiple actors may mutate the heap while the collector is run

ESOP'18

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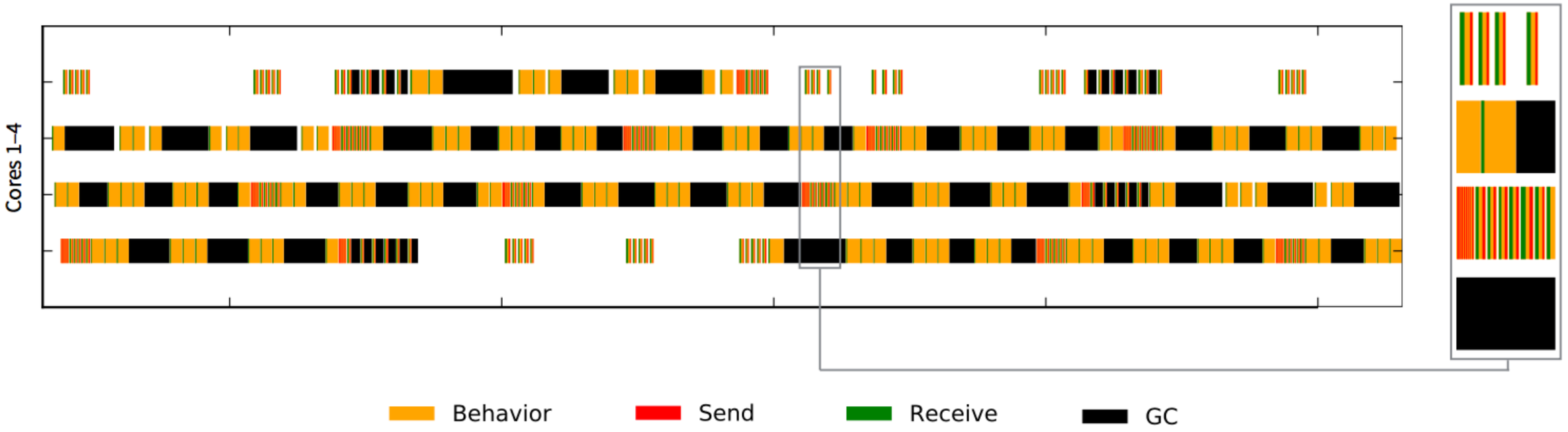
OOPSLA'17

ORCA is *fully concurrent*
ie no synchronization, lo locks, no barrier, no stop the world step.



GC & Concurrency Challenges

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Challenge_1: Who collects the objects?

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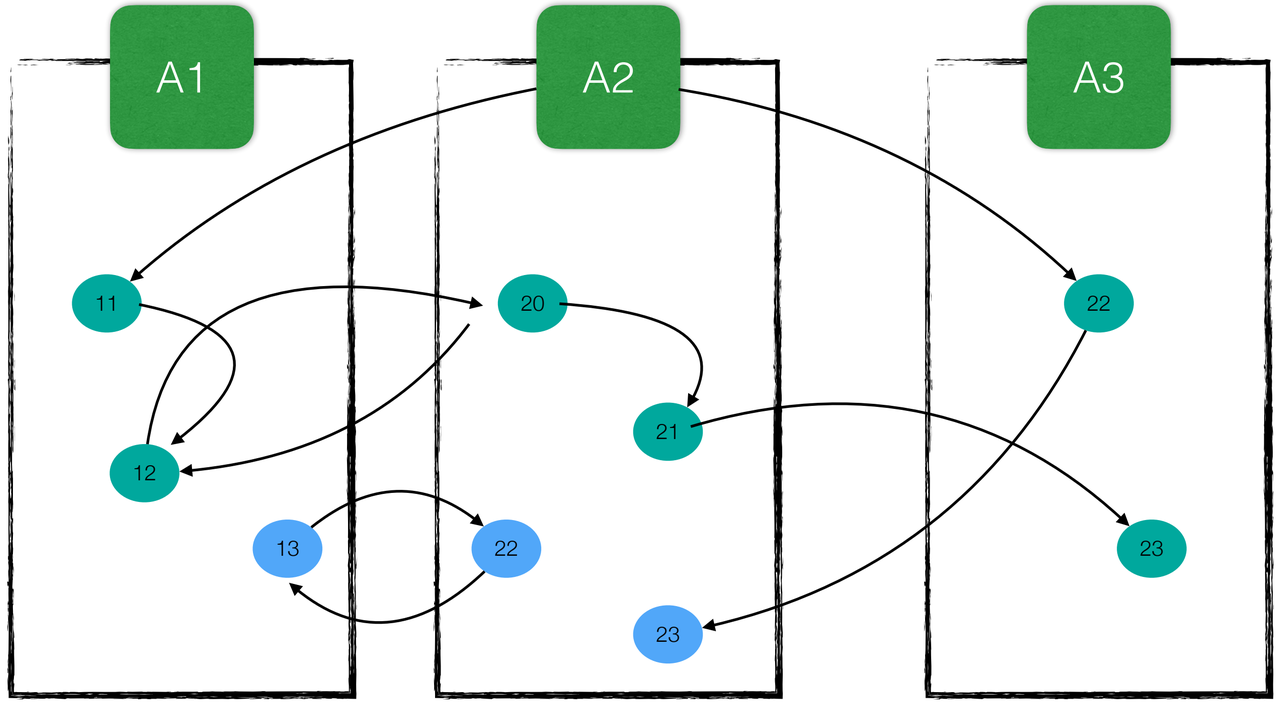
Tight Connection between Language and Runtime Design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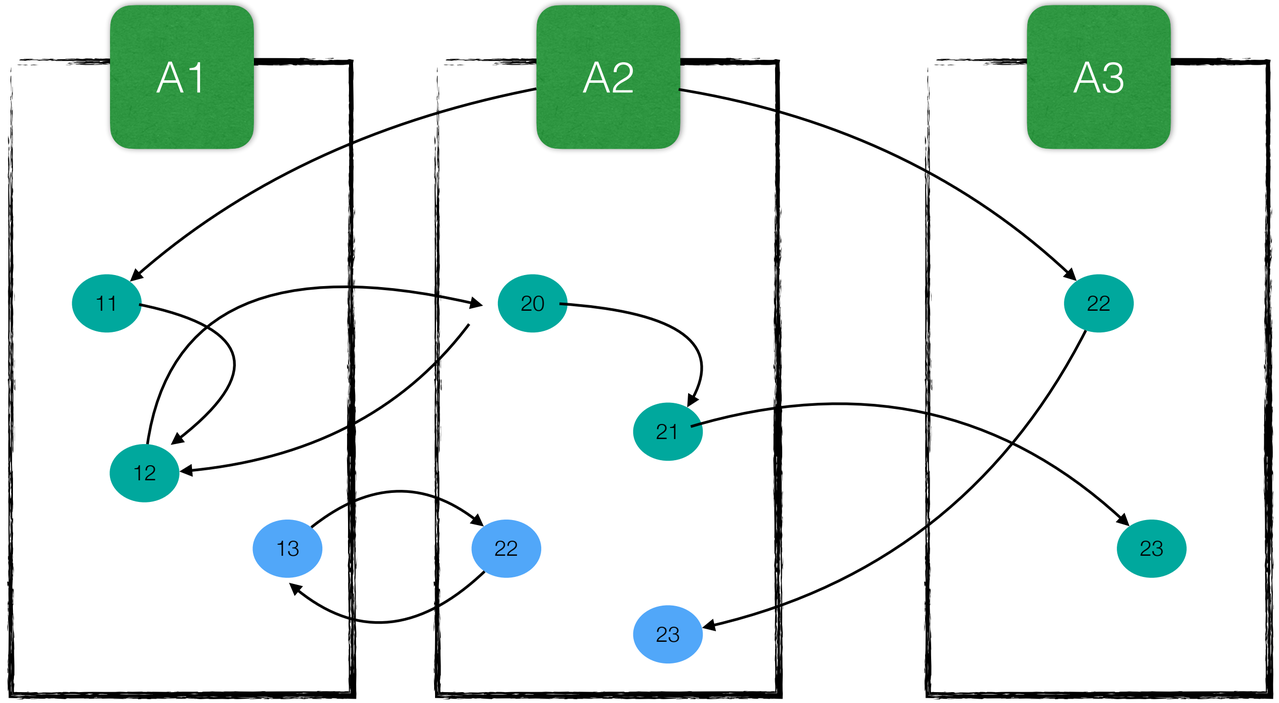
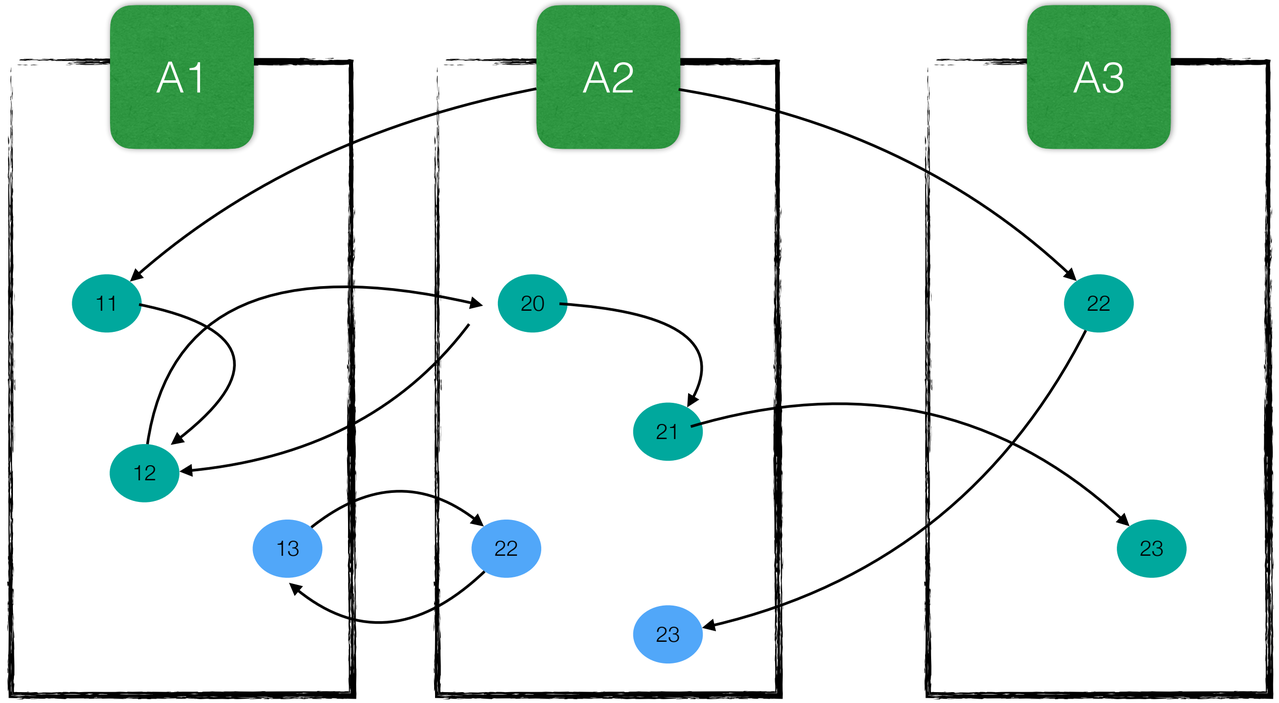
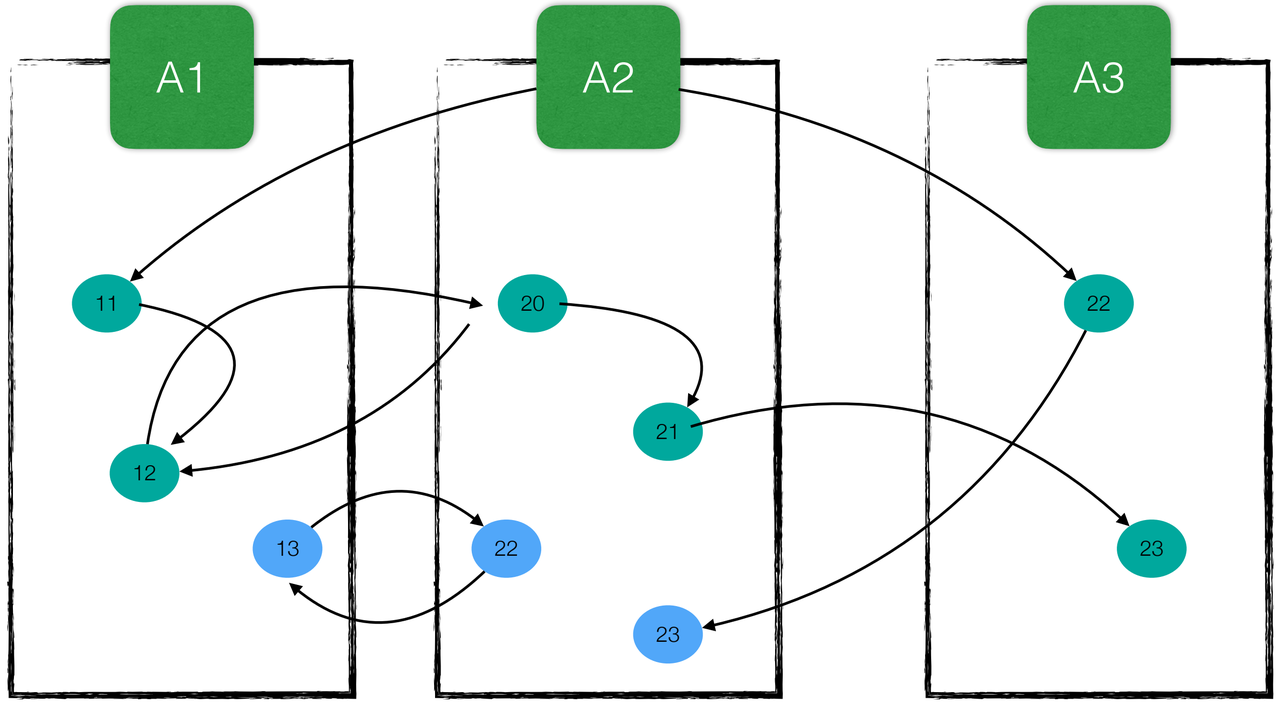


Challenges



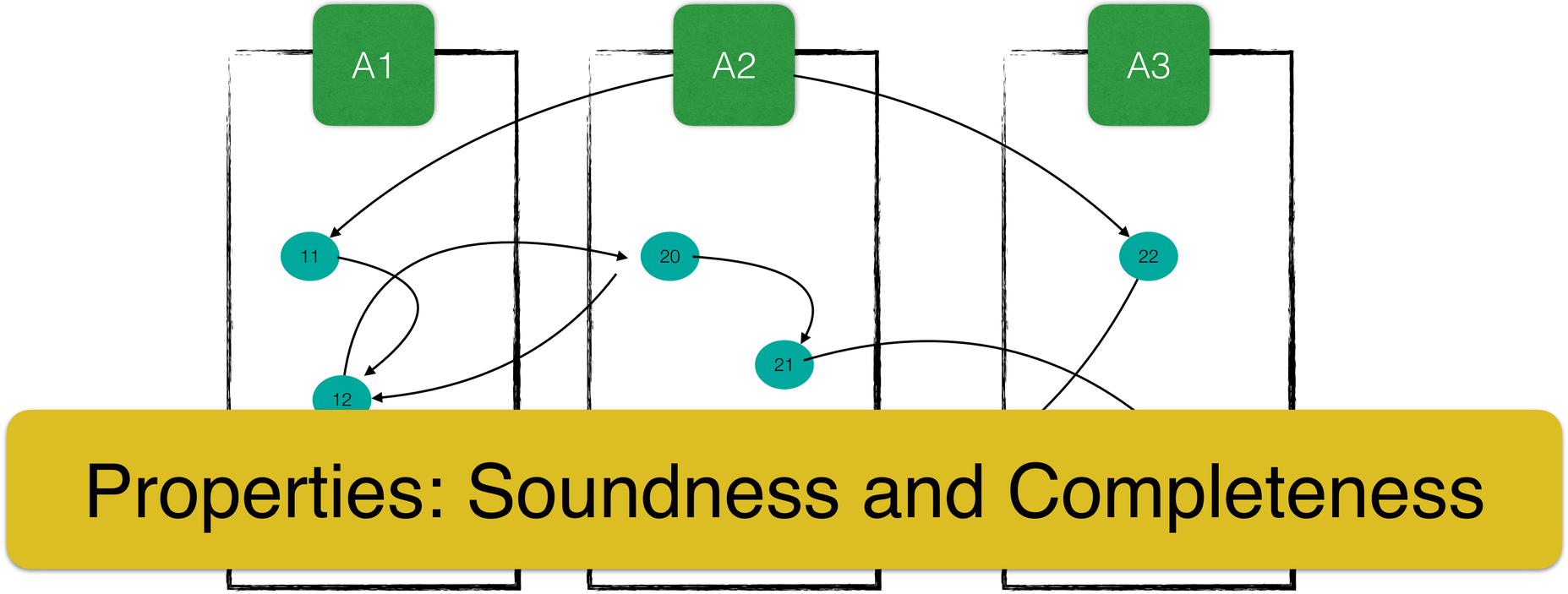
Challenges

- Owning actor might not have path to its live objects
- Cycles in object graph



Approach

- Owning actor keeps upper bound on number of actors which have a path to owned object
- Owning actor collects object when this number=0
- Foreign actor keeps count of references to un-owned objects
- Foreign actor informs owning actor when number of references to unowned objects changes (ie upon message send/receive or local tracing)



Properties: Soundness and Completeness

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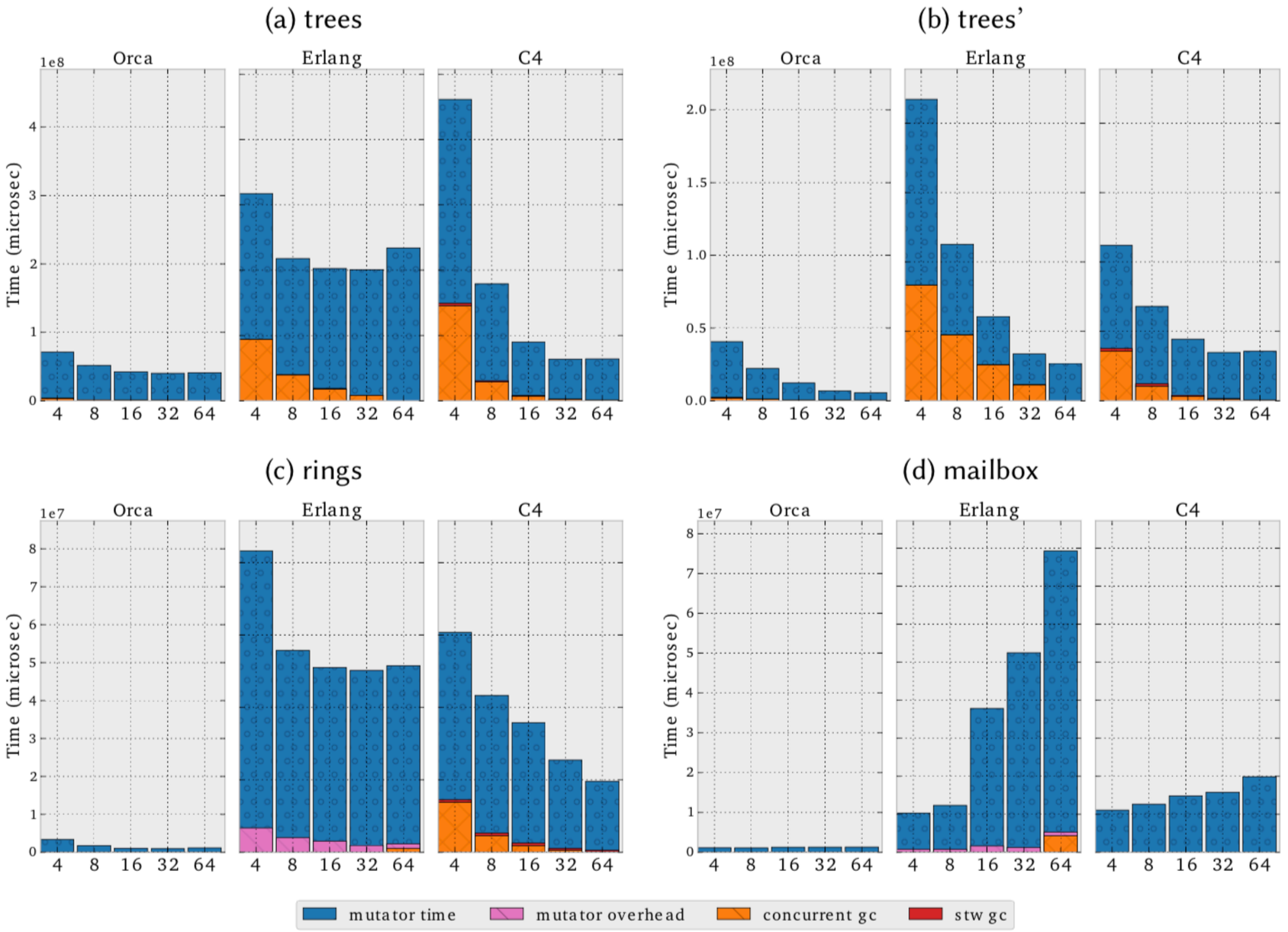
Pony vs Erlang vs Java



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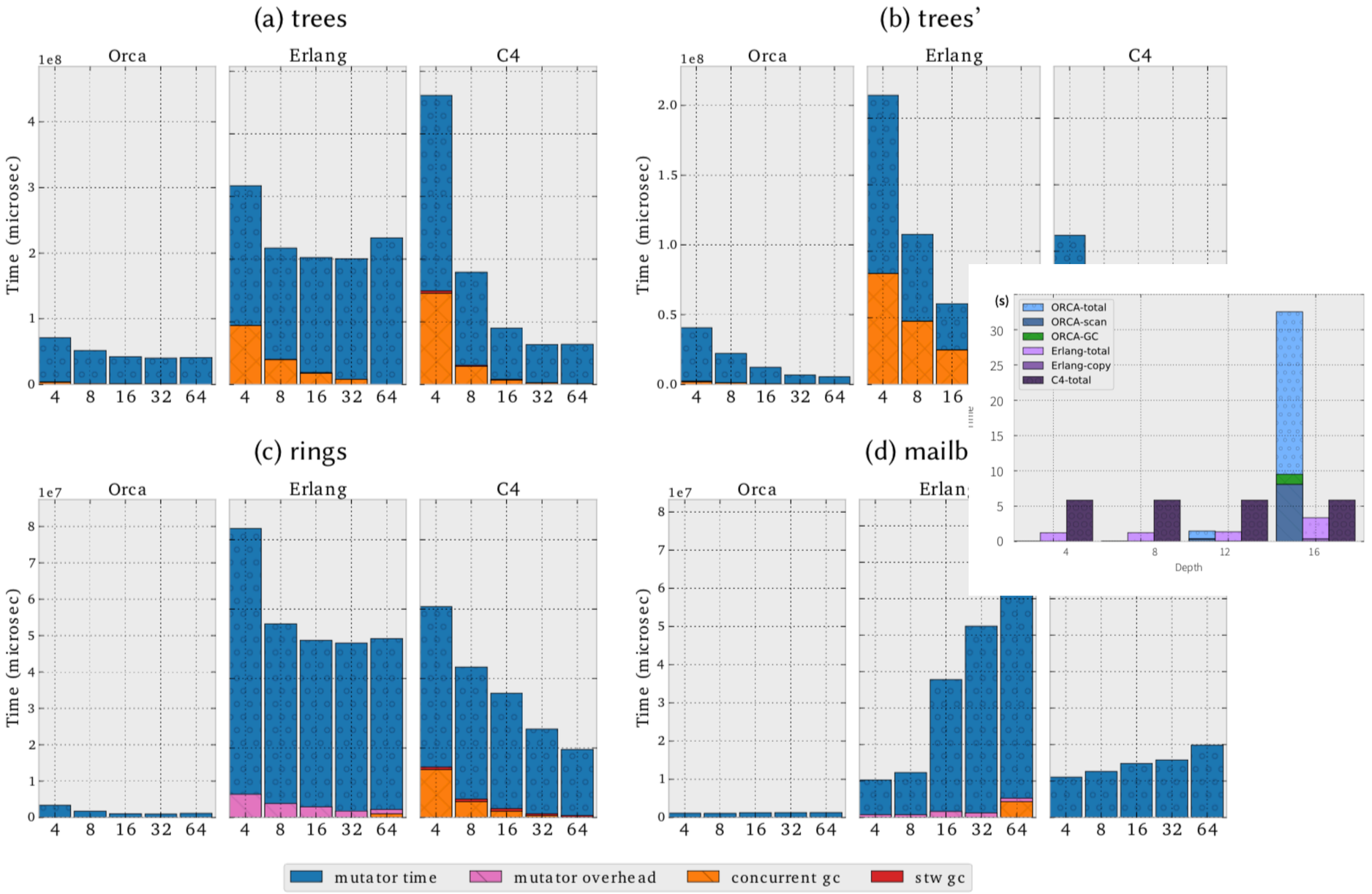
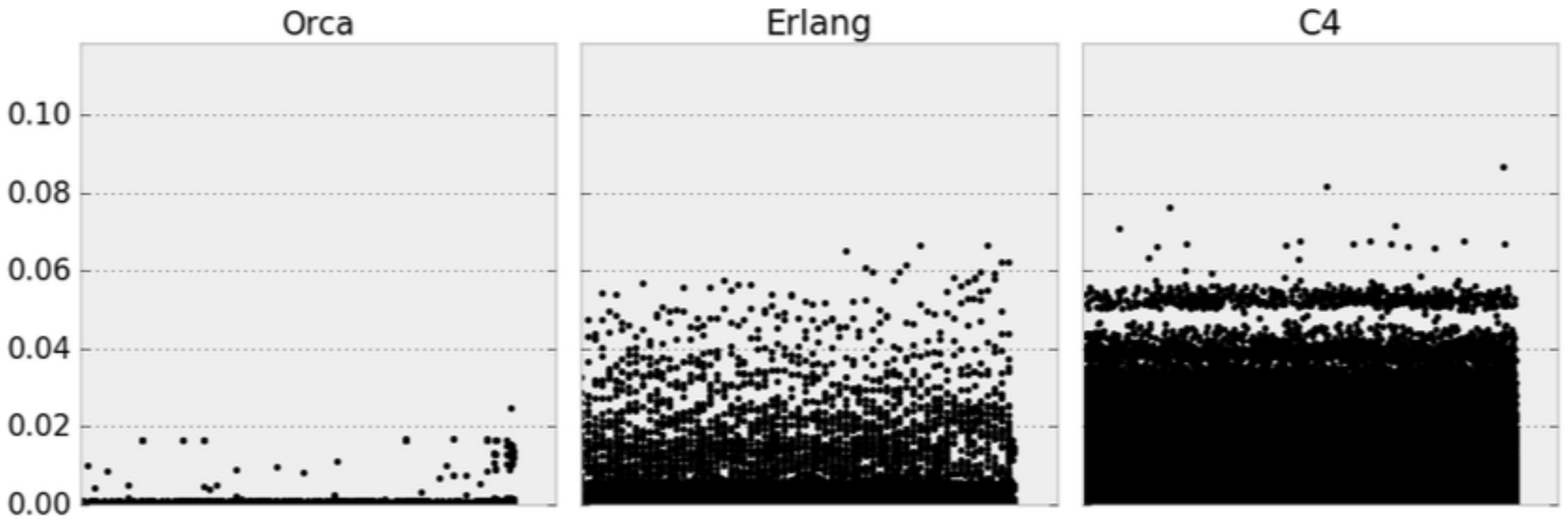


Responsiveness



Reflections on MAC

Is it useful?

Is it sound?

Is it complete?

What are its advantages/drawbacks?

Reflections on MAC

Is it useful? **YES**

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Reflections on MAC

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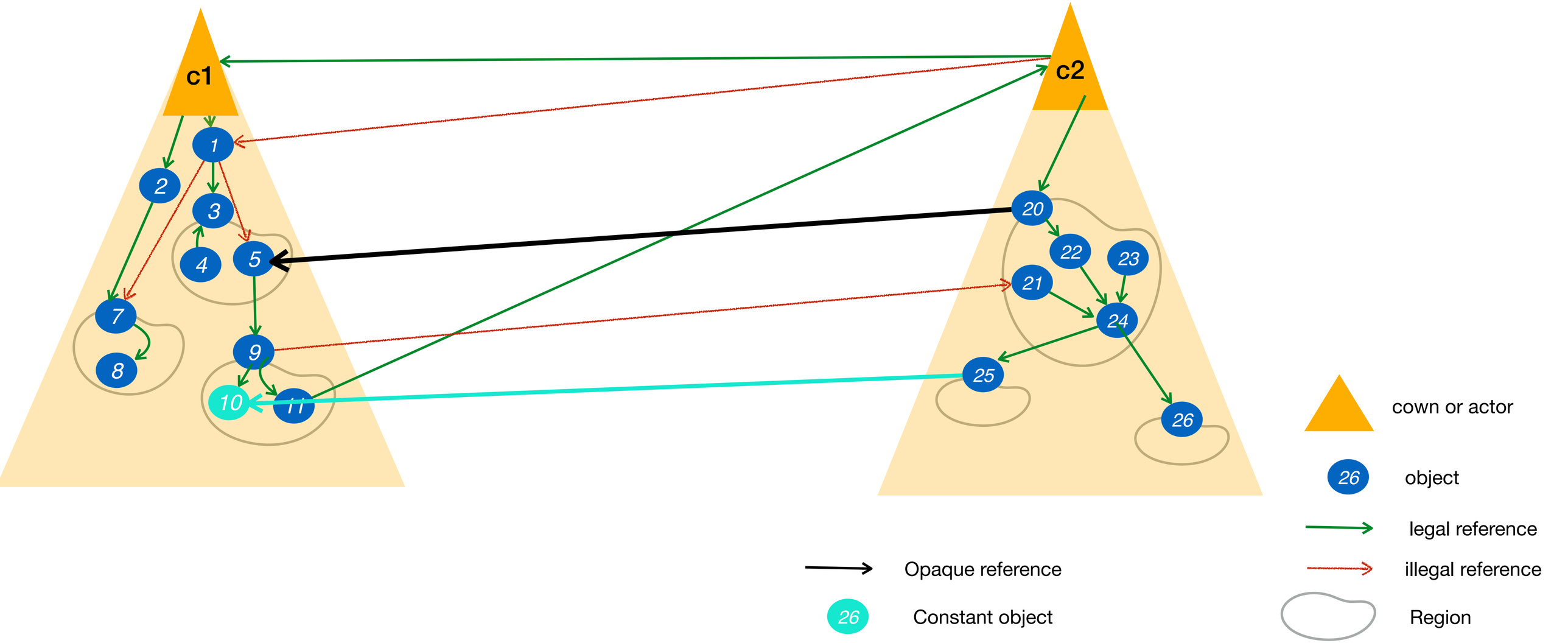
(-) We need to “scan” every application message upon send/receive.

Pony Actors share state safely - more truth



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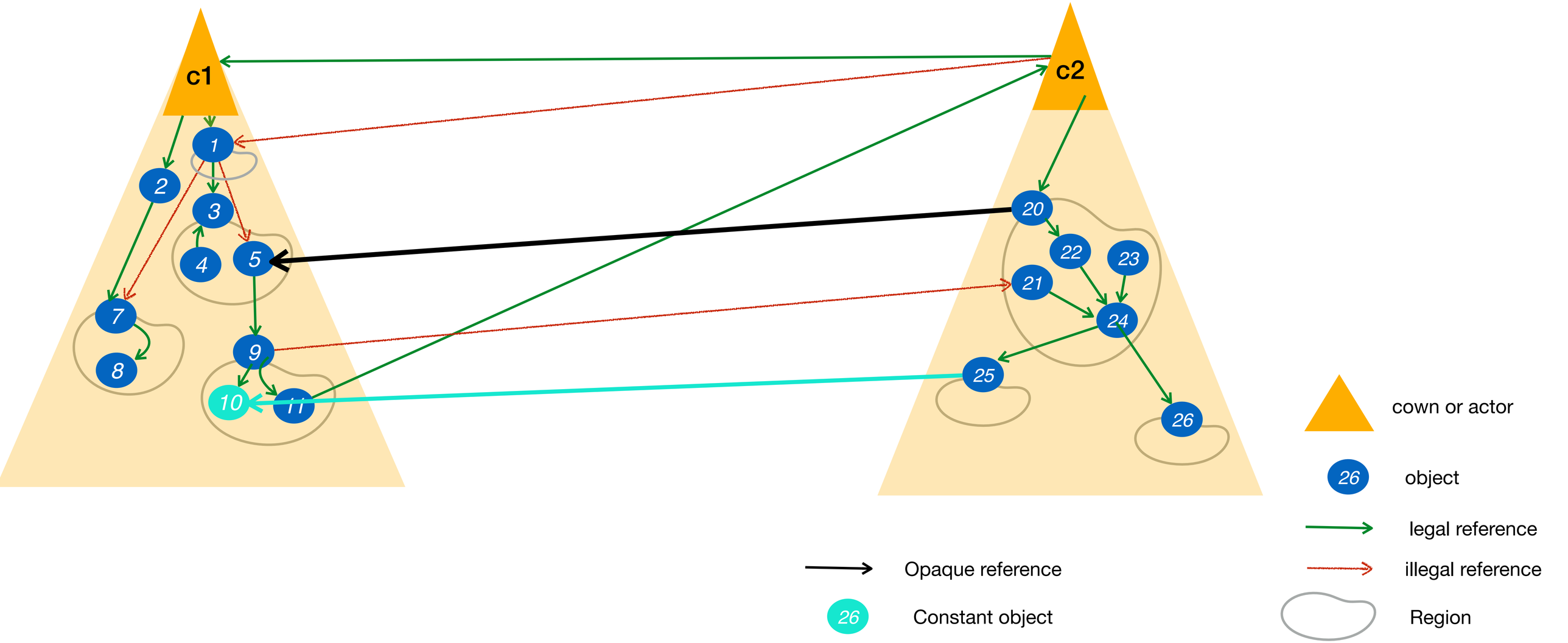

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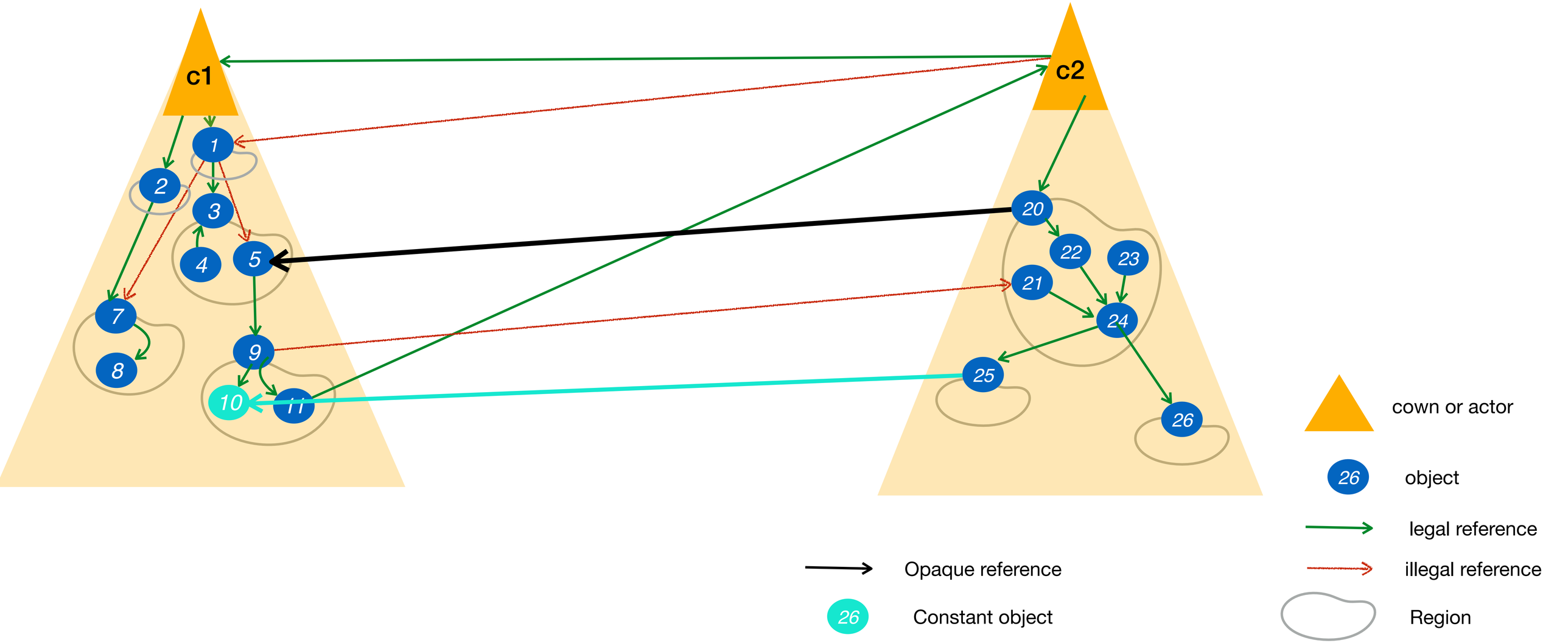

Types and Garbage Collection

for objects (Verona)