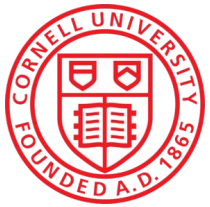
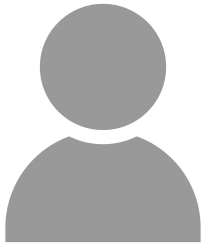
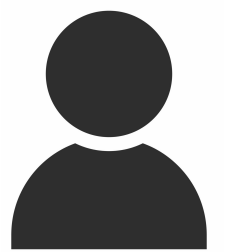
Implementability of Global Protocols modulo Network Architectures

Elaine Li Thomas Wies

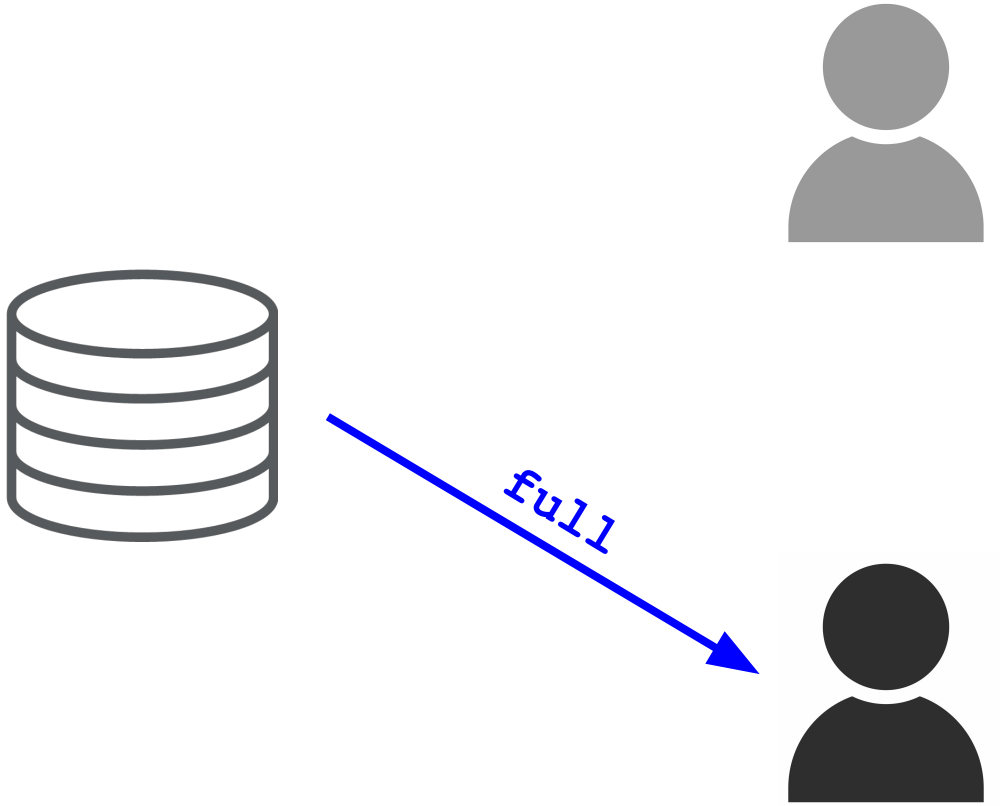


Task delegation protocol

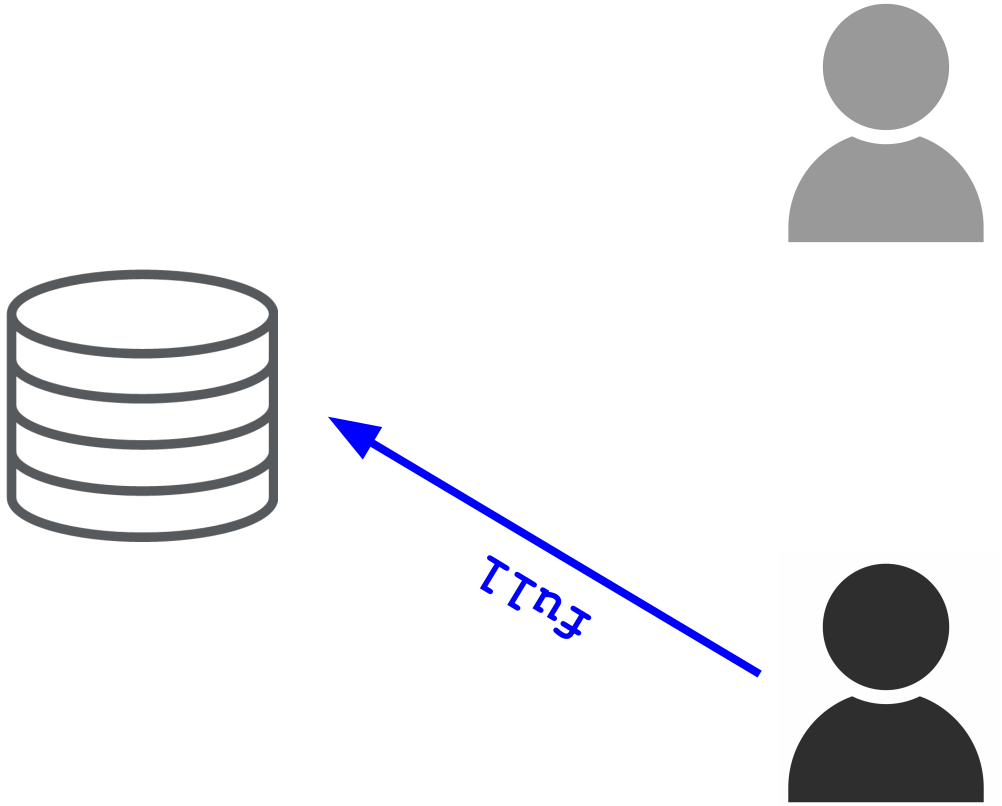




Task delegation protocol



Task delegation protocol



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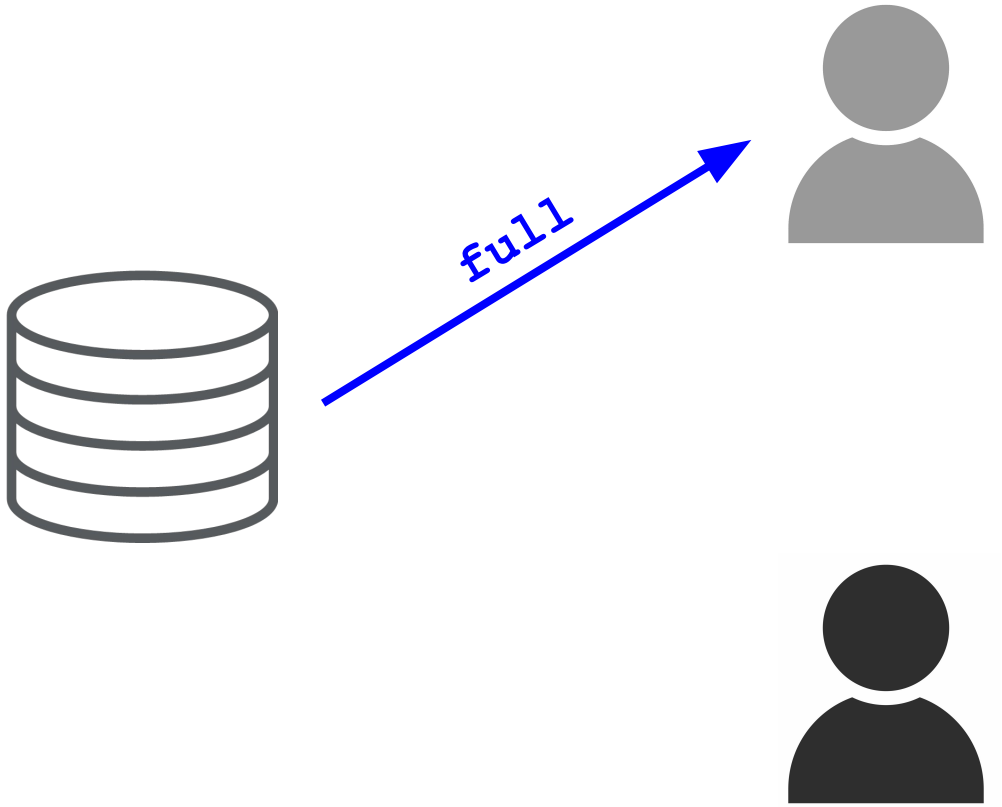

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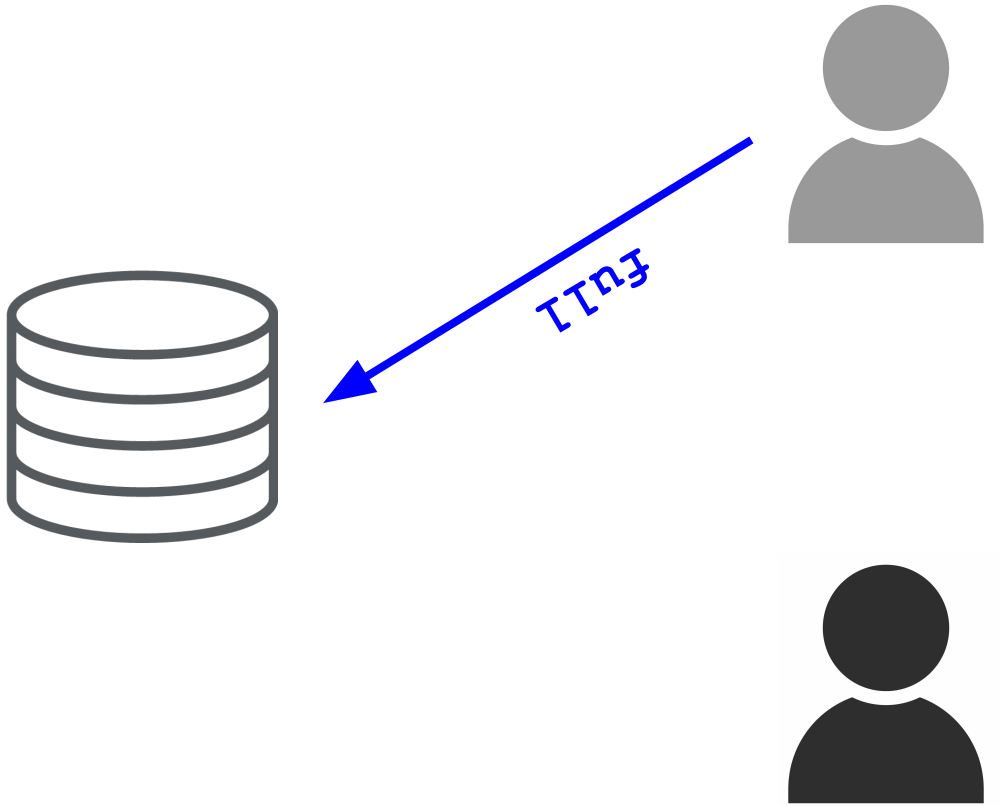

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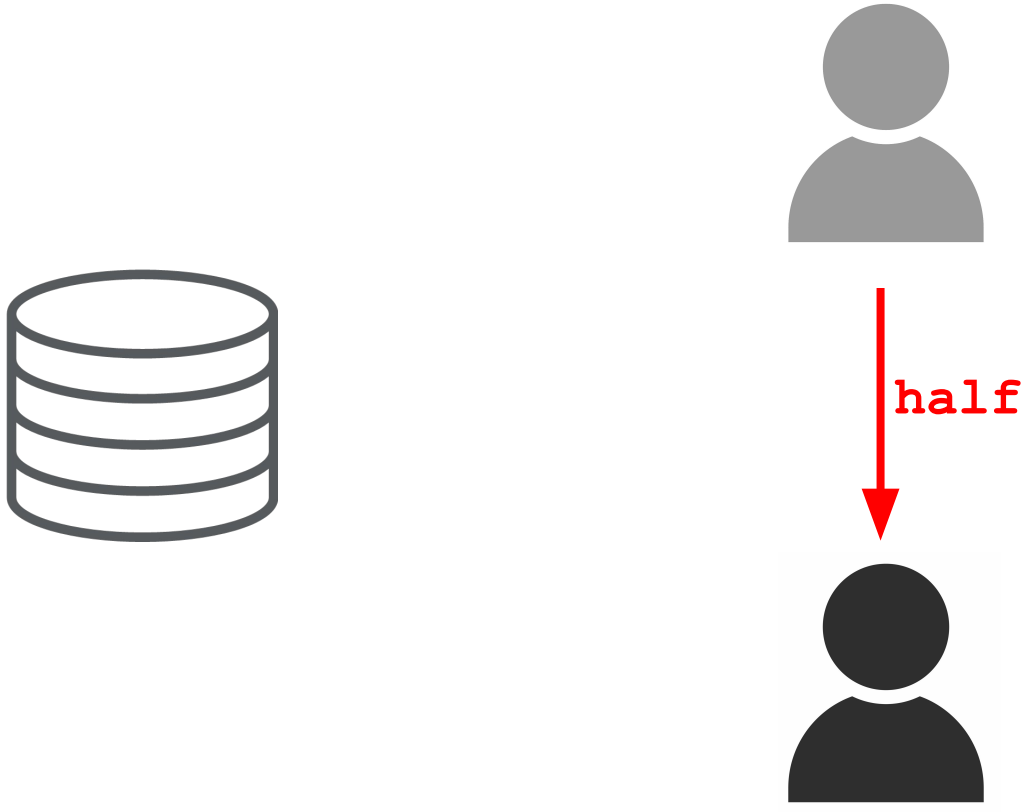

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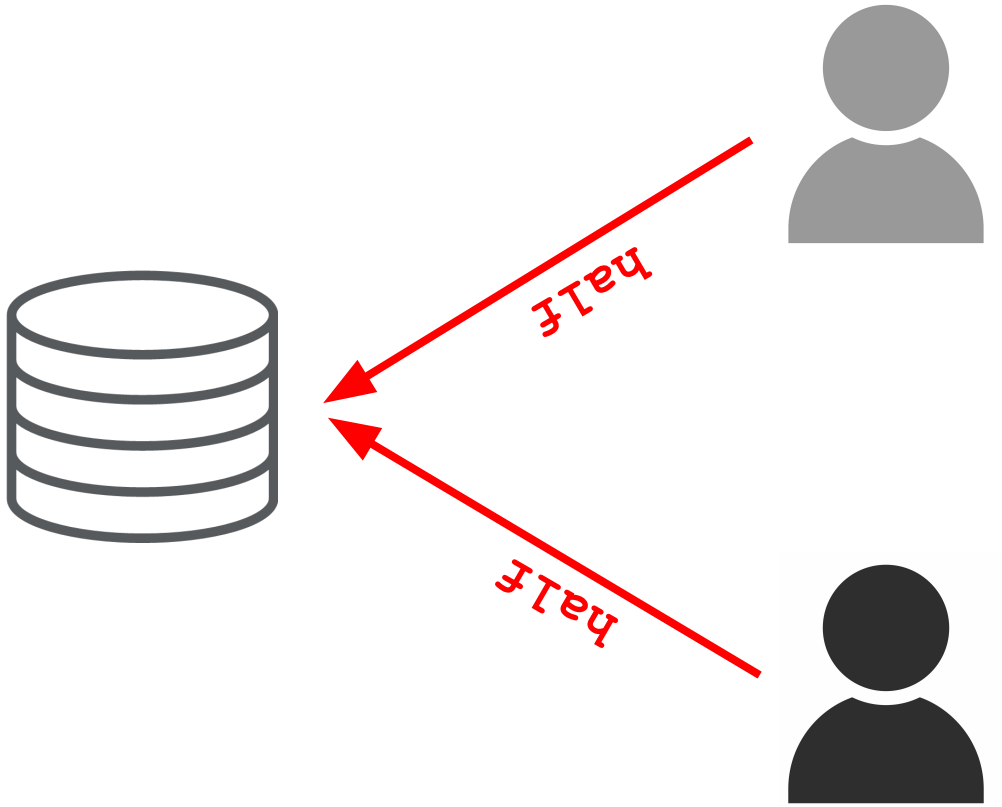
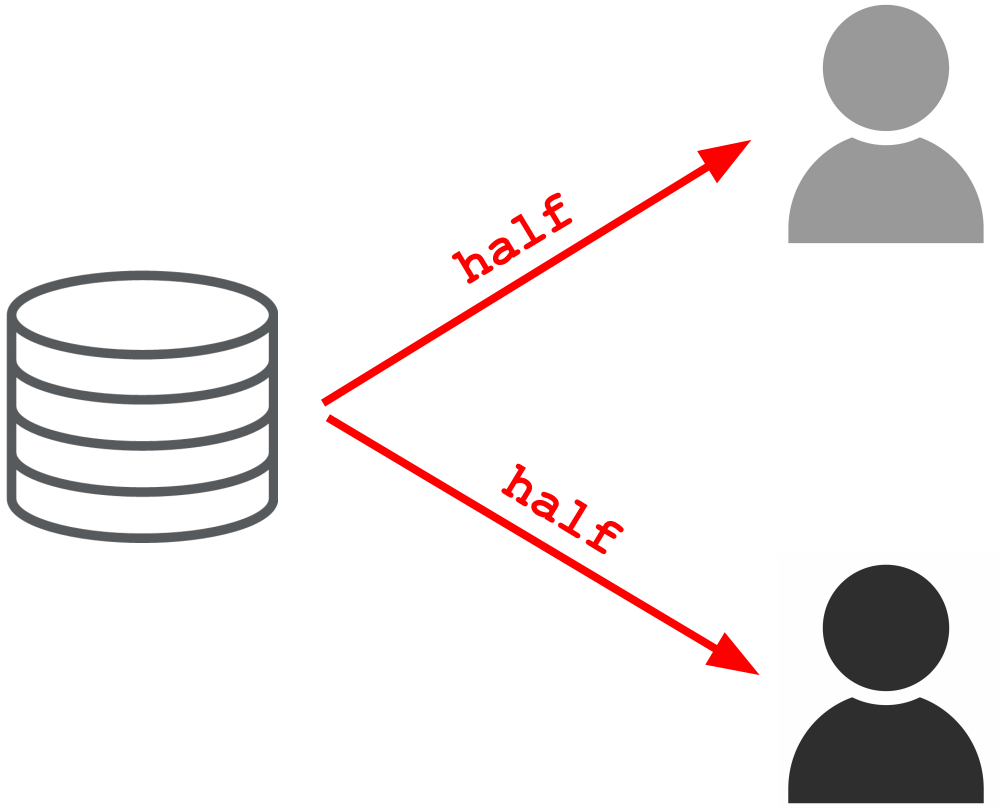


Task delegation protocol



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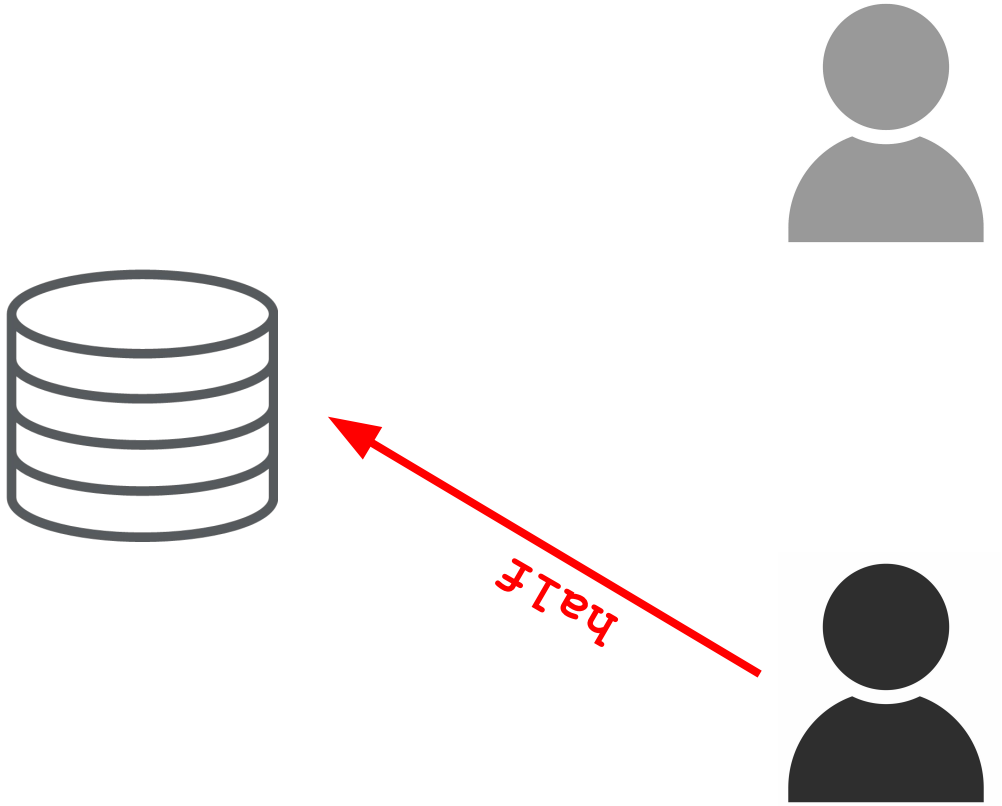

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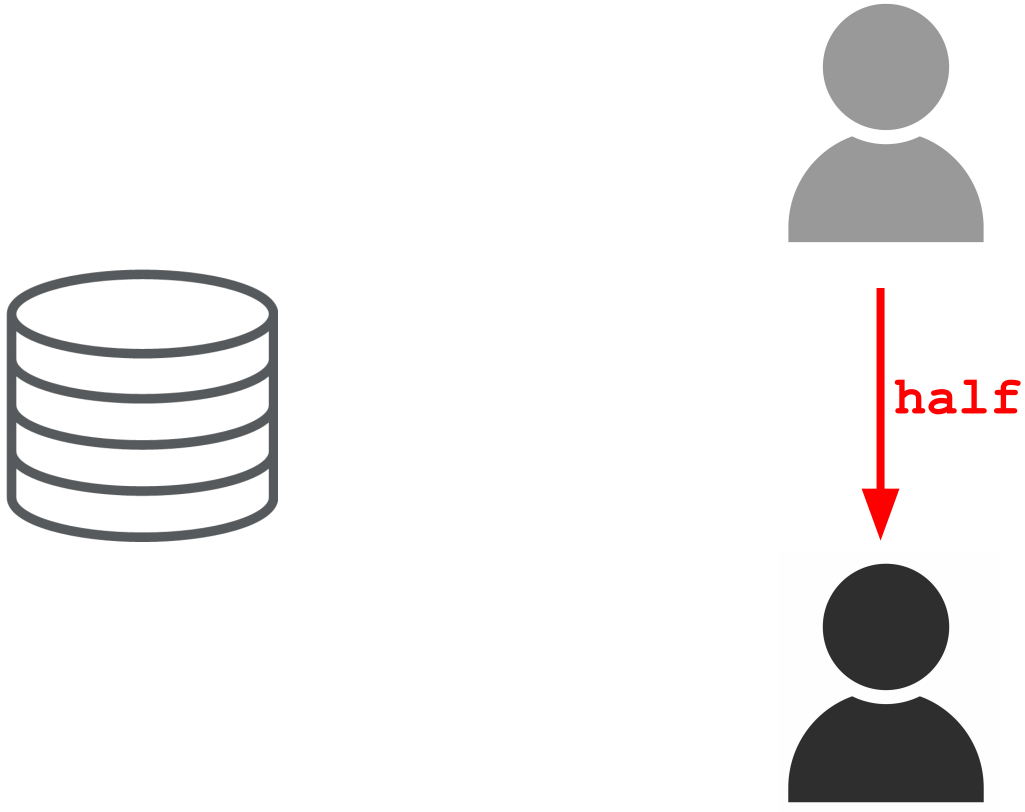
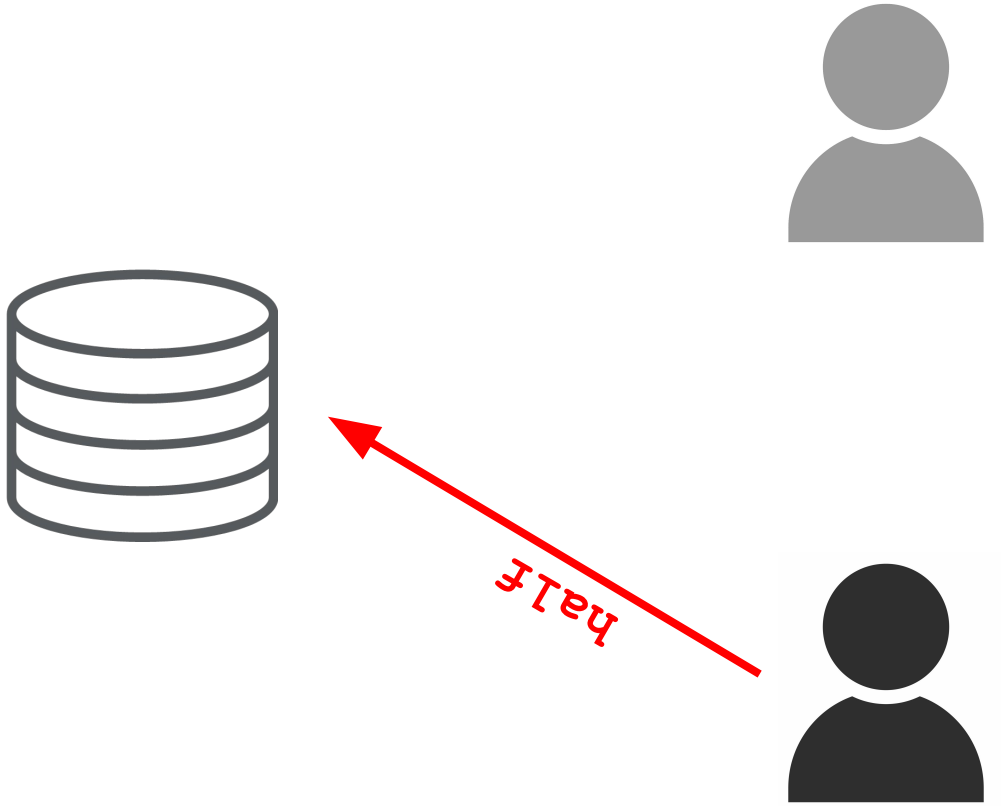
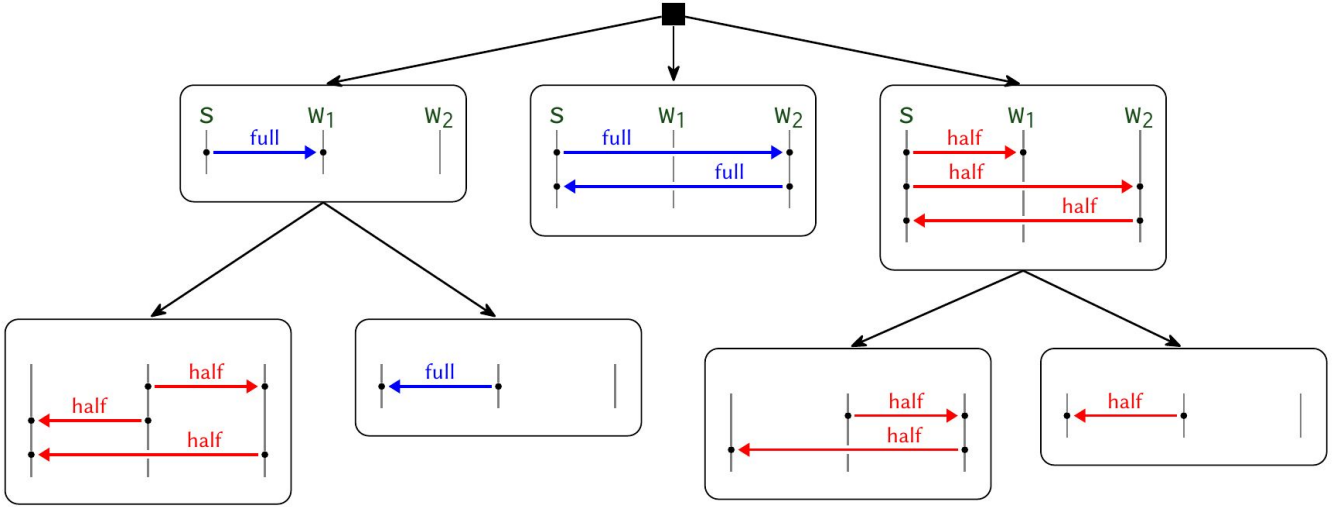


Task delegation protocol

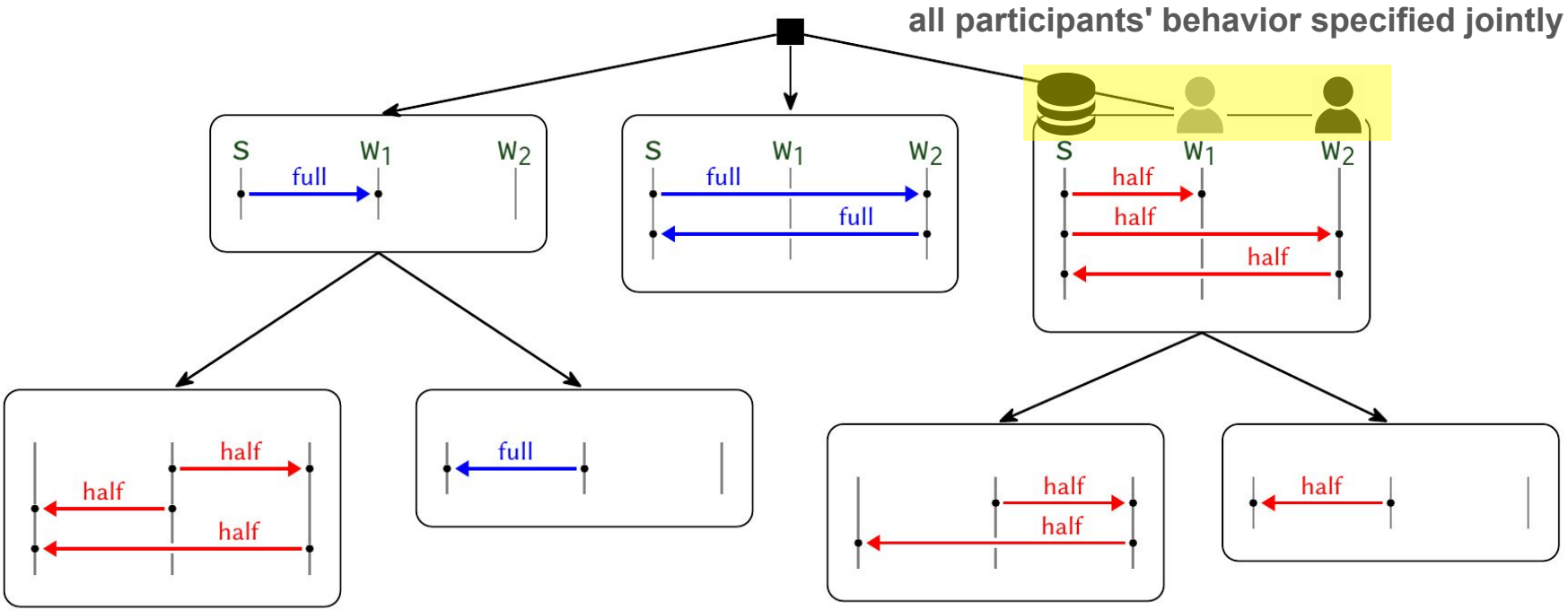


Global protocols

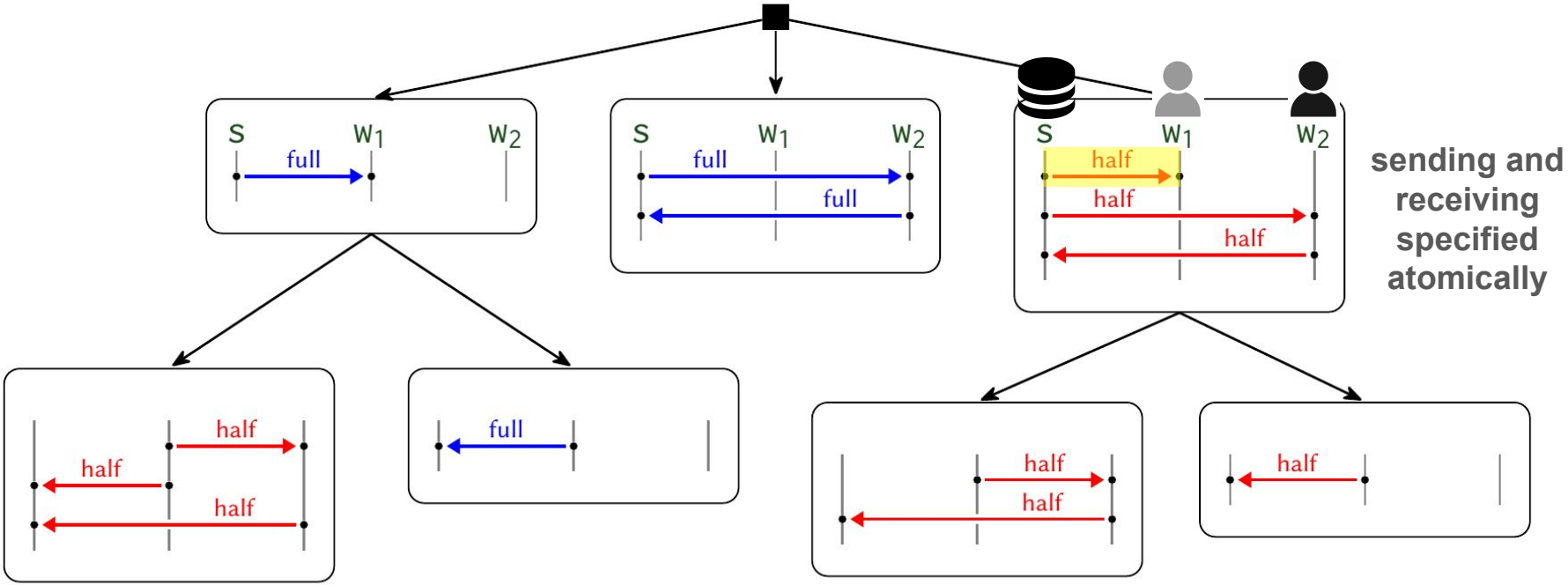


- High-level message sequence charts [Mauw and Reniers 97]
- Session types [Honda et al. 08]
- Choreographic programs [Carbone and Montesi 13]

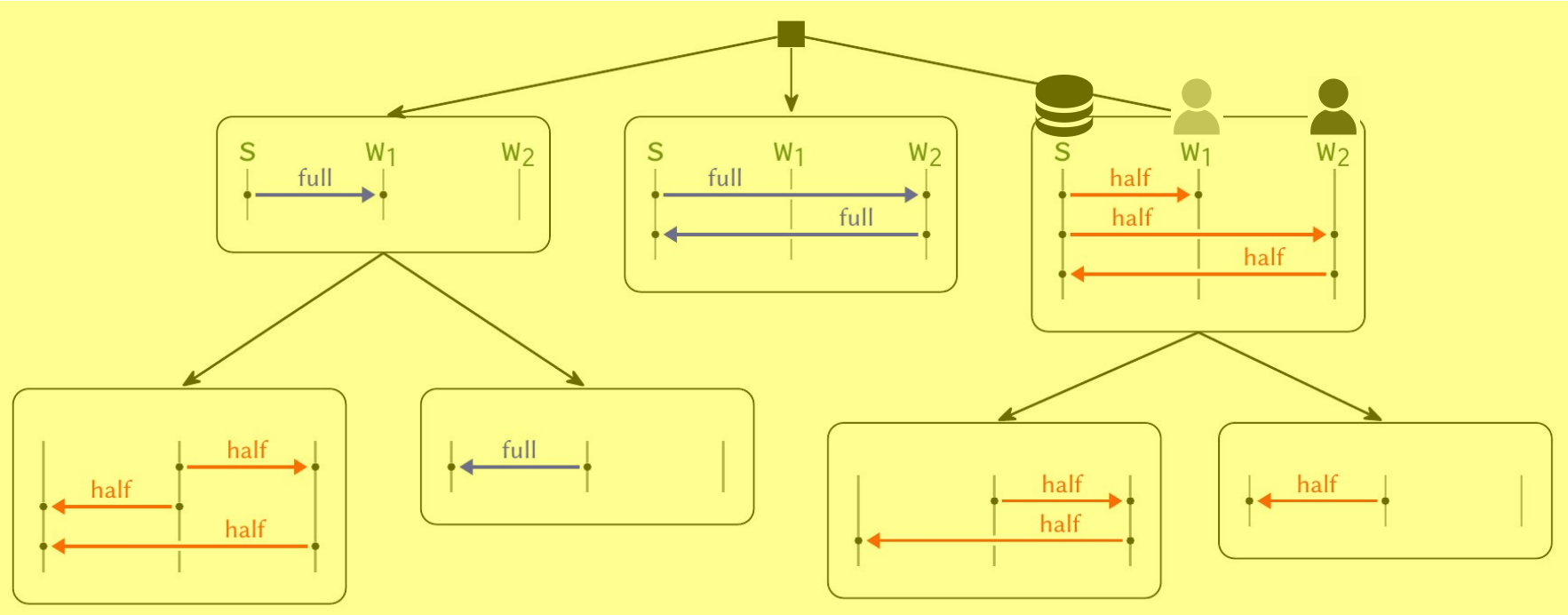
Global protocols



Global protocols

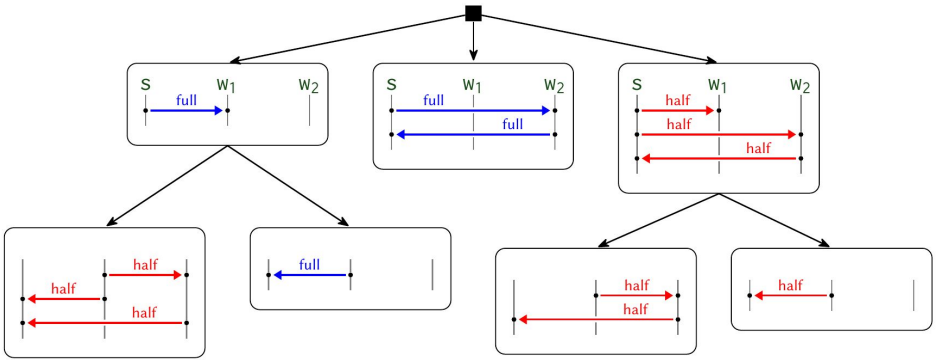


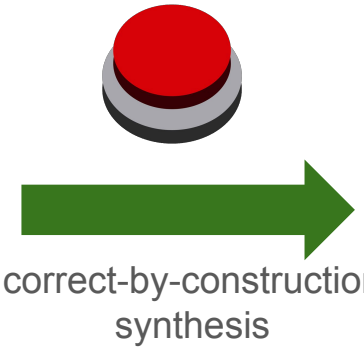
Global protocols

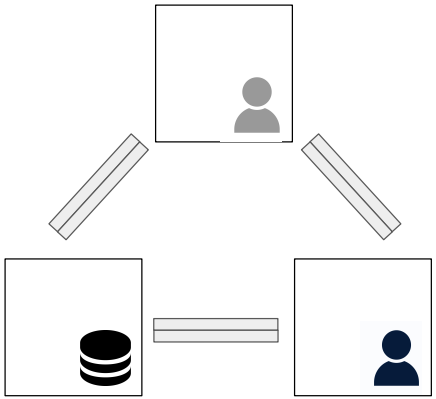


global control flow

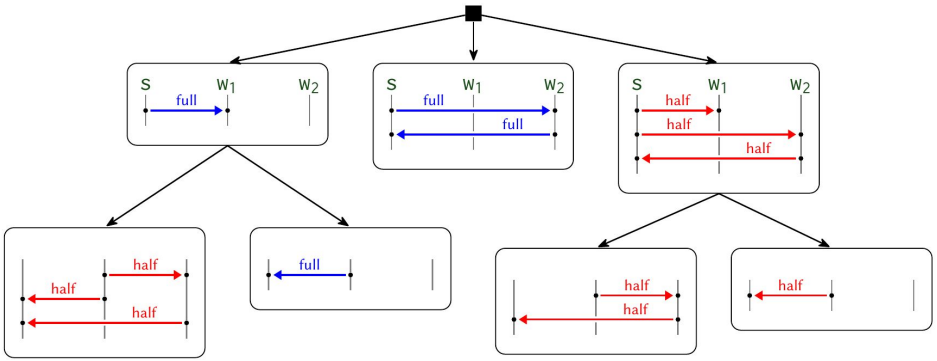
Top-down verification







Top-down verification

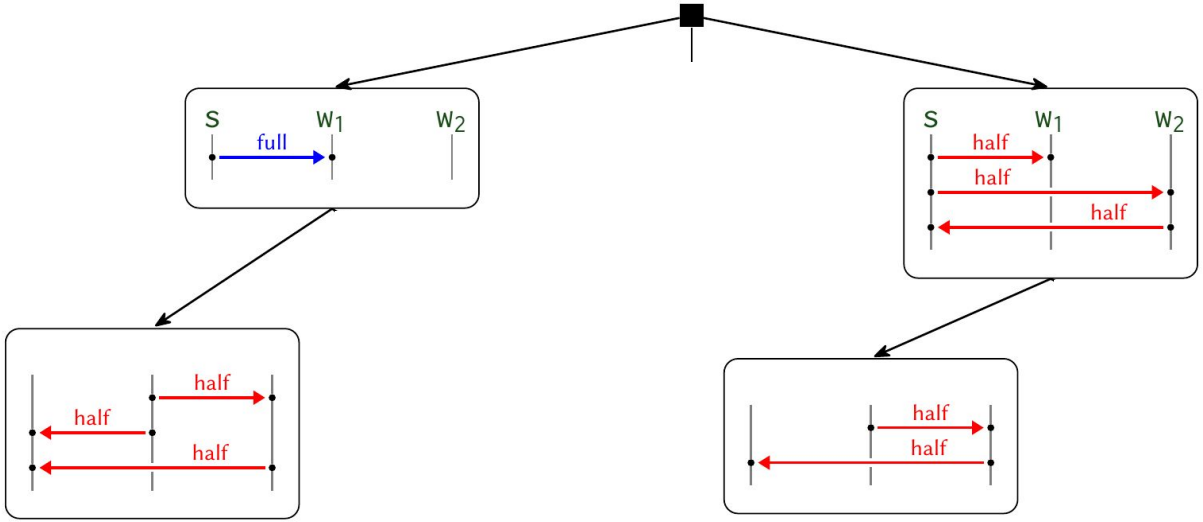


no message channels, omniscient coordinator etc.

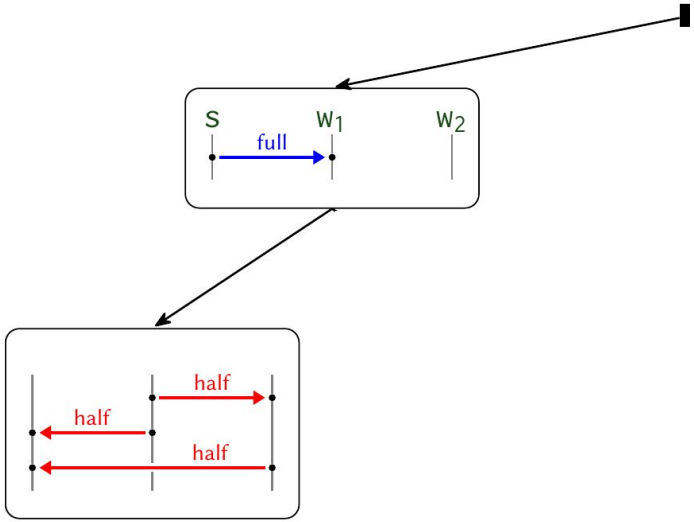
?

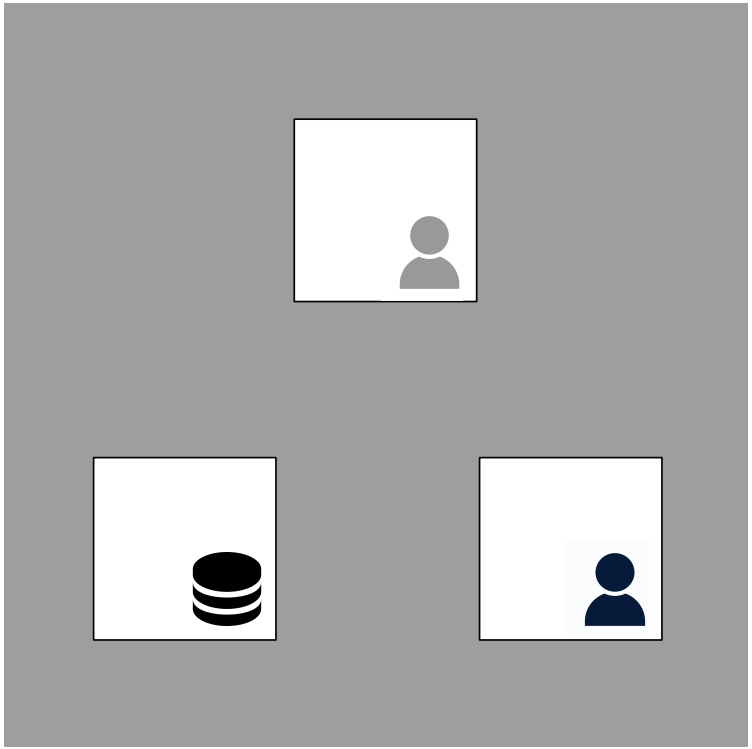
realizability/
implementability
[Alur et al. 00]

Non-implementability

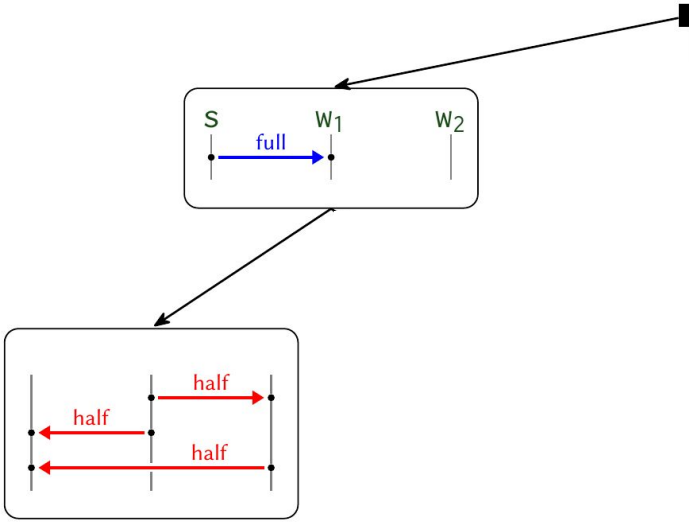


Non-implementability

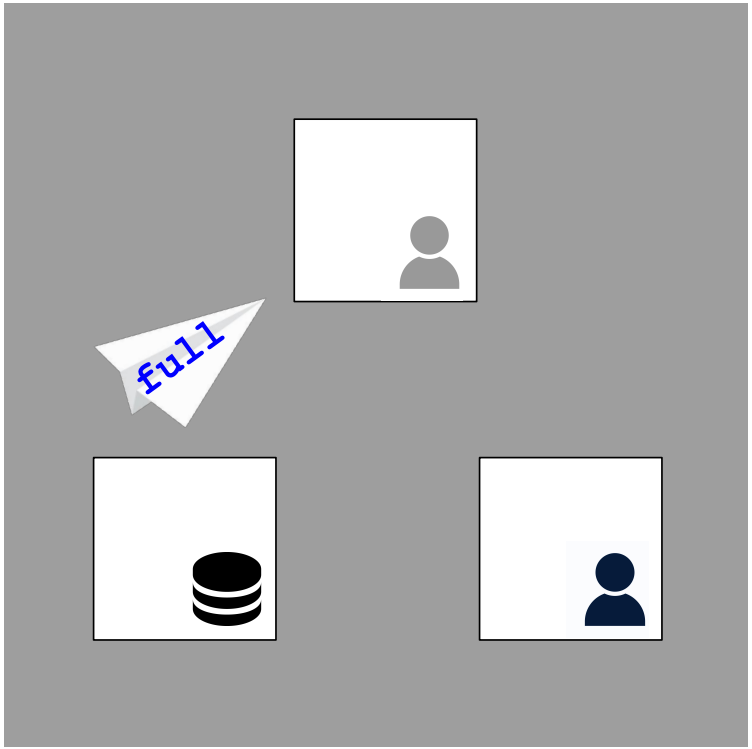




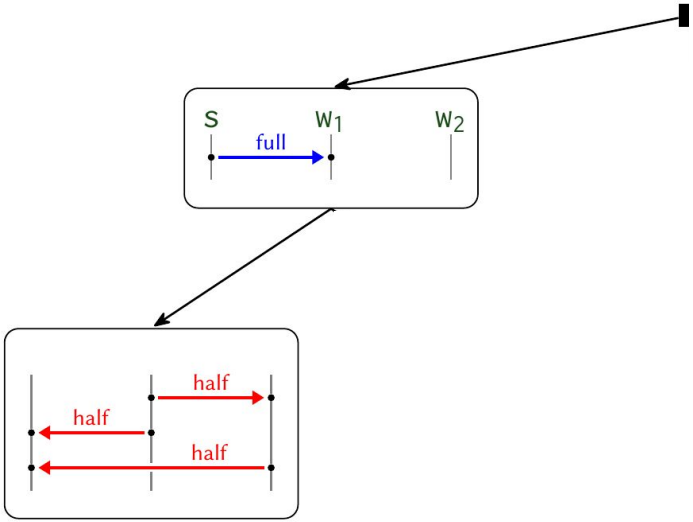
Non-implementability



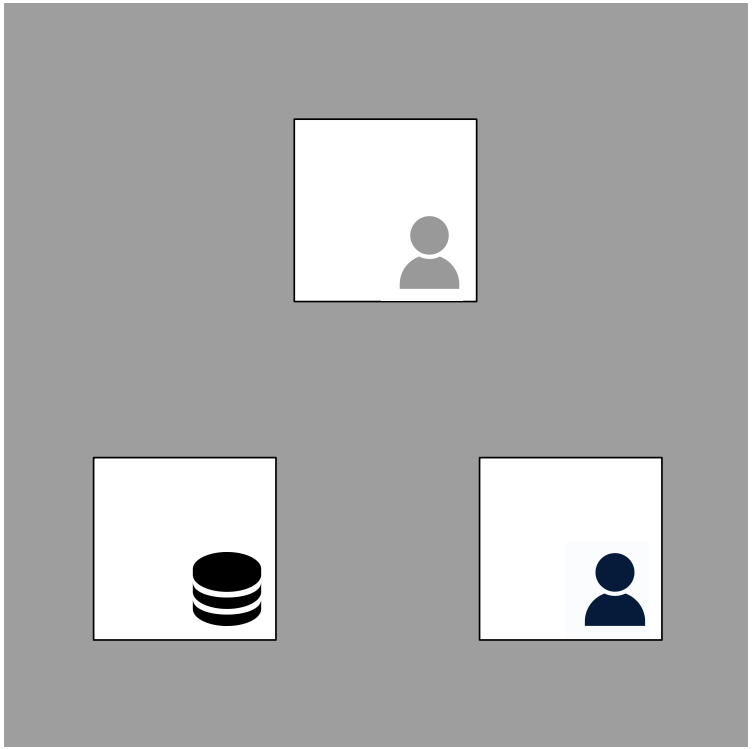
$u_1 = s \triangleright w_1 ! full$



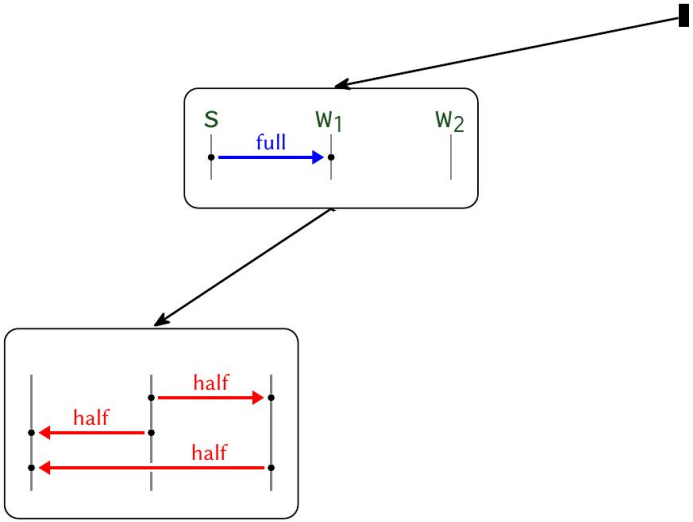
Non-implementability



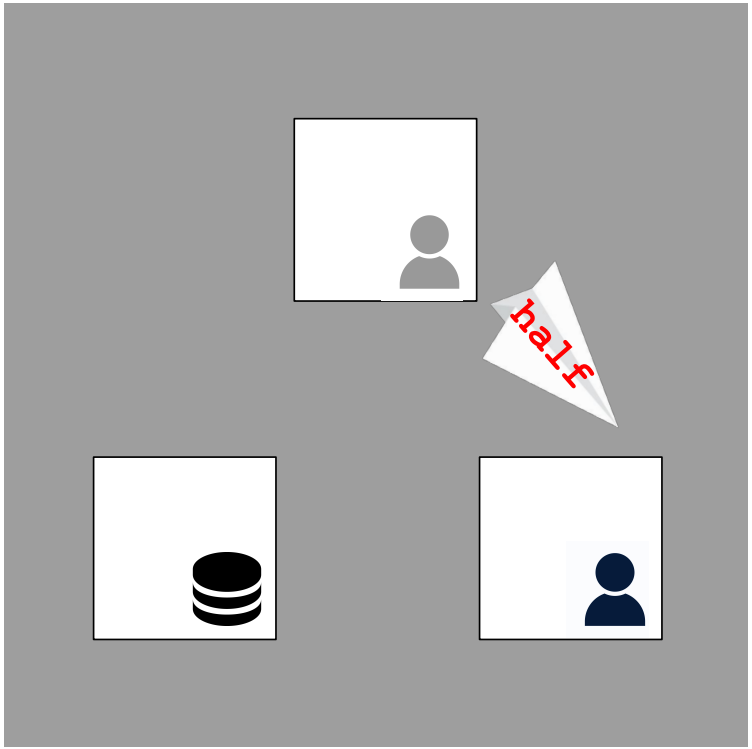
$u_1 = \mathsf{S} \triangleright \mathsf{W}_1!\mathsf{full} \cdot \mathsf{W}_1 \triangleleft \mathsf{S}?\mathsf{full}$



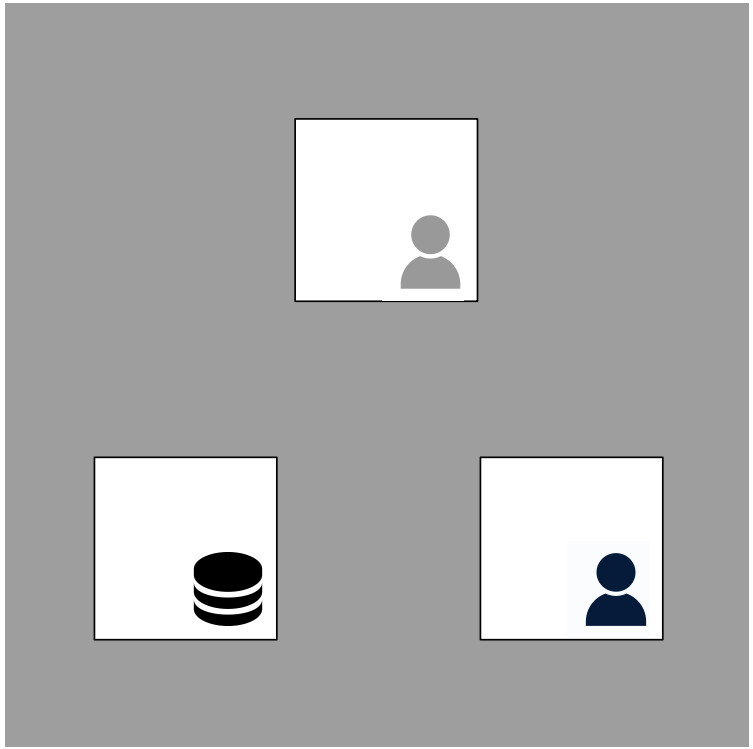
Non-implementability

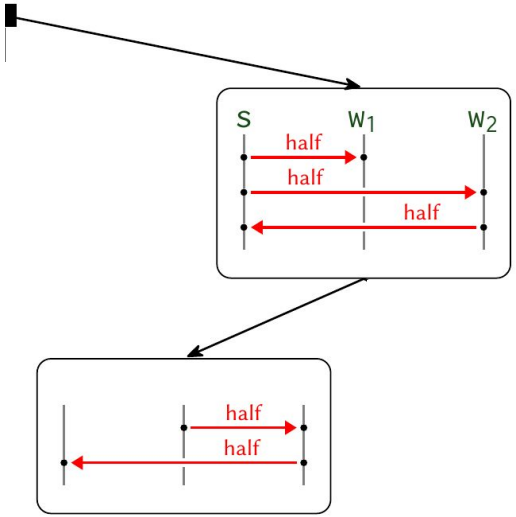


$u_1 = \mathsf{s} \triangleright \mathsf{w}_1!\mathsf{full} \cdot \mathsf{w}_1 \triangleleft \mathsf{s}?\mathsf{full} \cdot \mathsf{w}_1 \triangleright \mathsf{w}_2!\mathsf{half}$



Non-implementability





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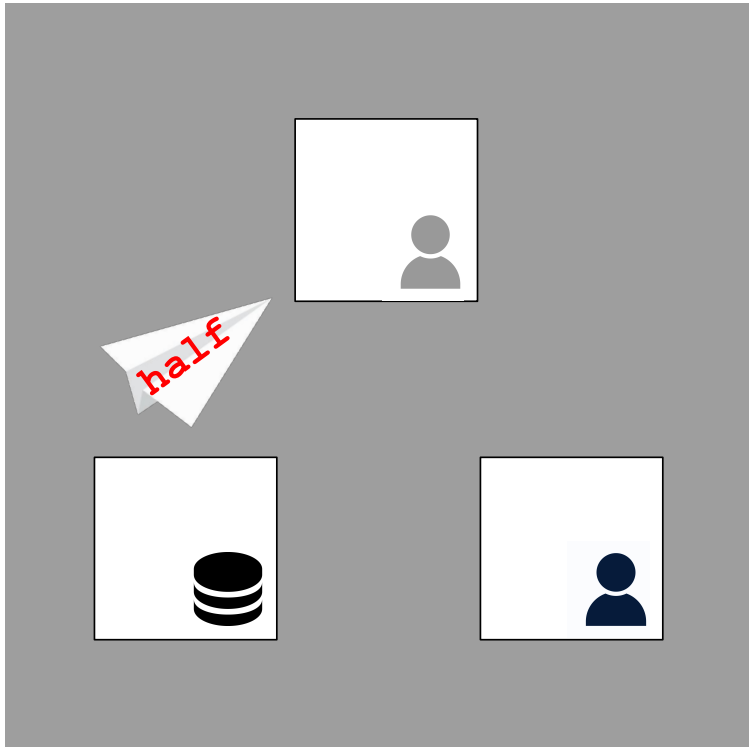
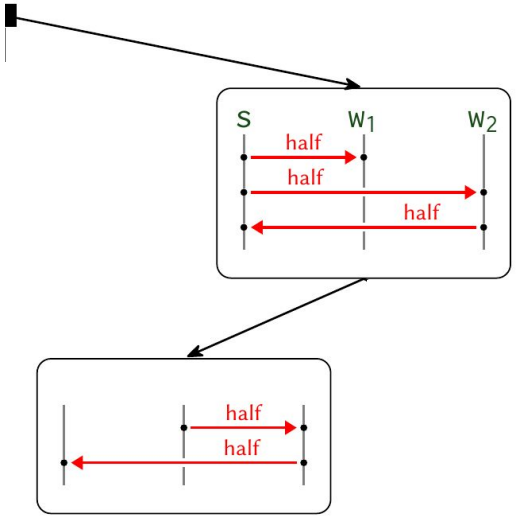
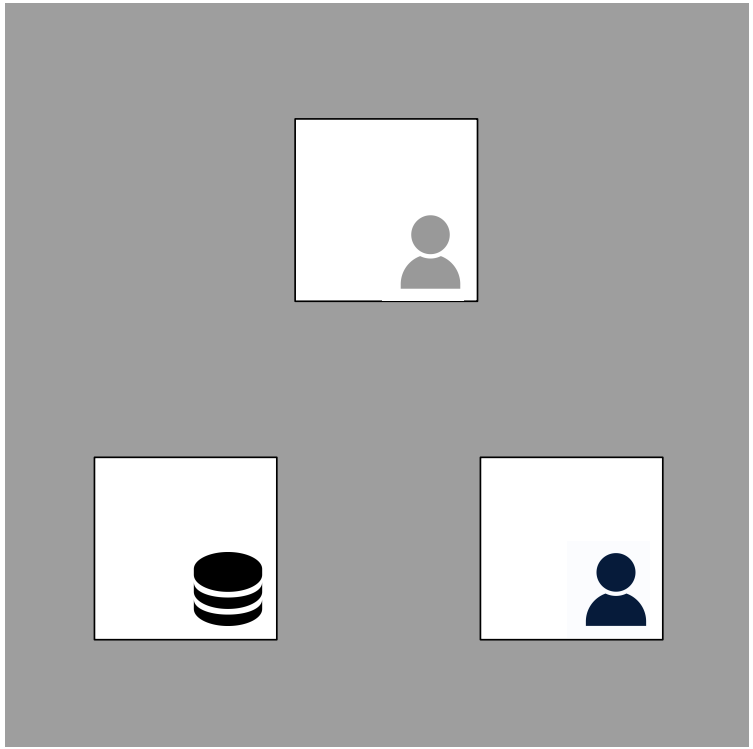
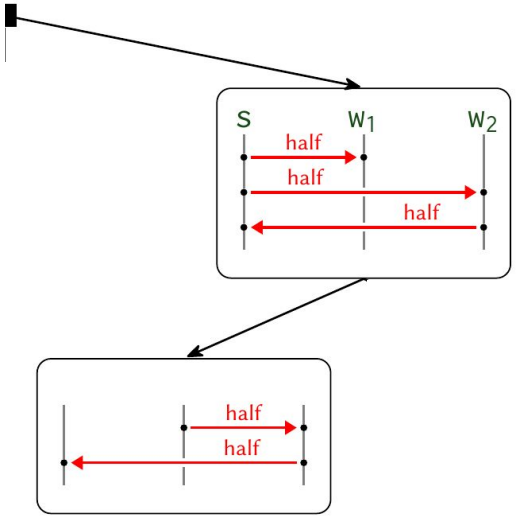




$u_2 = \mathsf{S} \triangleright \mathsf{W}_1!\mathsf{half}$

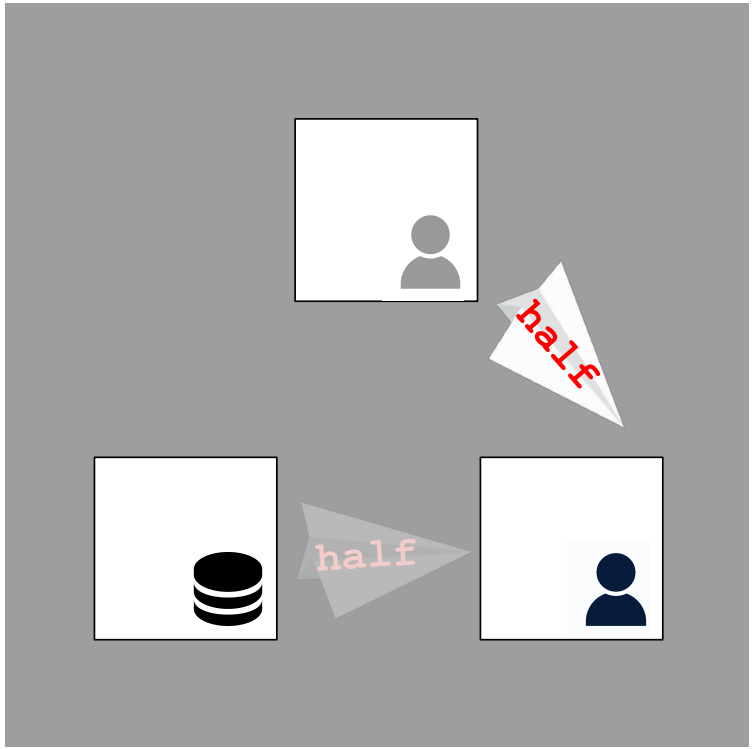
Non-implementability

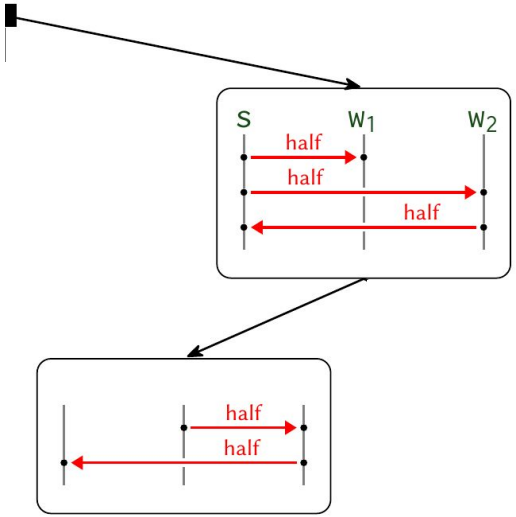




$u_2 = \mathsf{s} \triangleright \mathsf{w}_1!\mathsf{half} \cdot \mathsf{w}_1 \triangleleft \mathsf{s}?\mathsf{half}$

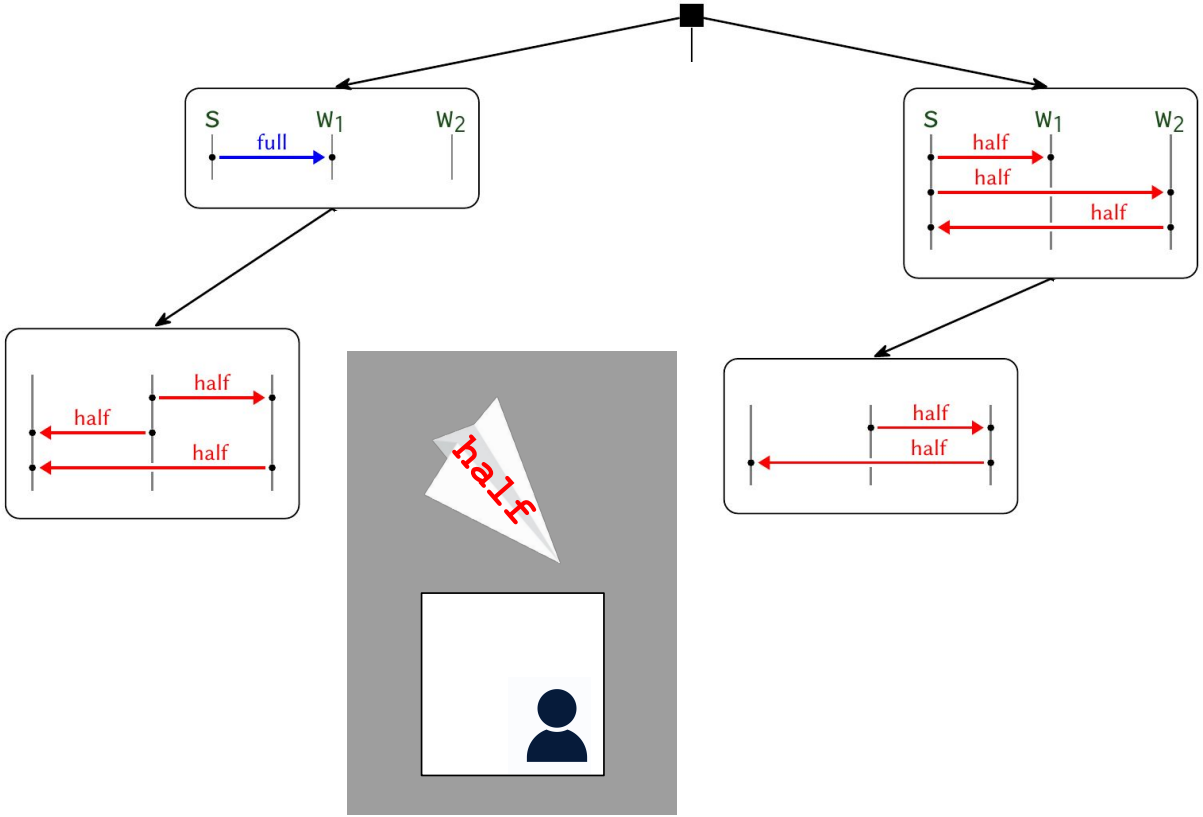
Non-implementability





$$u_2 = \mathsf{S} \triangleright \mathsf{W}_1!\mathsf{half} \cdot \mathsf{W}_1 \triangleleft \mathsf{S}?\mathsf{half} \cdot \mathsf{W}_1 \triangleright \mathsf{W}_2!\mathsf{half}$$

Non-implementability



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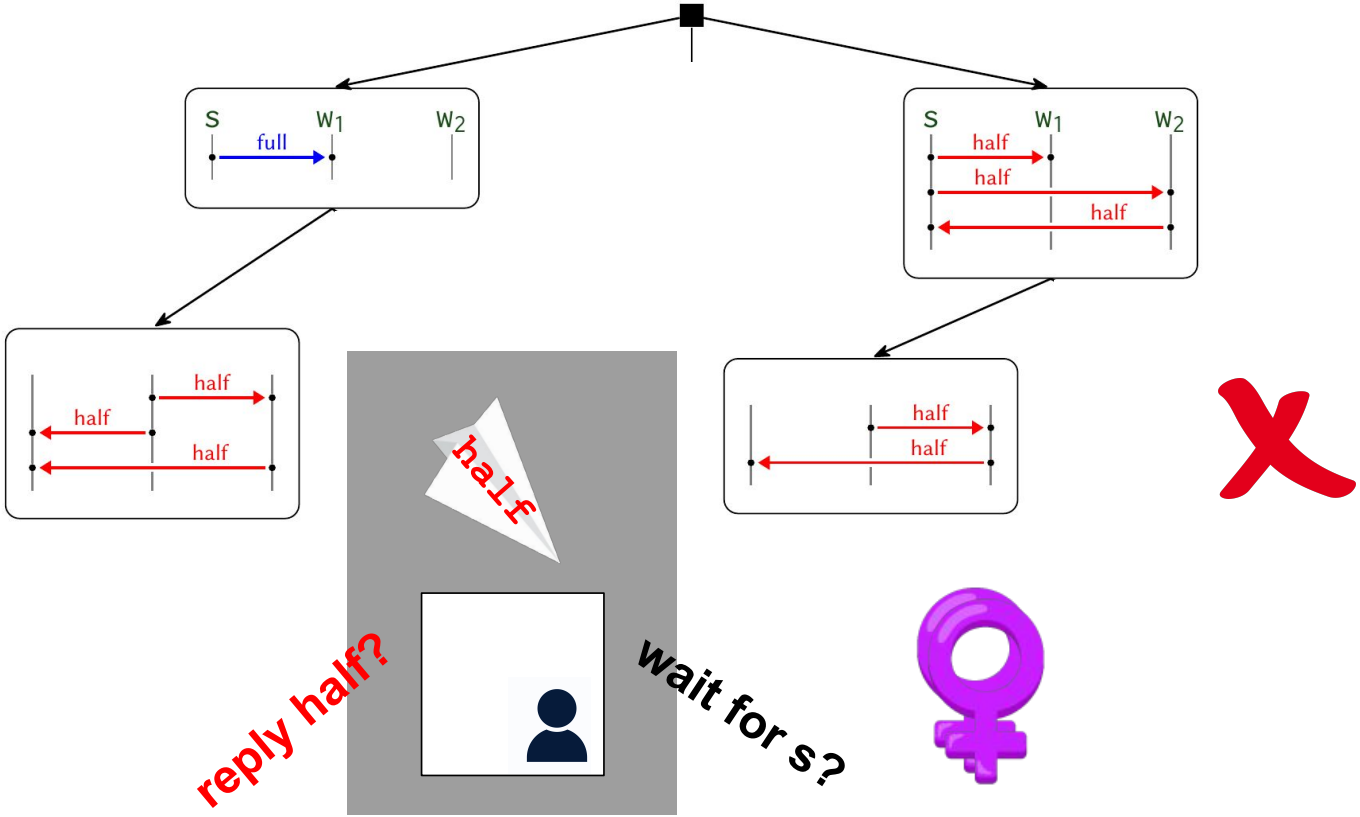

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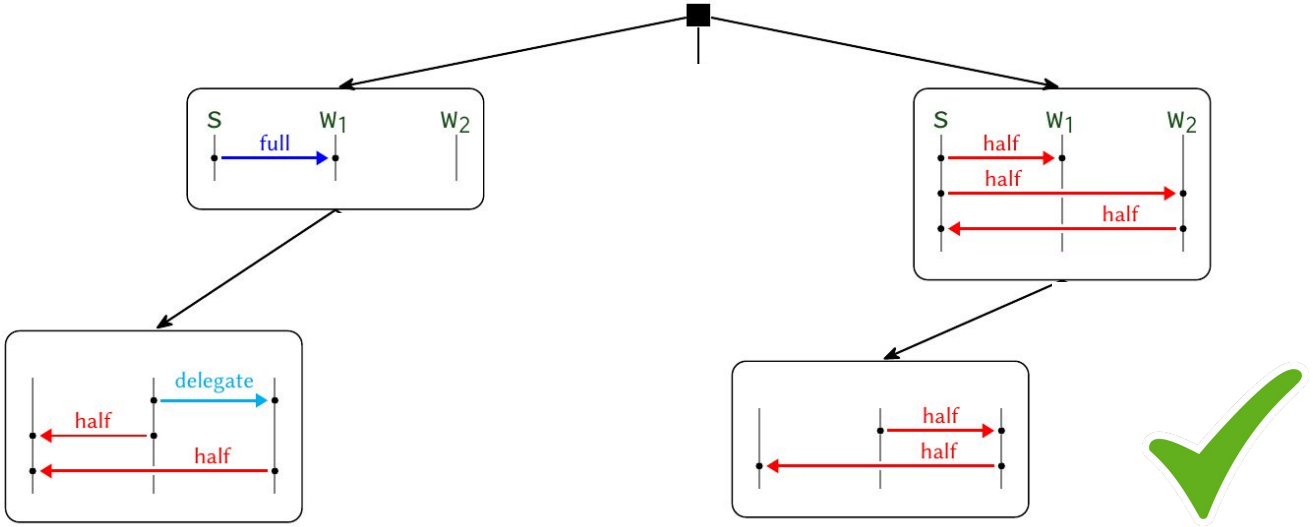

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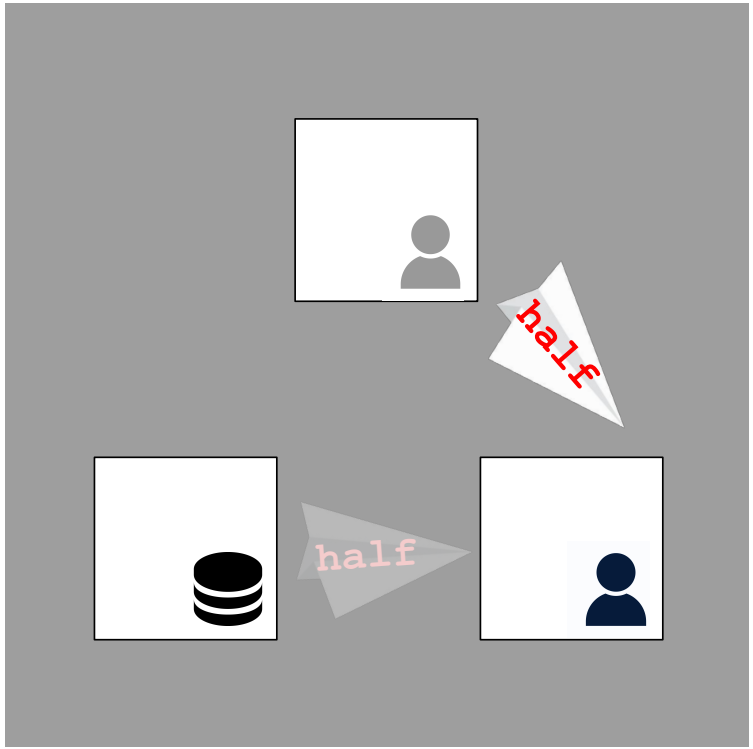
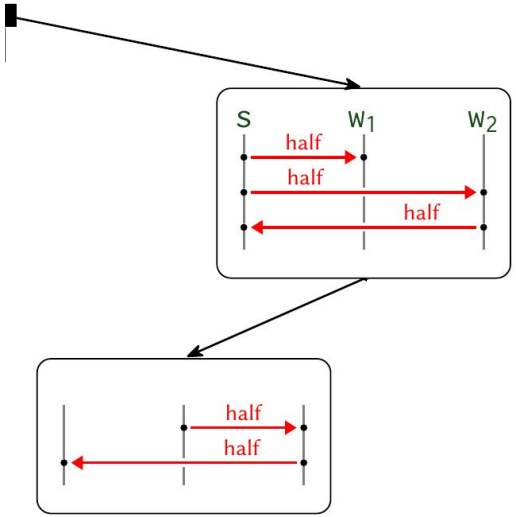
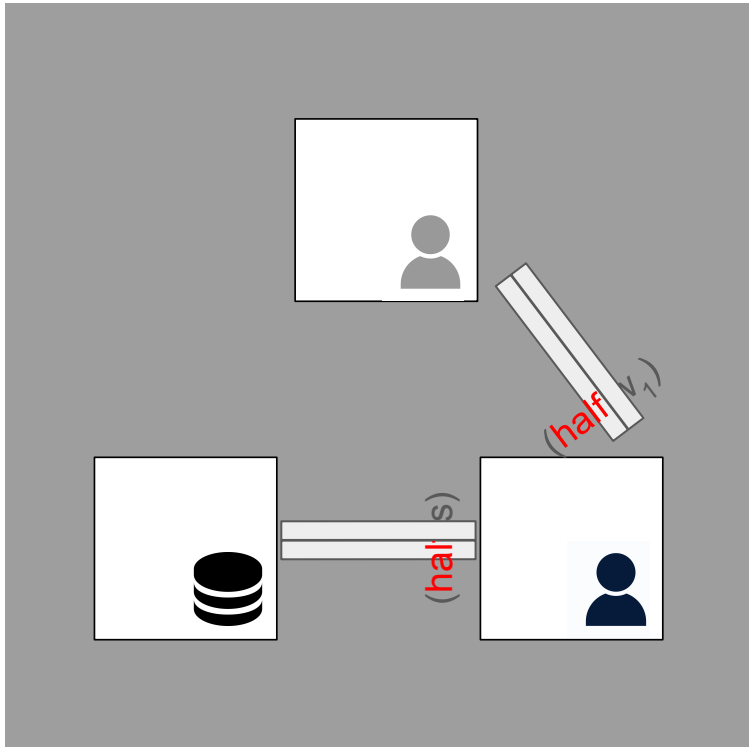
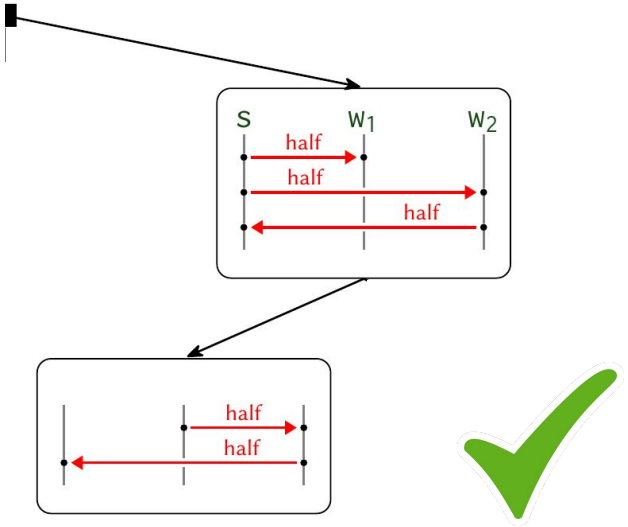




$$u_3 = \mathsf{s} \triangleright \mathsf{w}_1!\mathsf{half} \cdot \mathsf{w}_1 \triangleleft \mathsf{s}?\mathsf{half} \cdot \mathsf{w}_1 \triangleright \mathsf{w}_2!\mathsf{half} \cdot \mathsf{s} \triangleright \mathsf{w}_2!\mathsf{half}$$

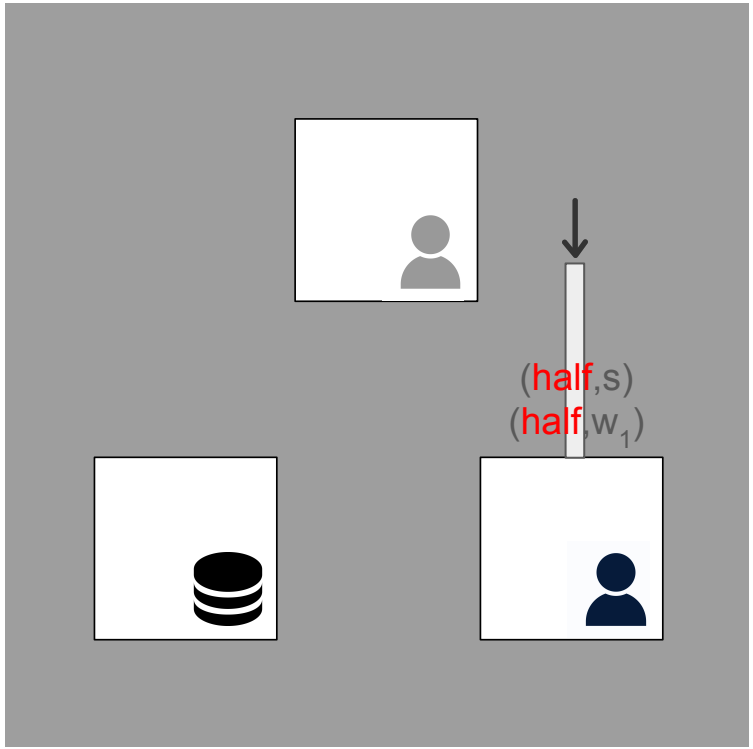
Non-implementability

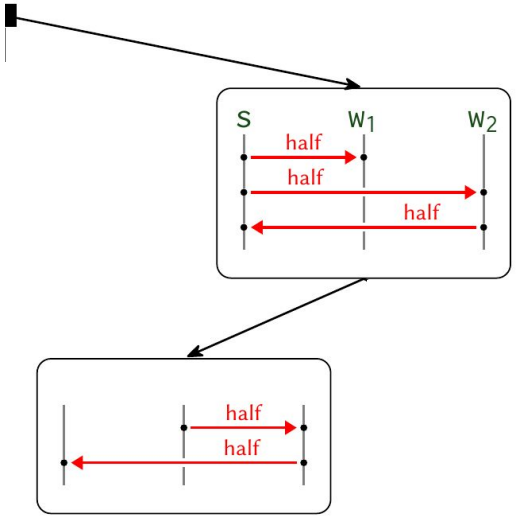




$u_3 = \mathsf{s} \triangleright \mathsf{w}_1!\mathsf{half} \cdot \mathsf{w}_1 \triangleleft \mathsf{s}?\mathsf{half} \cdot \mathsf{w}_1 \triangleright \mathsf{w}_2!\mathsf{half} \cdot \mathsf{s} \triangleright \mathsf{w}_2!\mathsf{half}$

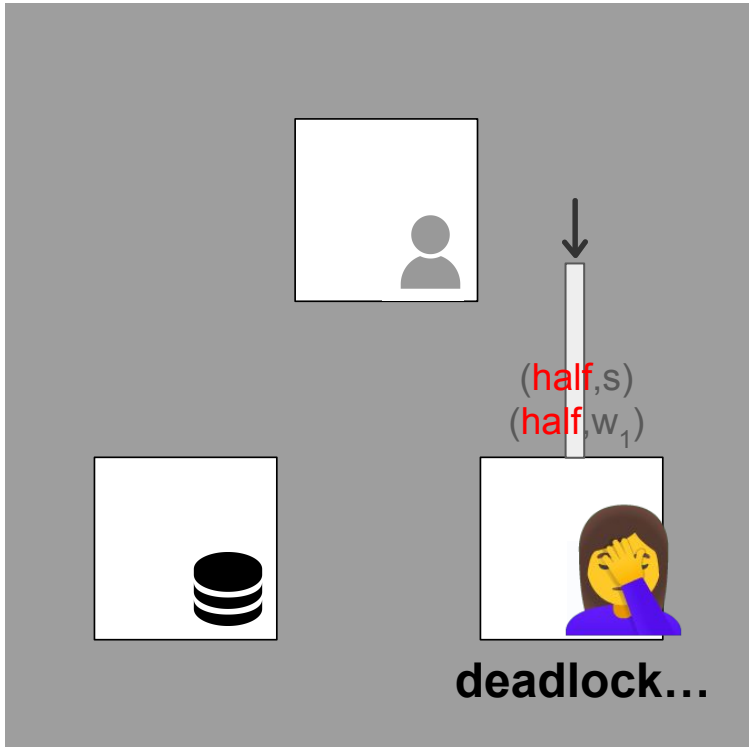
Non-implementability

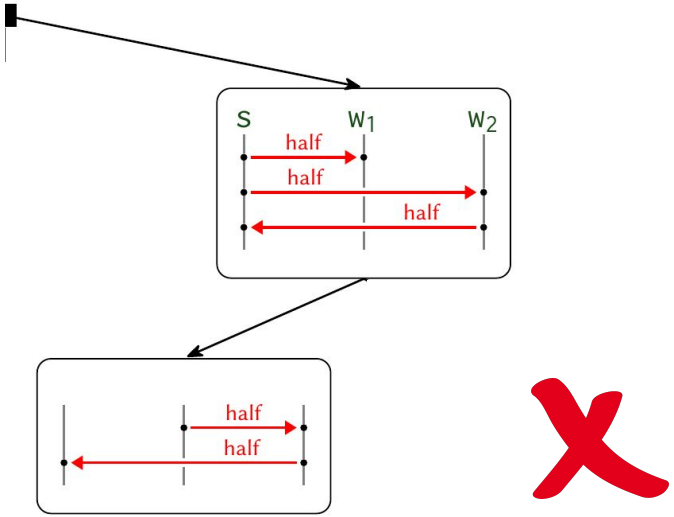




$$u_3 = s \triangleright w_1!\mathrm{half} \cdot w_1 \triangleleft s?\mathrm{half} \cdot w_1 \triangleright w_2!\mathrm{half} \cdot s \triangleright w_2!\mathrm{half}$$

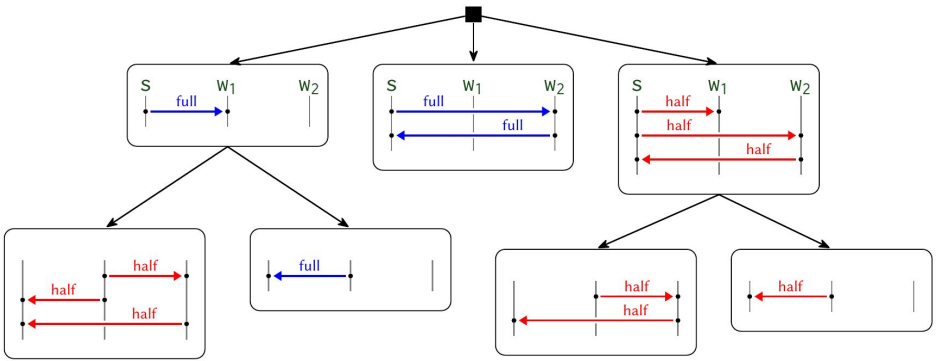
Non-implementability





$u_3 = s \triangleright w_1!\text{half} \cdot w_1 \triangleleft s?\text{half} \cdot w_1 \triangleright w_2!\text{half} \cdot s \triangleright w_2!\text{half}$

Network-parametric implementability



?

realizability/
implementability
under a given network?

Network-parametric goal

A single implementability characterization
and proof of preciseness
for all asynchronous networks

Network-parametric goal

A single implementability characterization
and proof of preciseness
for all **asynchronous networks**

"On the diversity of asynchronous communication" [Chevrou et al. 16]

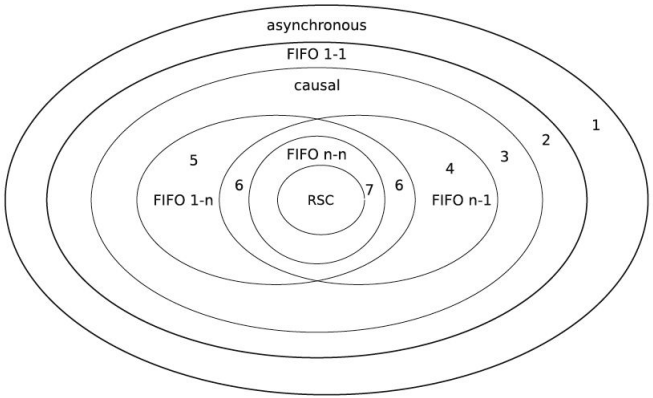
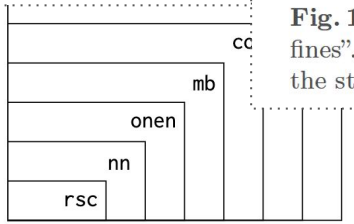


Fig. 7. Hierarchy of the communication models



(a) The hierarchy of MSC classes.

[Di Giusto et al. 23]

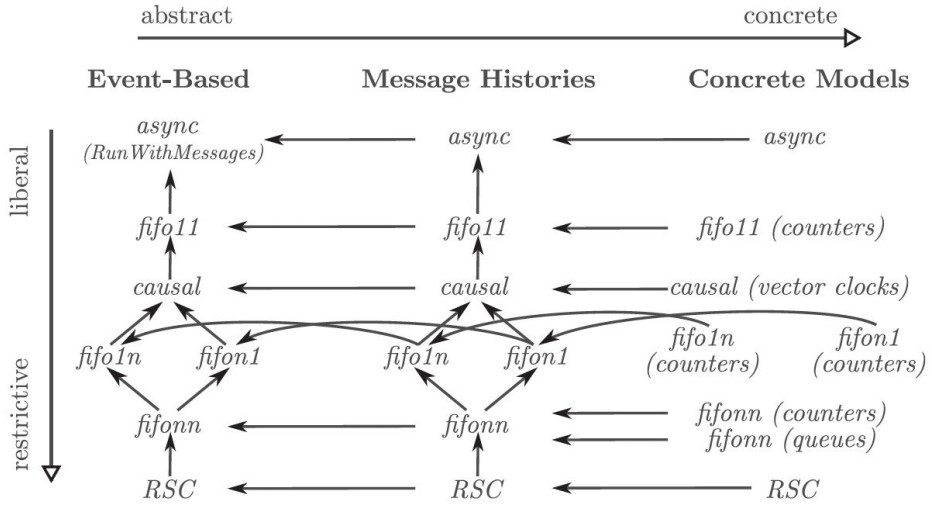
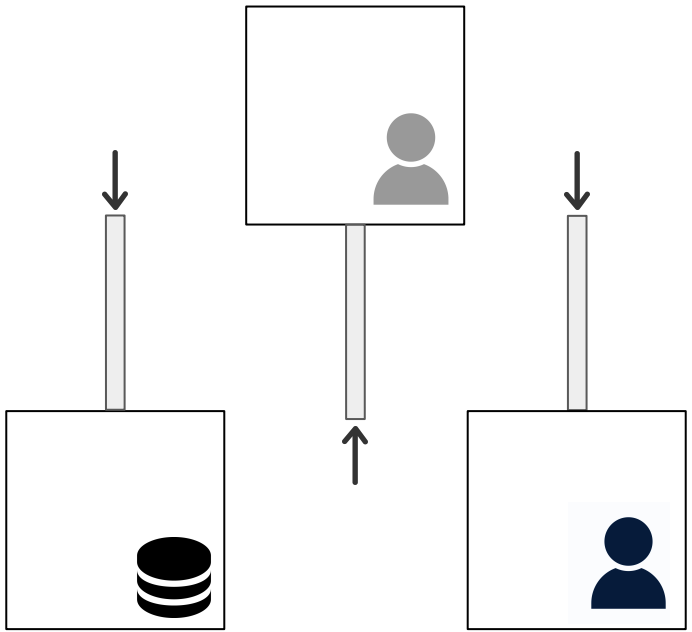


Fig. 1. Map of the Asynchronous Communication Models. A black arrow means "refines". The two axis of refinement are the level of abstraction (data refinement) and the strength of the ordering policy (reduction of non-determinism).

[Chevrou et al. 19]

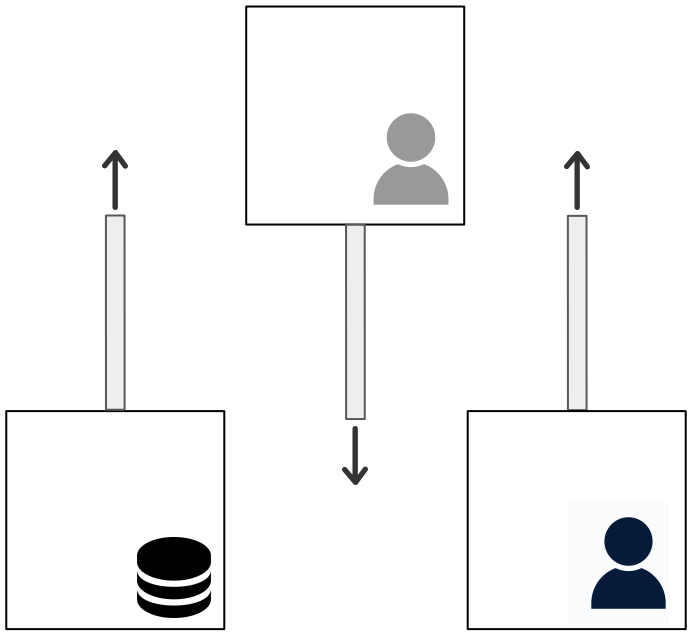
Asynchronous communication



Mailbox (FIFO n-1):

- Actor model: Elixir, Erlang
- Synchronizability and realizability [Etienne and Lozes 17, Muscholl and Delpy 24]

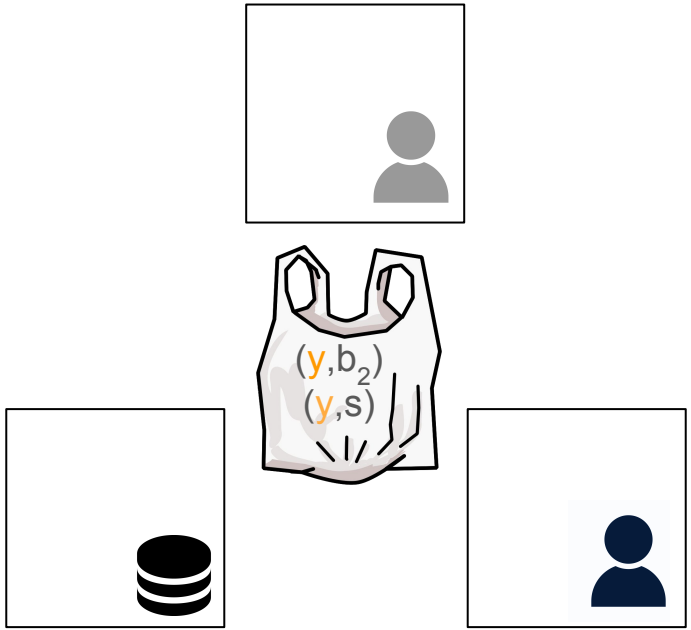
Asynchronous communication



Senderbox (FIFO 1-n):

- Work-stealing in parallel programming

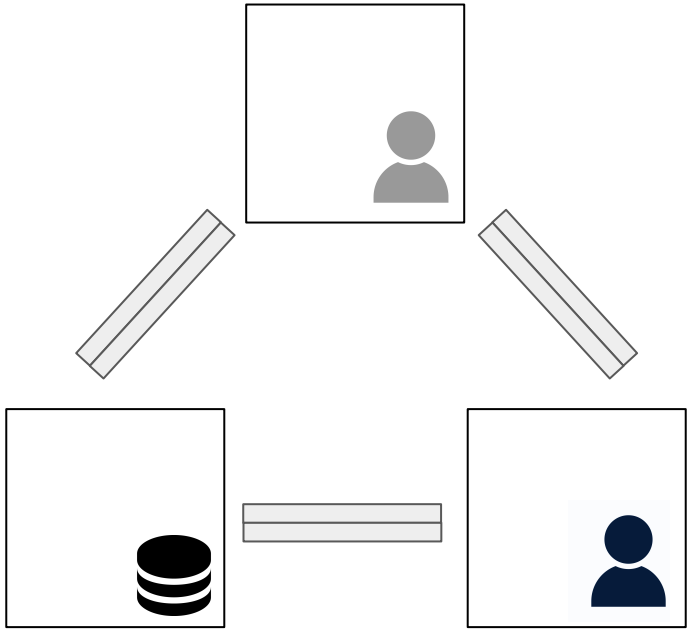
Asynchronous communication



Monobag (async):

- Consensus protocols

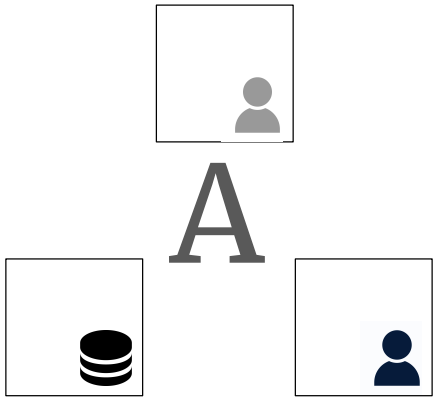
Asynchronous communication



Peer-to-peer FIFO (FIFO 1-1):

- Communicating state machines [Brand and Zafiropulo 83]
- Ubiquitous in theory and verification

What is a network?



A network architecture A is:

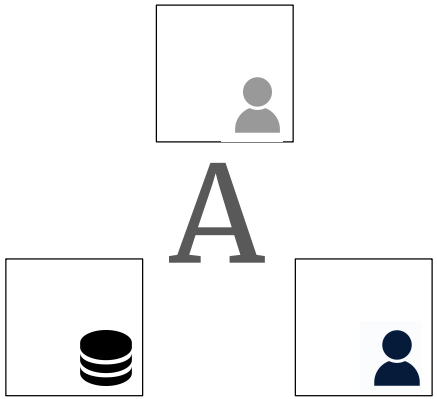
communication topology
(mapping sender and receiver pairs to buffers)

$\times$

buffer data structure
(empty, insert, remove)

What is a network?

Communicating Labeled Transition System (CLTS) = local implementations (controllable) + network architecture $\mathbb{A}$ (non-controllable)



A network architecture $\mathbb{A}$ is:

communication topology
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×

buffer data structure
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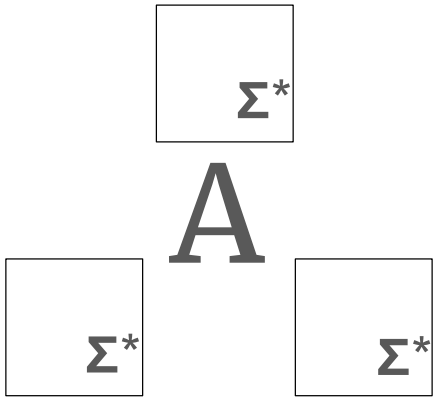
What is a network?

Communicating Labeled Transition System (CLTS) = local implementations (controllable) + network architecture (non-controllable) $\mathbb{A}$



A network architecture $\mathbb{A}$ is:

communication topology
(mapping sender and receiver pairs to buffers)

×

buffer data structure
(empty, insert, remove)

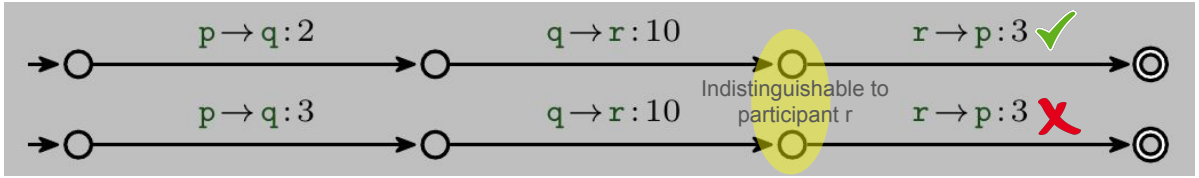
A network is the set of finite and infinite words executable by the *universal* CLTS under network architecture A.

Network-parametric goal

A single **implementability characterization**
and proof of preciseness
for all asynchronous networks

(L(A))

Coherence Conditions under p2p FIFO [Li et al. 25]



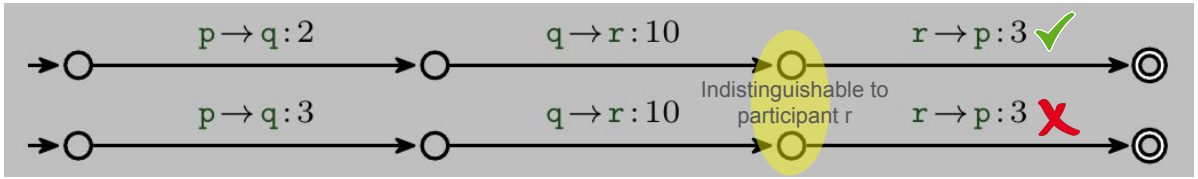
From two locally indistinguishable global states, a participant can either:

- Send a message permissible from both states (Send Coherence)
- Receive a message that distinguishes the two states (Receive Coherence)

but cannot choose between sending or receiving a message (No Mixed Choice)

Theorem. A concrete protocol is implementable if and only if it satisfies the Coherence Conditions.

Generalized Coherence Conditions under $\mathbf{A}$



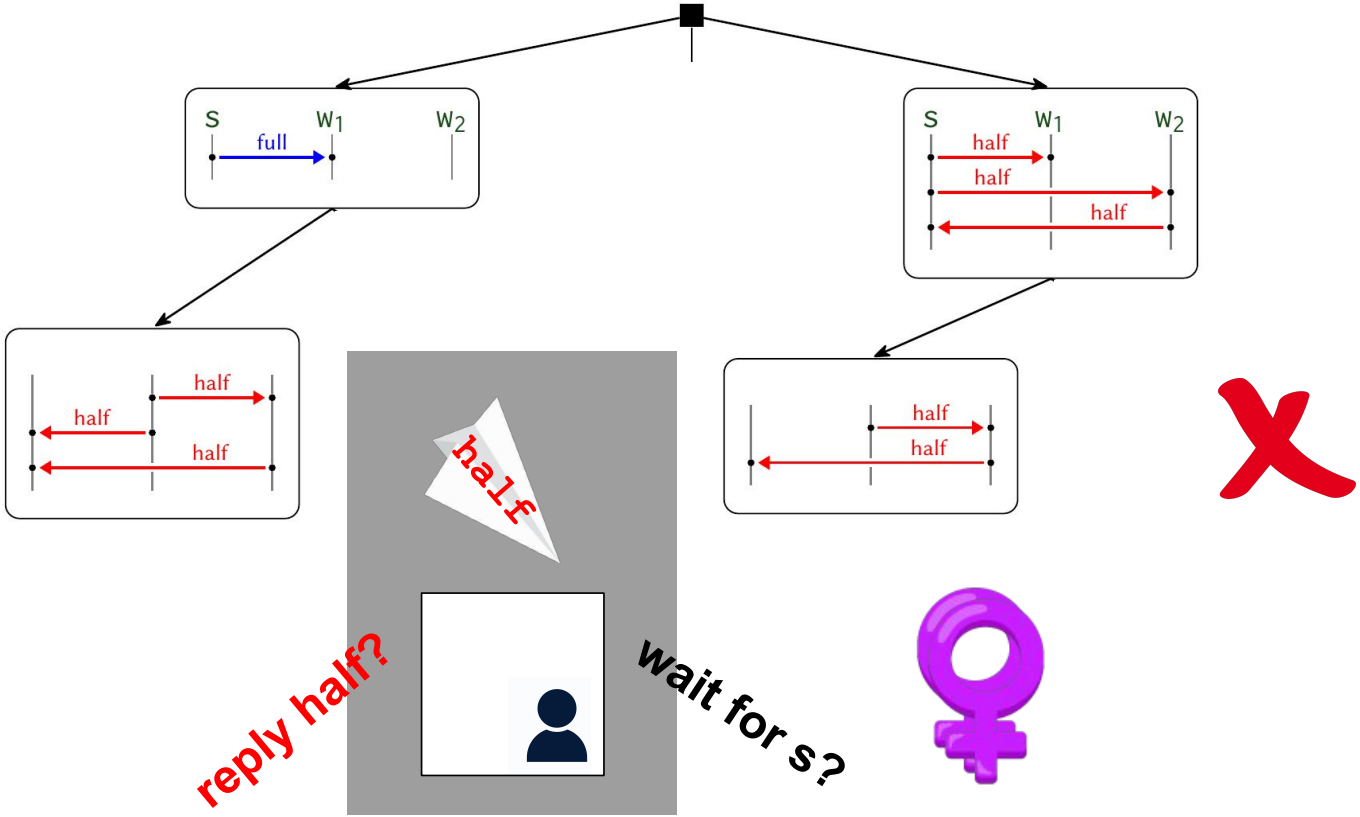
From two locally indistinguishable global states, a participant can either:

- Send a message permissible from both states (Send Coherence)
- **Receive a message under $\mathbf{A}$ that distinguishes the two states (Generalized Receive Coherence)**

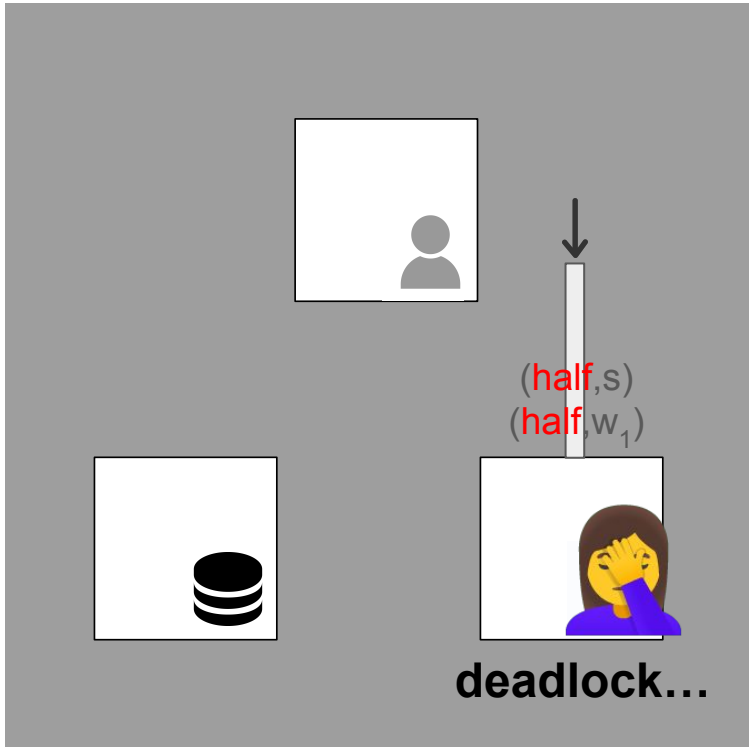
but cannot choose between sending or receiving a message (No Mixed Choice)

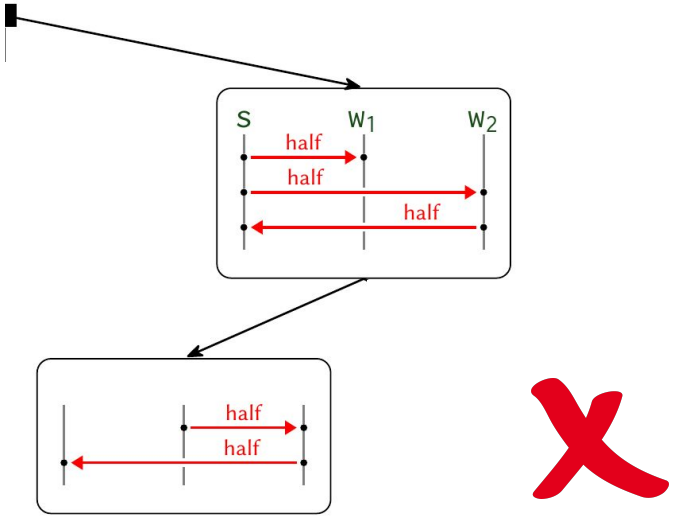
Moreover, the protocol must not contain runs that deadlock under $\mathbf{A}$ despite perfect information (Prefix Extensibility)

Violation of Generalized Receive Coherence (all)



Violation of Prefix Extensibility (mailbox, monobox)





$u_3 = s \triangleright w_1!\text{half} \cdot w_1 \triangleleft s?\text{half} \cdot w_1 \triangleright w_2!\text{half} \cdot s \triangleright w_2!\text{half}$

Network-parametric goal

(Generalized Coherence Conditions under A)

A <u>single</u> implementability characterization
and proof of preciseness
for <u>all</u> **asynchronous networks***

($\mathrm{L}(\mathrm{A})$)

Channel compliance (≈ L(A)) facts

F1 For all $x \in \Sigma_!$, wx is channel-compliant.
F2 For all $\mathsf{p} \neq \mathsf{q} \in \mathcal{P}$ and $m \in \mathcal{V}$, $|w\Downarrow_{\mathsf{p}\triangleright\mathsf{q}!m}| \geq |w\Downarrow_{\mathsf{q}\triangleleft\mathsf{p}?m}|$.
F3 For all $\rho \in \Gamma^*_{sync}$, $\mathtt{split}(\rho)$ is channel-compliant.
F4 For all $\rho \in \Gamma^*_{sync}$, if $w \equiv_{\mathcal{P}} \mathtt{split}(\rho)$, then w is channel-matched.
F5 For all $x \in \Sigma_!$, $y \in \Sigma_?$, if wy is channel-compliant then wxy is channel-compliant.
F6 Let $\alpha, \beta \in \Gamma^*_{sync}$, $\mathsf{p} \neq \mathsf{q} \in \mathcal{P}$ and $m \in \mathcal{V}$ such that for all $\mathsf{p} \in \mathcal{P}$, $w\Downarrow_{\Sigma_\mathsf{p}} \leq \mathtt{split}(\alpha\beta)\Downarrow_{\Sigma_\mathsf{p}}$, and $w\Downarrow_{\Sigma_\mathsf{q}} = \mathtt{split}(\alpha)\Downarrow_{\Sigma_\mathsf{q}}$, and $w \cdot \mathsf{q} \triangleleft \mathsf{p}?m$ is channel-compliant. Then, there exists w' such that w' is compliant with β, $w'\Downarrow_{\Sigma_\mathsf{q}} = \varepsilon$ and $w' \cdot \mathsf{q} \triangleleft \mathsf{p}?m$ is channel-compliant.

Network-parametric goal

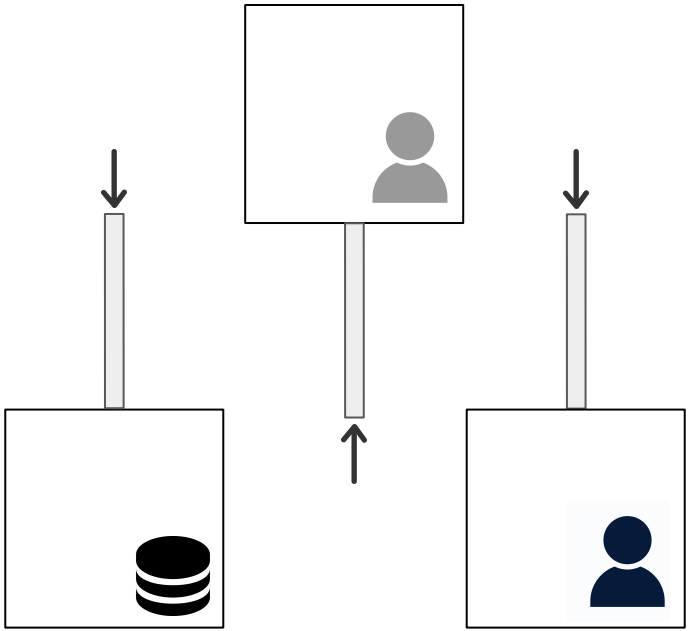
(Generalized Coherence Conditions under $\mathbb{A}$)

A single implementability characterization
and **proof of preciseness**
for all asynchronous networks*

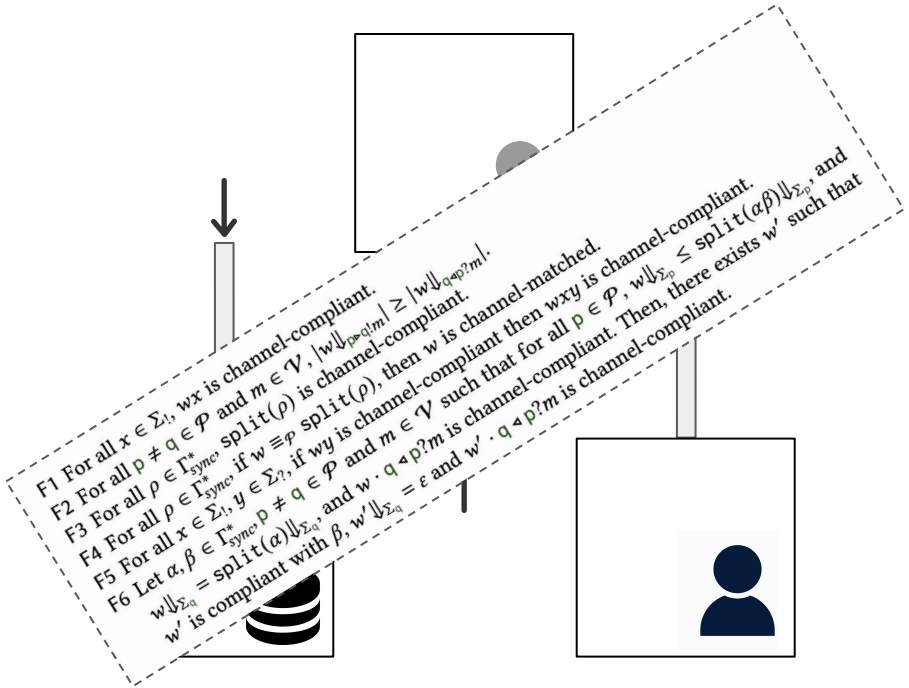
(network architectures $\mathbb{A}$ satisfying F1-F6)

Theorem. Let $\mathbb{A}$ satisfy F1-F6. Then, G is implementable under $\mathbb{A}$ iff G satisfies Generalized Coherence Conditions under $\mathbb{A}$.

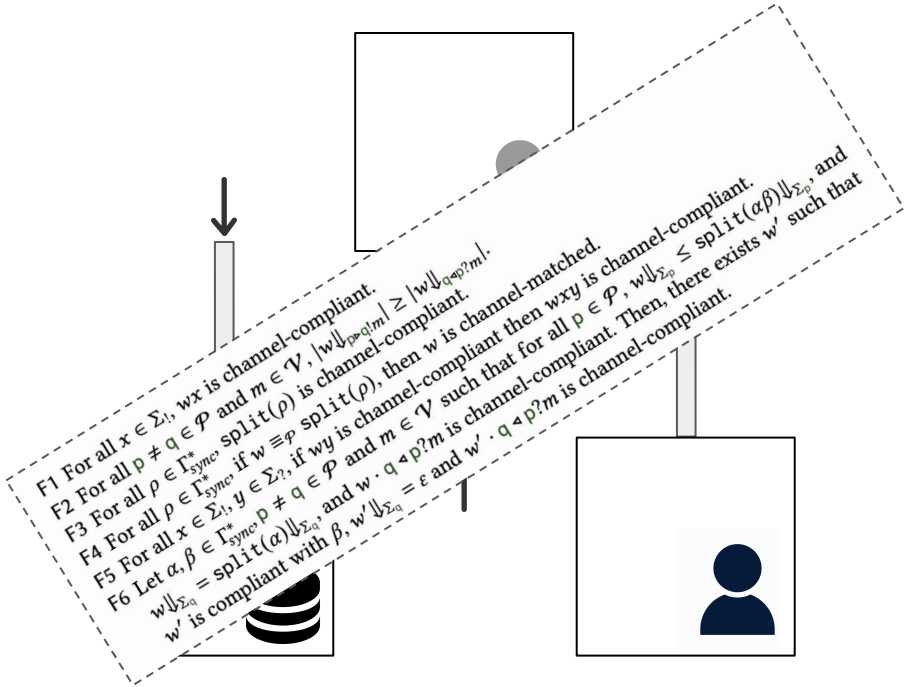
Using the framework

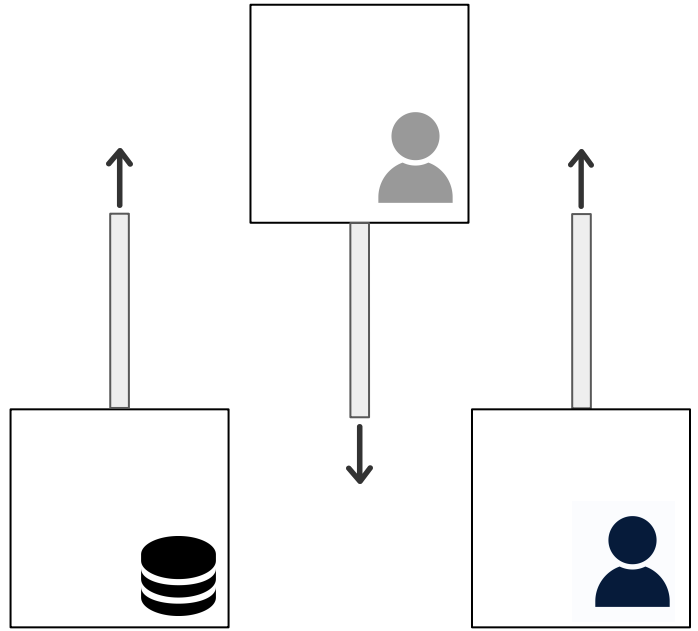


Using the framework



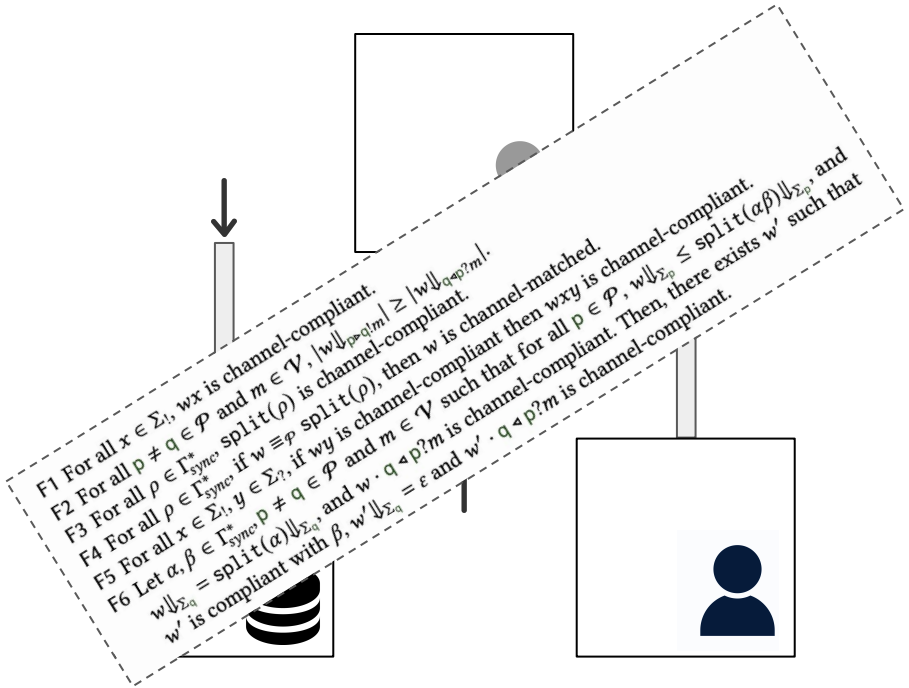
Using the framework

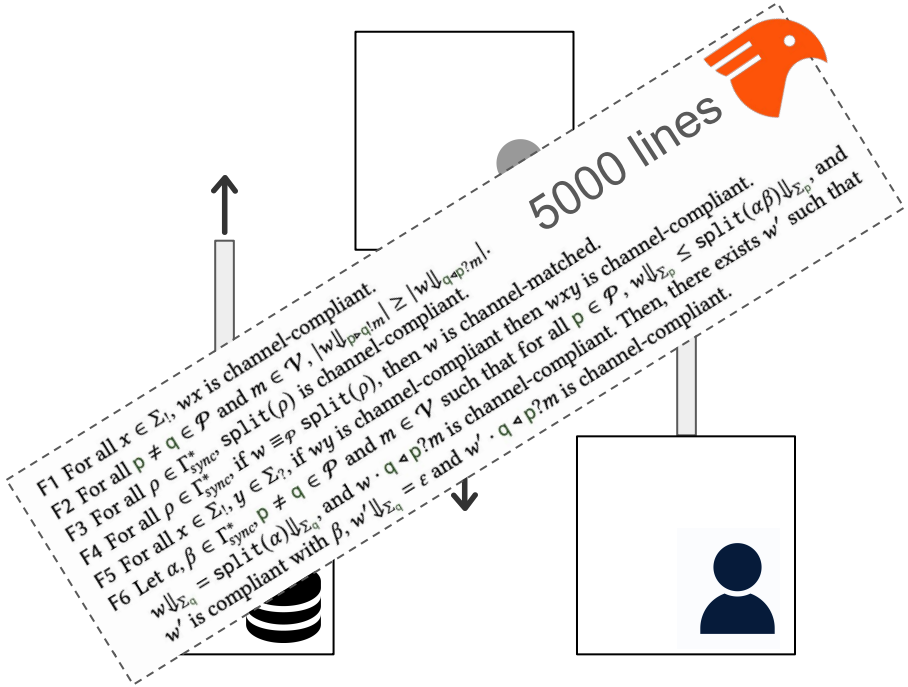




L(mailbox) ≠ L(senderbox)

Using the framework





L(mailbox) ≠ L(senderbox)

Buffer axioms

B1 $b \bullet ins(x)$ is defined.
B2 $b_0 \bullet ins(x) \bullet rem(x)$ is defined.
B3 $b_0 \bullet rem(x)$ is undefined.
B4 If $b \bullet rem(x)$ is defined, then $b \bullet ins(y) \bullet rem(x)$ is defined.
B5 If $b \bullet ins(x) \bullet \delta$ is defined and $rem(x)$ does not occur in δ, then $b \bullet \delta$ is defined.
B6 If $b \bullet rem(x)$ is defined, then $b \bullet ins(x) \bullet rem(x) = b \bullet rem(x) \bullet ins(x)$.
B7 If $x \neq y$, then $b \bullet ins(x) \bullet rem(y) = b \bullet rem(y) \bullet ins(x)$.
B8 If $b \bullet rem(x)$ is undefined, $b \bullet ins(x) \bullet \delta \bullet rem(x)$ is defined, and $rem(x)$ does not occur in δ, then $b \bullet ins(x) \bullet \delta \bullet rem(x) = b \bullet \delta$.

Buffer axioms

B1 $b \bullet ins(x)$ is defined. ~~bounded channels~~
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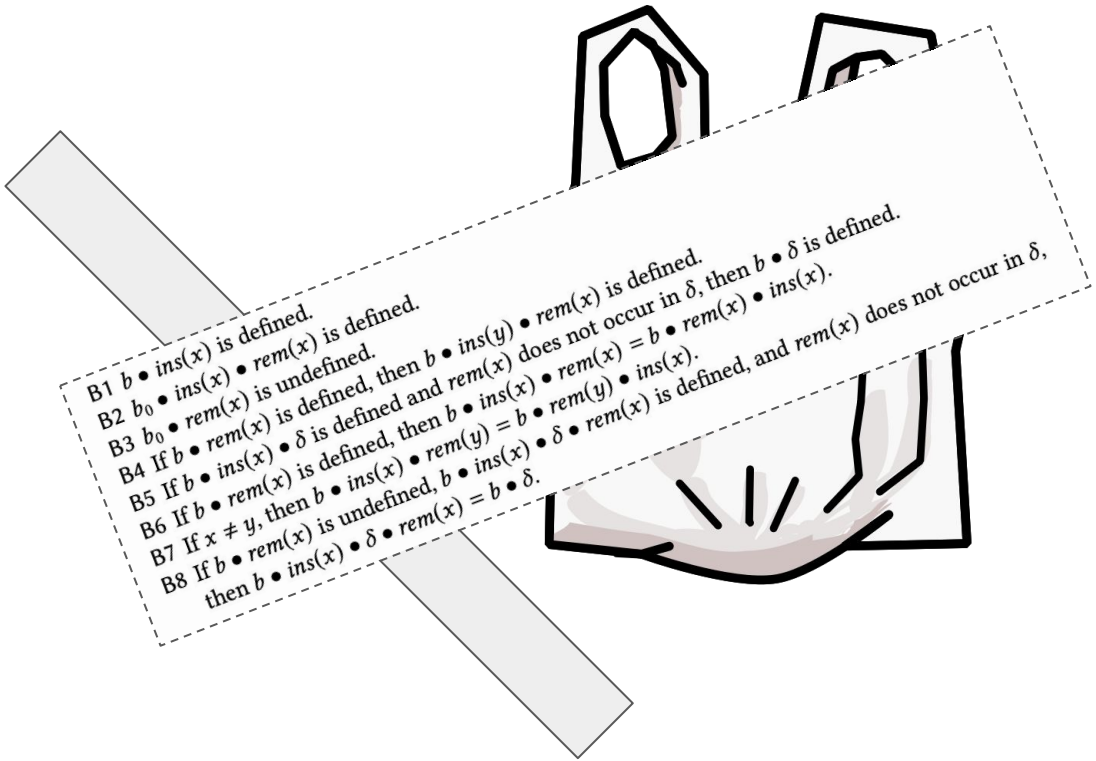
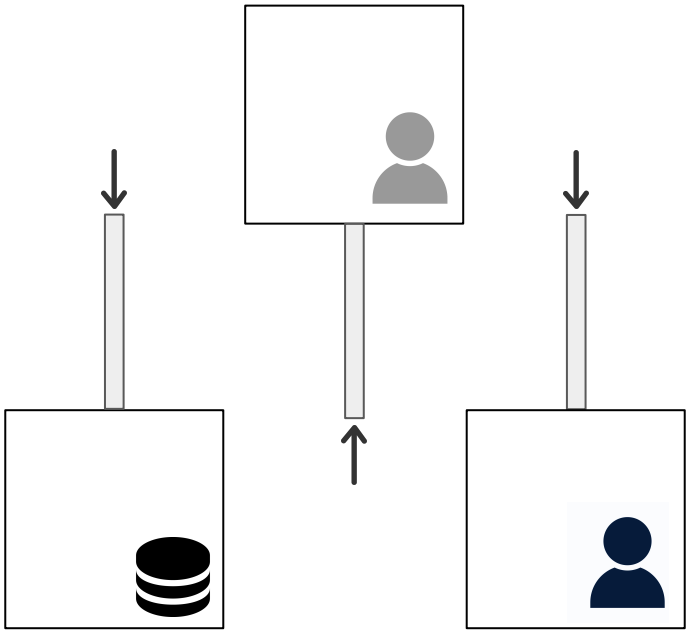
FIFO queues, multisets

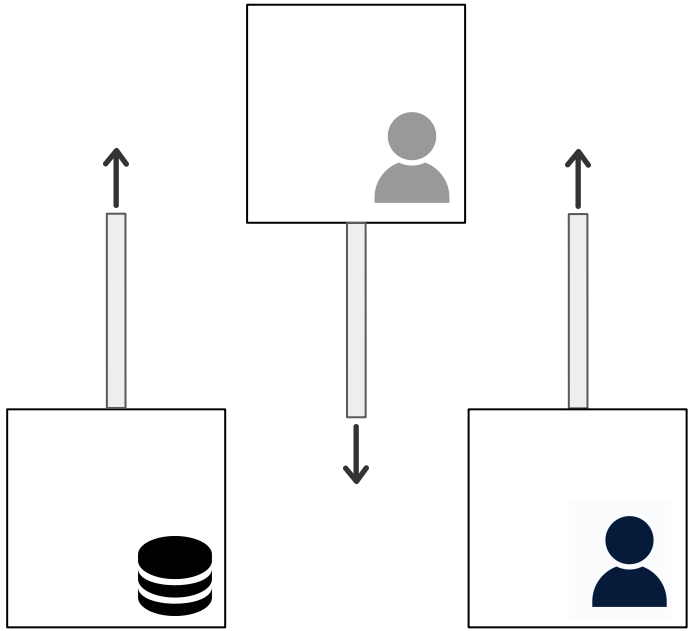
Using the framework, take two



Using the framework, take two



Using the framework, take two



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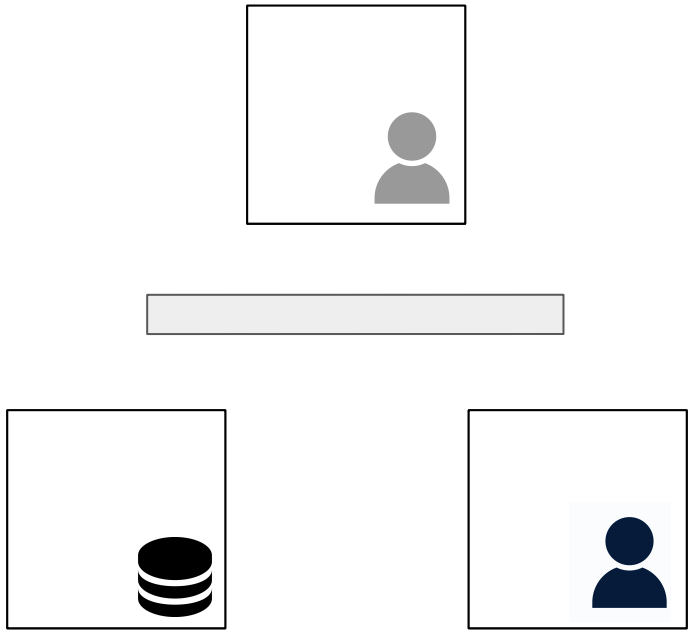

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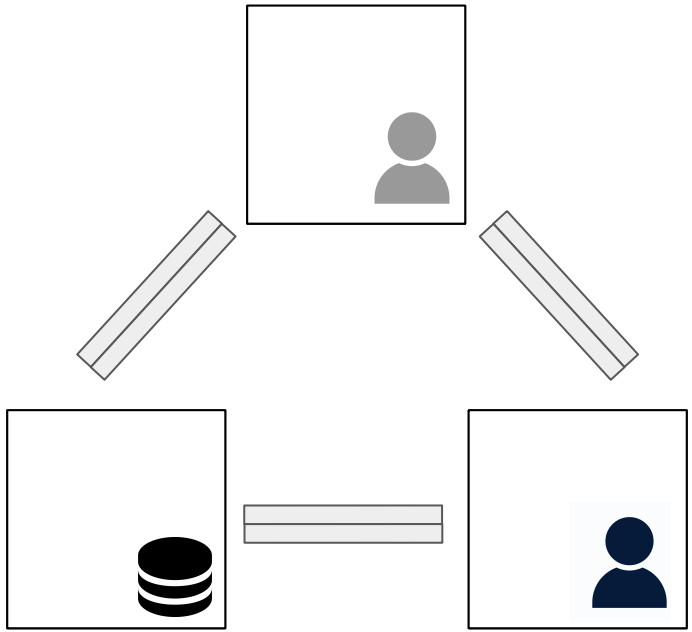

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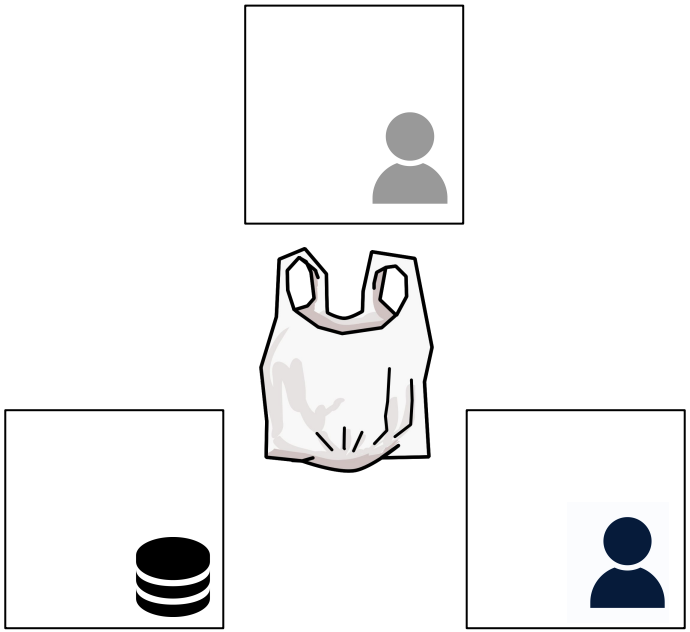
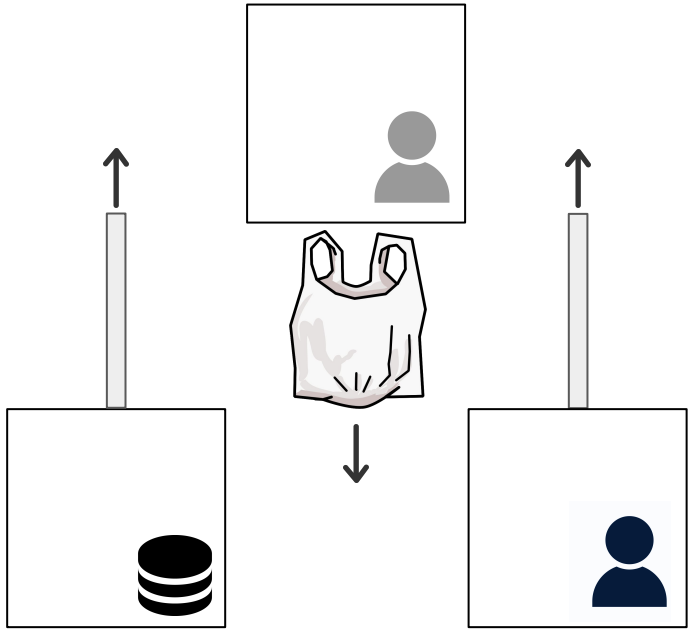


Using the framework, take two



SPROUT(A) [Li et al. CAV'25]

```
Initial state: (0)
Initial register assignments: ry=0, rc=0, rz1=0, rz2=0
(0) B1->S:y{(y>987000000000/\y<9880000000000)/\ry'=y} (1)
(1) B1->B2:y{y=ry} (2)
(2) S->B1:z{z>0/\rc'=z} (3)
(3) B1->B2:b1{b1>rz1/\rz1'=b1} (4)
(4) B2->S:quit{quit=0} (5)
(5) S->B1:quit{quit=0} (6)
(4) B2->B1:b2{b2>rz2/\b2<rc/\rz2'=b2} (7)
(7) B1->S:succ{succ=1/\rz1+rz2>=rc} (8)
(8) S->B2:succ{succ=1} (6)
(7) B1->B2:cont{cont=2/\rz1+rz2<rc} (3)
Final states: (6)
```

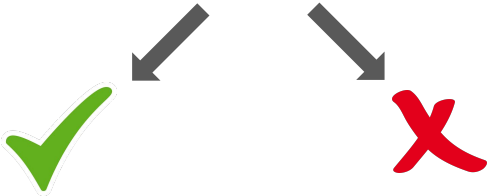
+ $A \in$ {p2pbox, senderbox, mailbox, monobox, bag}

sound and complete μCLP reduction (first order fixpoint logic)

Generalized Symbolic Coherence Conditions

calls solver

MuVal [Unno et al. 23]



Efficiency

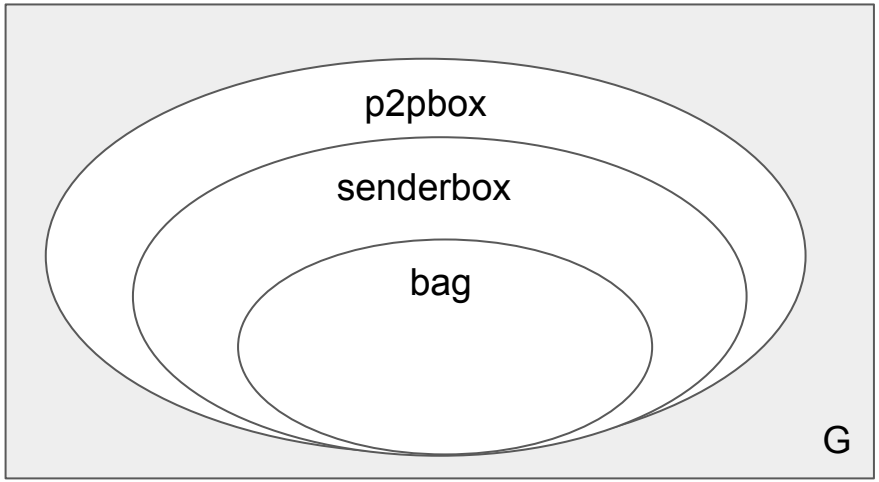
[Li et al. CAV'25]

Source	Example	$\|\mathcal{P}\|$	p2p	Time	sb	Time	mb	Time	monob	Time	bag	Time
[87]	Calculator	2	✓	0.6s	✓	0.7s	✓	0.7s	✓	0.8s	×	16.5s
	Fibonacci	2	✓	0.5s	✓	0.5s	✓	0.5s	✓	0.5s	×	3.3s
	HigherLower	3	✓	15.8s	✓	13.6s	×	17.0s	×	18.5s	×	45.6s
	HTTP	2	✓	0.5s	✓	0.4s	✓	0.4s	✓	0.5s	×	24.4s
	Negotiation	2	✓	1.0s	✓	1.0s	✓	1.0s	✓	1.0s	×	26.1s
	OnlineWallet	3	✓	17.5s	✓	16.6s	✓	16.5s	✓	20.6s	×	100.0s
	SH	3	✓	237.1s	✓	244.0s	✓	256.1s	✓	257.2s	?	T/O
	Ticket	2	✓	0.6s	✓	0.6s	✓	0.6s	✓	0.6s	×	3.8s
	TravelAgency	2	✓	9.6s	✓	9.7s	×	12.2s	×	11.6s	×	18.3s
	TwoBuyer	3	✓	4.2s	✓	4.0s	×	6.3s	×	6.3s	✓	9.3s
[83]	DoubleBuffering	3	✓	1.5s	✓	1.5s	×	2.4s	×	2.3s	✓	2.5s
	OAuth	3	✓	6.5s	✓	6.6s	✓	10.5s	✓	10.3s	×	18.1s
	PlusMinus	3	✓	5.5s	✓	5.3s	×	7.7s	×	8.6s	✓	13.2s
	RingMax	7	✓	3.7s	✓	3.6s	✓	5.3s	✓	6.8s	✓	16.5s
	SimpleAuth	2	✓	0.5s	✓	0.5s	✓	0.5s	✓	0.5s	×	4.7s
	TravelAgency2	2	✓	0.5s	✓	0.5s	✓	0.5s	✓	0.5s	✓	3.7s
[56]	send-validity-yes	4	✓	1.9s	✓	2.7s	✓	2.7s	✓	2.7s	✓	3.6s
	send-validity-no	4	×	1.9s	×	1.9s	×	2.7s	×	2.7s	×	3.6s
	receive-validity-yes	3	✓	5.3s	✓	5.3s	✓	6.5s	✓	5.9s	✓	7.8s
	receive-validity-no	3	×	3.7s	×	3.8s	×	4.6s	×	4.0s	×	5.4s
[57]	symbolic-two-bidder-yes	3	✓	24.0s	✓	21.6s	✓	25.2s	✓	22.0s	✓	31.7s
	symbolic-two-bidder-no1	3	×	23.9s	×	20.3s	×	22.9s	×	18.3s	×	29.5s
	figure12-yes	3	✓	2.0s	✓	2.0s	✓	8.7s	✓	8.5s	✓	12.8s
	figure12-no	3	×	3.0s	×	3.0s	×	9.7s	×	10.7s	×	13.8s
	symbolic-send-validity-yes	4	✓	6.6s	✓	6.5s	✓	10.0s	✓	10.5s	✓	16.0s
	symbolic-send-validity-no	4	×	5.6s	×	5.4s	×	8.3s	×	8.8s	×	13.2s

...

Implementability relationships

Source	Example	$\lvert\mathcal{P}\rvert$	p2p	Time	sb	Time	mb	Time	monob	Time	bag	Time
new	bag-no-p2p-yes	2	✓	0.4s	✓	0.4s	✓	3.4s	✓	0.6s	✗	1.8s
	mb-no-p2p-yes	3	✓	0.9s	✓	0.9s	✗	1.3s	✗	1.3s	✓	1.3s
	p2p-no-sb-yes	4	✗	4.0s	✓	4.1s	✗	5.3s	✗	5.3s	✗	6.7s
	mb-no-monob-no	3	✗	3.2s	✓	3.2s	✗	4.1s	✗	4.1s	✗	5.4s
	monob-no-mb-no	4	✓	1.3s	✓	1.3s	✗	1.9s	✗	1.9s	✓	1.9s
	Average			6.7s		5.8s		7.6s		7.1s		12.6s

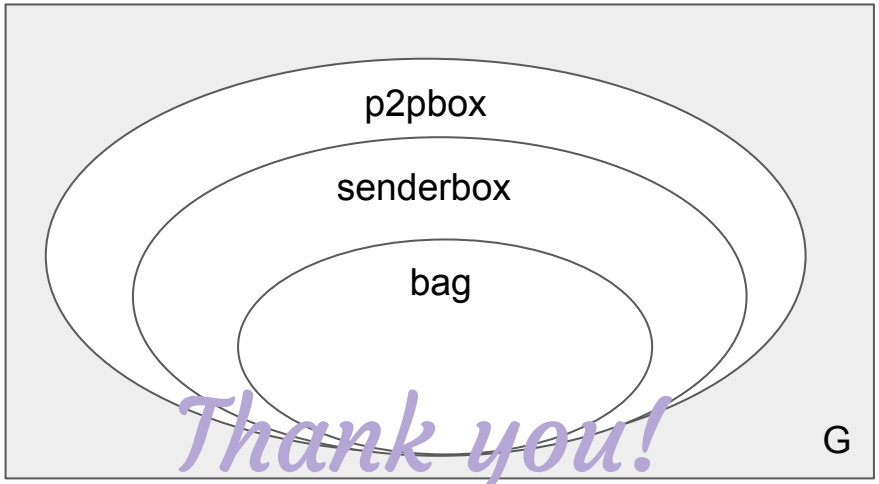


Corollary.

Implementability relationships

Source	Example	$\lvert\mathcal{P}\rvert$	p2p	Time	sb	Time	mb	Time	monob	Time	bag	Time
new	bag-no-p2p-yes	2	✓	0.4s	✓	0.4s	✓	3.4s	✓	0.6s	✗	1.8s
	mb-no-p2p-yes	3	✓	0.9s	✓	0.9s	✗	1.3s	✗	1.3s	✓	1.3s
	p2p-no-sb-yes	4	✗	4.0s	✓	4.1s	✗	5.3s	✗	5.3s	✗	6.7s
	mb-no-monob-no	3	✗	3.2s	✓	3.2s	✗	4.1s	✗	4.1s	✗	5.4s
	monob-no-mb-no	4	✓	1.3s	✓	1.3s	✗	1.9s	✗	1.9s	✓	1.9s
	Average			6.7s		5.8s		7.6s		7.1s		12.6s

Corollary.



Thank you!