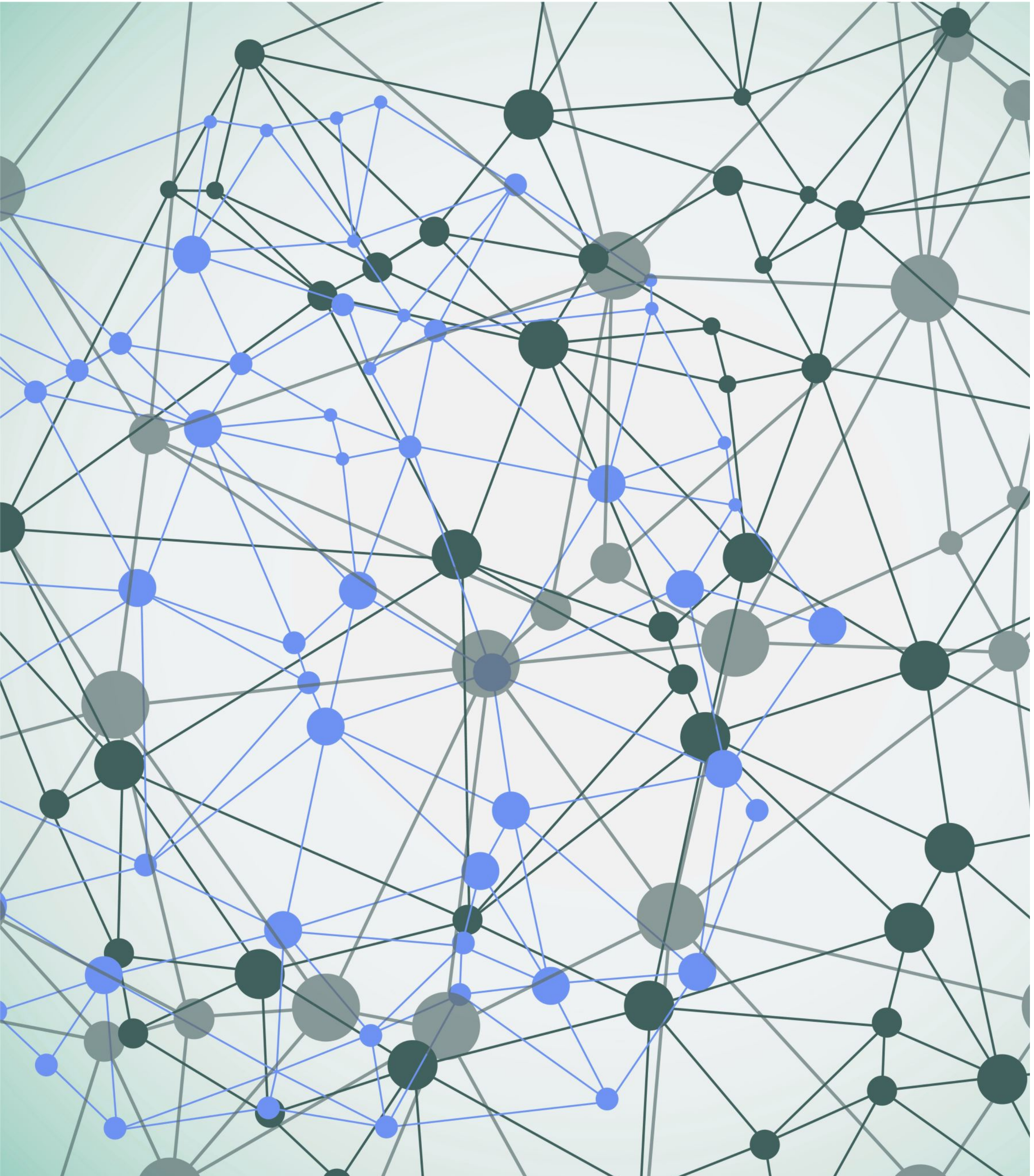

CRYPTO 2020

Order-Fairness for Byzantine Consensus

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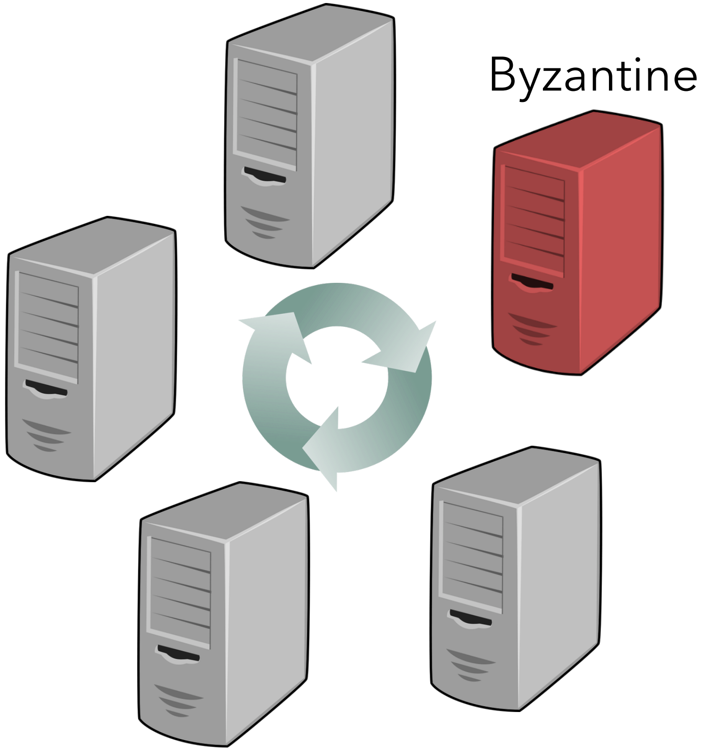
Joint work with
Fan Zhang,
Steven Goldfeder,
and Ari Juels

State Machine Replication (SMR)

also Byzantine consensus, linearly-ordered log

Transactions from clients



Consensus Nodes

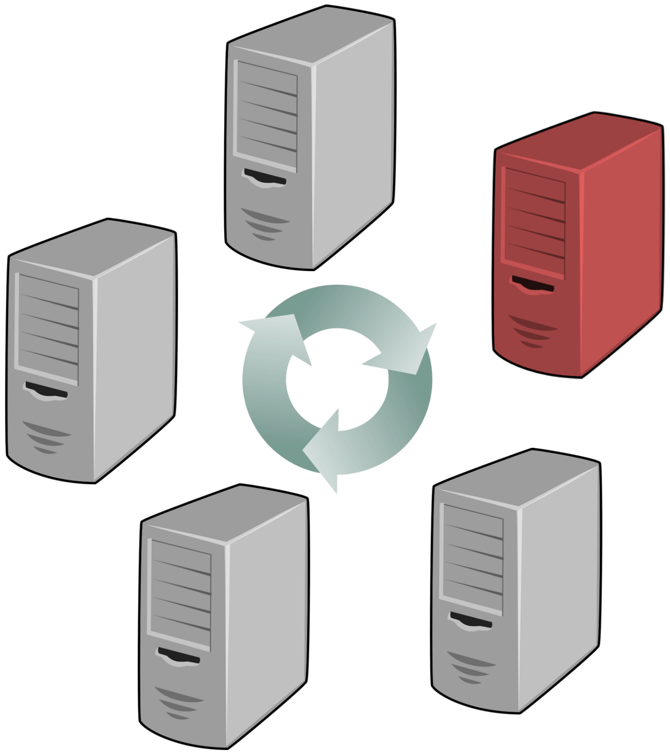
Agree on a consistent ordered transaction log

State Machine Replication (SMR)

also Byzantine consensus, linearly-ordered log

Consistency or **Safety**
Honest nodes output the same log

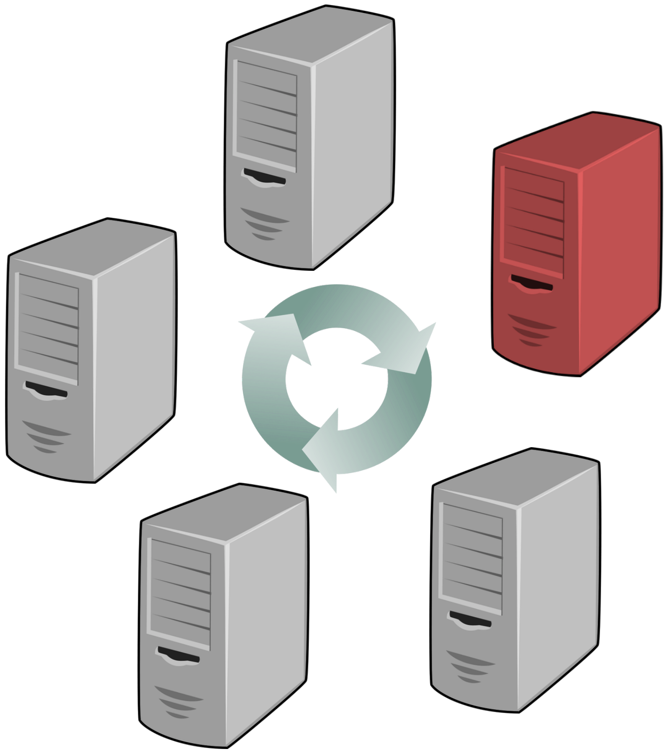
Liveness
New TXs are incorporated soon



State Machine Replication (SMR)

also Byzantine consensus, linearly-ordered log

- **No restriction** on the **actual ordering**
- Often **easy to manipulate**



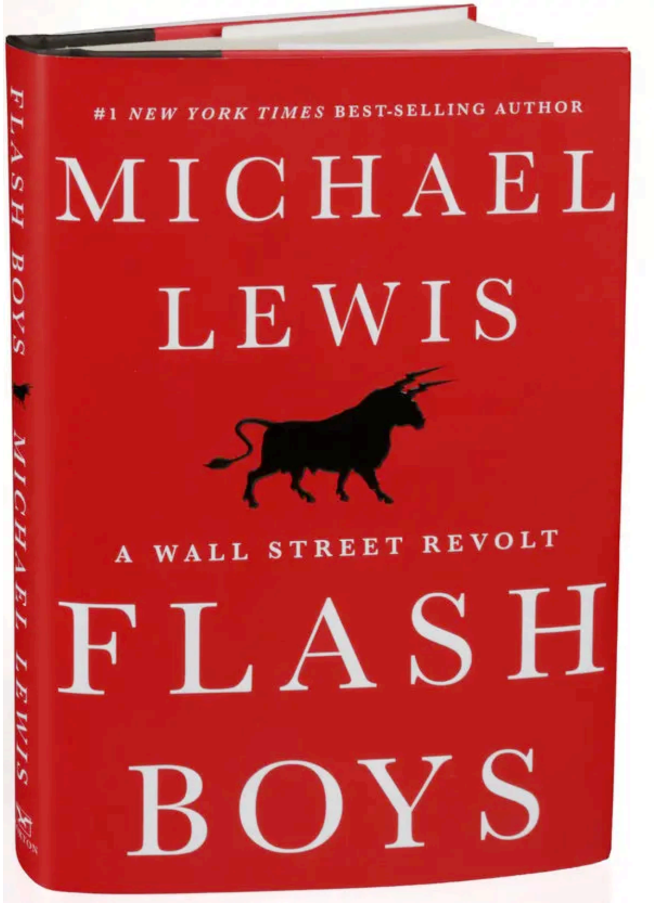
- Almost all classical consensus protocols are leader-based
  - E.g., PBFT, Paxos, Hotstuff etc.

- Leader node **can propose any ordering**
  - Adversarial leader can arbitrarily manipulate ordering

- No previous protocol guarantees fair ordering.

Why is ***fair ordering*** important?

Why is *fair ordering* important?



- 2014 exposé on ***high-frequency trading*** on wall street.
- HFT characteristics
  - Front-running
  - Arbitrage
- Investigation and fines after Lewis' book (FBI, SEC, etc.)

Why is *fair ordering* important?

- HFT back in a new form on decentralized exchanges
- Wild west without much regulation

Flash Boys 2.0: Frontrunning, Transaction Reordering, and Consensus Instability in Decentralized Exchanges

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Daian et al. (IEEE S&P 2020)

Why is *fair ordering* important?

Independent Theoretical Motivation

- Natural Analog of **Validity** condition in Byzantine Agreement (BA)
- Validity **forgotten** when BA generalized to SMR

If all honest nodes are input value v, **then** all honest nodes will agree on v.

Agreement Validity

$\Rightarrow$

If all honest nodes are input m_1 before m_2, **then** all honest nodes will agree on m_1 before m_2.

Order-Fairness

Comparison to current techniques

- Censorship Resistance [HoneybadgerBFT, Omniledger etc]
  - Reordering and insertion still possible
- Random leader election [Algorand, Ouroborous etc]
  - Adversarial leader can still order unfairly
- Threshold Encryption [HoneybadgerBFT]
  - Transactions ordered before content is revealed
  - Can still reorder transactions from colluding client first
  - Possible to blindly reorder

Order-Fairness is strictly stronger than previous notions

Defining Fair Ordering

Model

- Permissioned system with n nodes, f of which may be adversarial
- Clients **can** collude with protocol nodes

Model

- **External Network**
  - Communication between clients and protocol nodes
  - Clients send transactions to **all** nodes
  - Adversary $\mathcal{A}$ **not** in charge of message delivery

- **Internal Network**
  - Communication amongst protocol nodes
  - Adversary $\mathcal{A}$ handles all message delivery

Model: Synchrony Definitions

Δ_{ext} -External Synchrony

If a transaction is input to some node in round r,
then all honest nodes will receive it as input by round $r + \Delta_{ext}$.

Δ_{int} -Internal Synchrony

If a message is sent by an honest node in round r,
then all recipient(s) will receive it by round $r + \Delta_{int}$.

So how do we define the **fair ordering**?

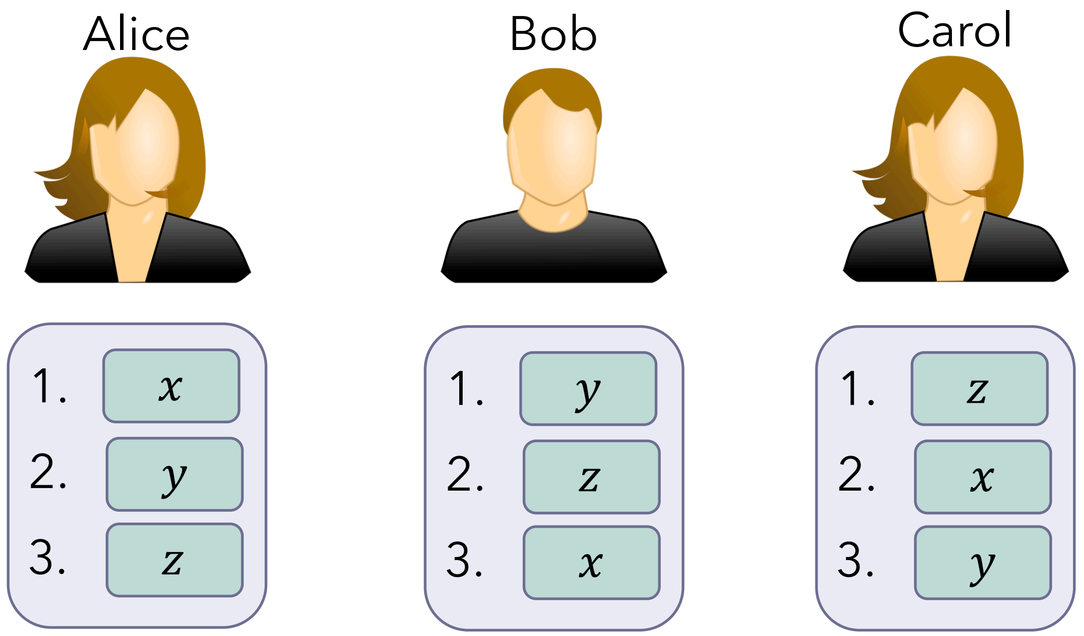
Definition (informal): γ-Receive-Order-Fairness

$\frac{1}{2} < \gamma \leq 1$

If γn nodes are input m_1 before m_2,
then all honest nodes will deliver m_1 before m_2.

Condorcet Paradox

- Global ordering can be **non-transitive** even when individual orderings are transitive



Condorcet Paradox

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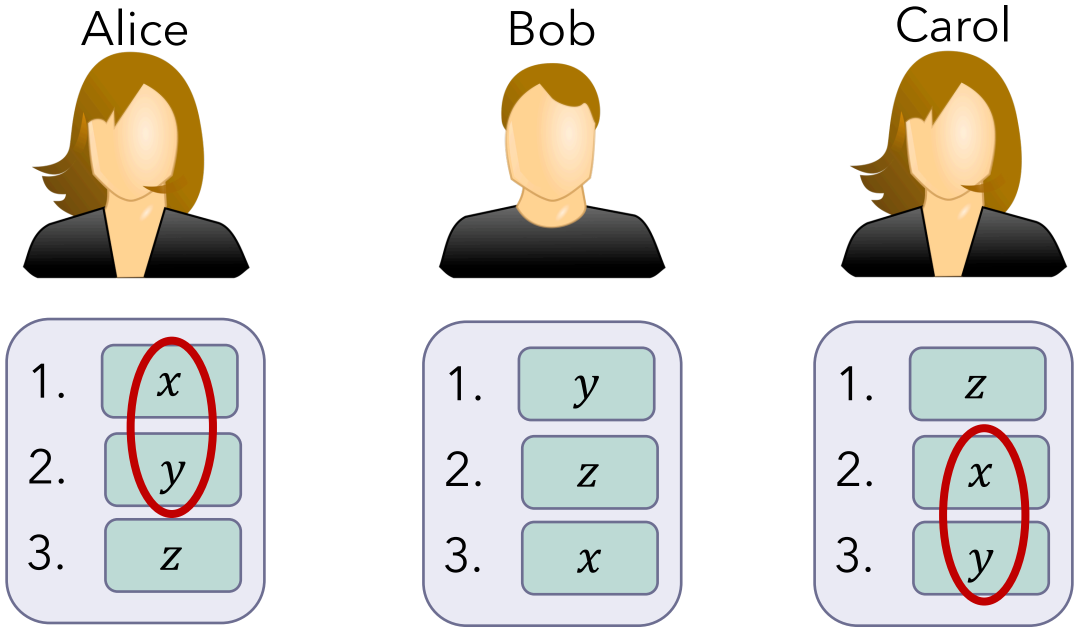

$x \ll y$

Condorcet Paradox

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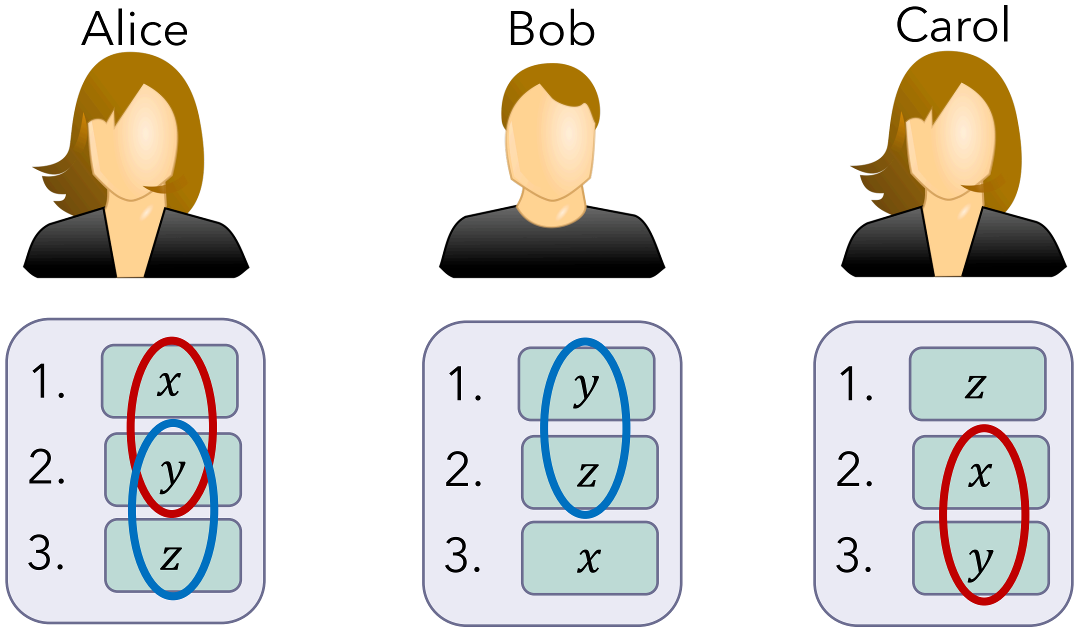

$x \ll y$

$y \ll z$

Condorcet Paradox

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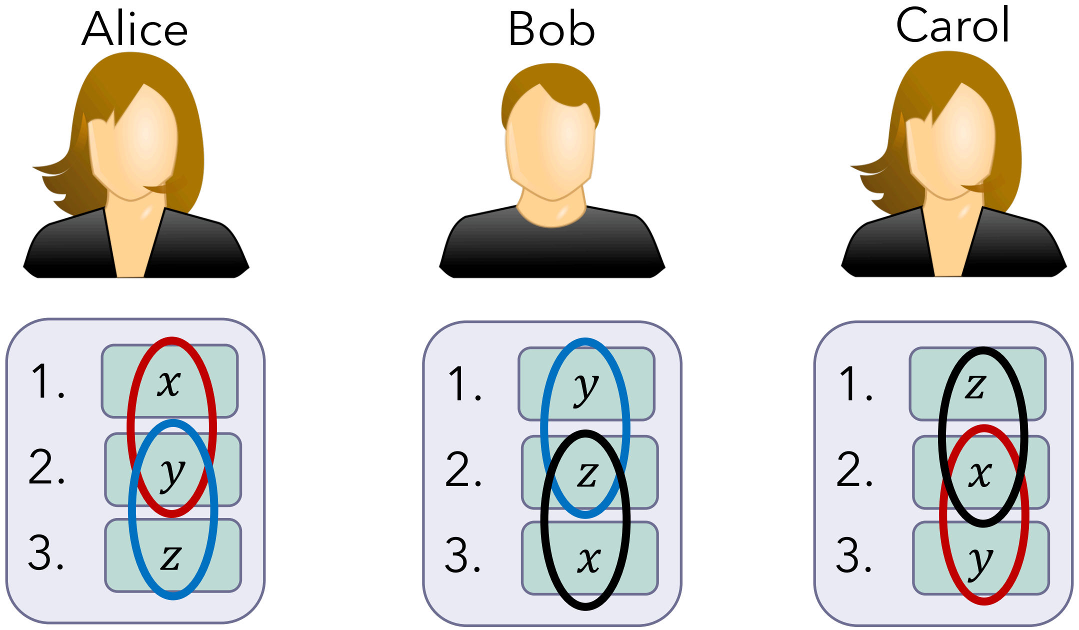

$x \ll y$

$y \ll z$

$z \ll x$

Condorcet Paradox

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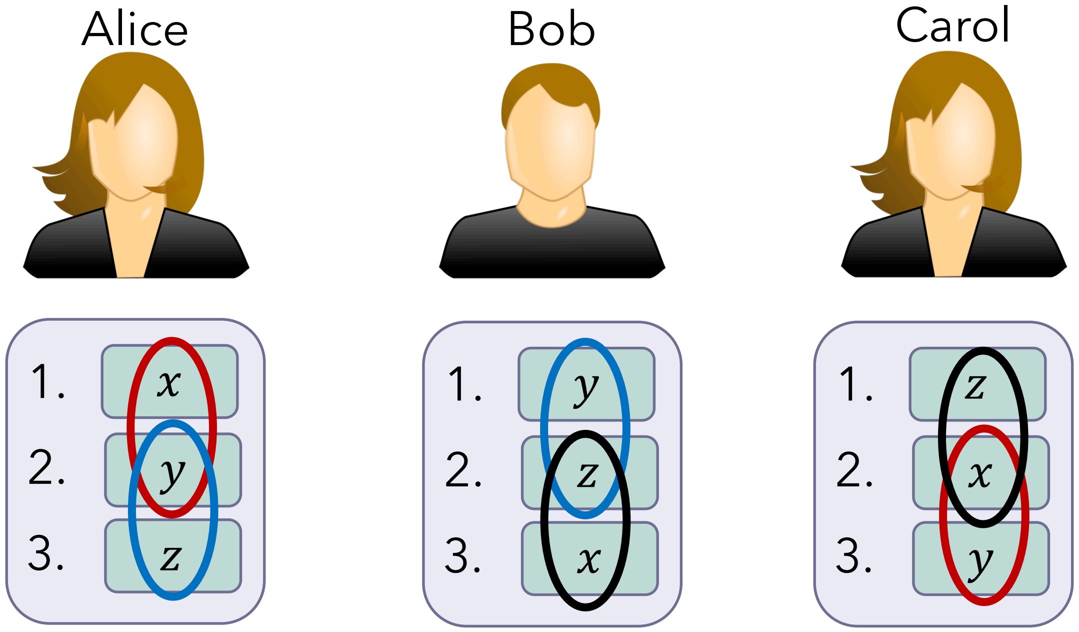

$x \ll y$

$y \ll z$

$z \ll x$

Cyclic Ordering!

<u>Theorem</u> (informal): **Impossibility of Receive-Fairness**

For any $n, f \geq 1$ and γ, no protocol can achieve all of consistency, liveness and γ-receive-order-fairness when $\Delta_{ext} \geq n$.

Block-Order-Fairness

Definition (informal): γ-Block-Order-Fairness

If γn nodes are input m_1 before m_2,
then all honest nodes will deliver m_1 no later than m_2.

Block-Order-Fairness

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If γn nodes are input m_1 before m_2,
then all honest nodes will deliver m_1 no later than m_2.

- Key Idea: Deliver transactions with non-transitive ordering in the same block

Why can't we just order based on **median** timestamp?

- A single adversarial node can cause unfair ordering

Round Number	A	B	C	D	E
1	tx_1	tx_1			
2	tx_2	tx_2			tx_1
3					tx_2
4			tx_1	tx_1	
5			tx_2	tx_2	

Why can't we just order based on **median** timestamp?

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Round Number	A	B	C	D	E
1	tx_1	tx_1			
2	tx_2	tx_2			tx_1
3					tx_2
4			tx_1	tx_1	
5			tx_2	tx_2	

$$2 = med(tx_1) \leq med(tx_2) = 3$$

Why can't we just order based on **median** timestamp?

- A single adversarial node can cause unfair ordering

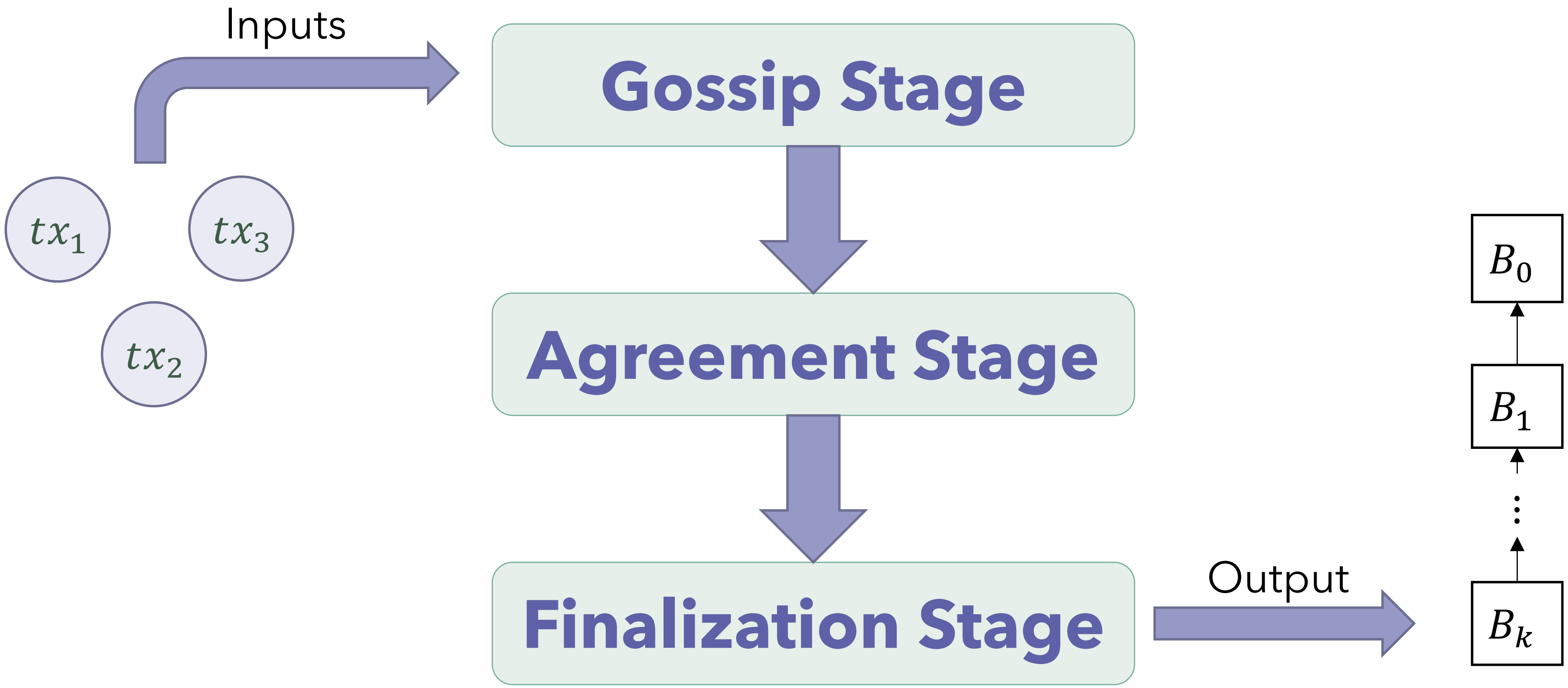
	A	B	C	D	E
1	tx_1	tx_1			
2	tx_2	tx_2			tx_2
3					tx_1
4			tx_1	tx_1	
5			tx_2	tx_2	

Round Number

$$3 = med(tx_1) \nleq med(tx_2) = 2$$

Fair Ordering Protocols

Aequitas: A Fair-Ordering Protocol



The Gossip Stage

(1) Honest nodes broadcast transactions they to all nodes as they are received

(2) Honest nodes store broadcasts received from other nodes in *local logs* $locallog_i^j$ contains i's view of broadcasts by j

Guarantees that honest nodes have **consistent** local logs

The Gossip Stage

- **FiFo (First-In-First-Out) Broadcast**
  - Messages broadcast by an honest sender are delivered in the **same order** as they were broadcast
  - Messages broadcast by an adversarial sender are delivered in a consistent order by all honest nodes

  - Can be realized from standard reliable broadcast [HDvR 07]

Agreement Stage

- Agree on which local logs to use to order a transaction

- Can be done using standard Byzantine agreement

Guarantees that honest nodes use the same local logs to *finalize* a transaction

Finalization Stage

- The finalization stage orders the transaction in the final output log
- Leaderless
  - No extra communication

Finalization Stage

Ordering two transactions

- If many (e.g., $\gamma n - f$) local logs contain tx' before tx, then tx is said to **wait** for tx'
- Relations between transactions are viewed in a **dependency** or **waiting graph**.
  - Vertices represent transactions
  - Edge (a,b) represents b waiting for a

Leaderless Finalization

What if there is no clear winner in the two transactions?

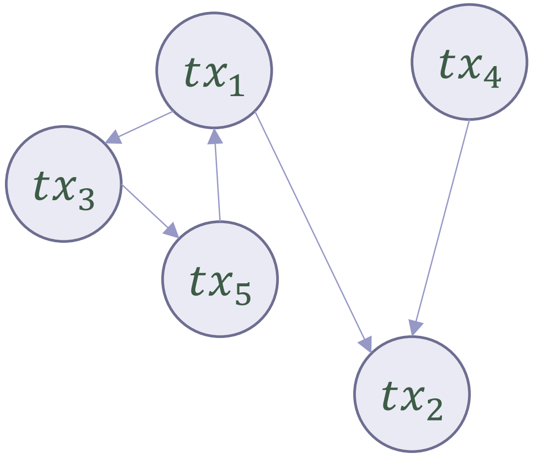
Two problems to solve

1. Graph may not be complete or even connected.
   - Some transactions may not be comparable
2. Graph may not be acyclic.

Leaderless Finalization

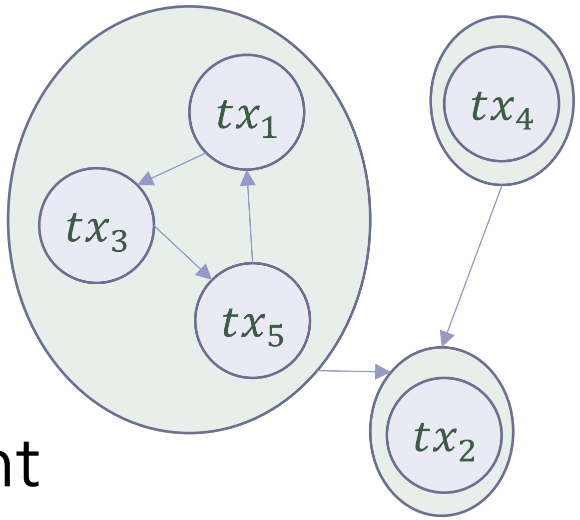
<u>Key Idea</u>

- Wait for common descendant for transactions without an edge in the graph
- Order using maximum number of dependents



Leaderless Finalization

- Graph can still have cycles
- To get a total ordering, compute the **condensation** graph by collapsing the strongly-connected components
- Deliver transactions in the same component into the **same block**.



- Synchronous protocol requires $\boldsymbol{n} > \frac{\mathbf{2}\boldsymbol{f}}{\mathbf{2}\boldsymbol{\gamma}-\mathbf{1}}$
  - i.e., $n > 2f$ even when $\gamma = 1$

- Asynchronous protocol requires $\boldsymbol{n} > \frac{\mathbf{4}\boldsymbol{f}}{\mathbf{2}\boldsymbol{\gamma}-\mathbf{1}}$

Some Caveats

- Only Achieves **Weak-Liveness**
  - New transactions must be input *sufficiently late* in order to deliver current transactions
  - Conventional Liveness achieved when external network has *small synchrony bound*

Some Caveats

- Adversary can unfairly order if it controls the **entire** Internet, i.e. if it can also control a client's connection to the consensus protocol nodes

- In our modeling, this is handled by assuming adversary **does not** control the external network

A general order-fairness compiler

- FiFo-broadcast and Byzantine Agreement are weak primitives
  - They can be realized from any consensus protocol

- General compiler that takes **any** consensus protocol and transforms it into one that also provides order-fairness

Final Thoughts

- Our work is the first to formalize order-fairness and provide protocols that realize it
- Order-Fairness is important for many blockchain applications
  - Decentralized exchanges (2.4 billion USD market)
  - ICO token sales (12 billion USD market)
  - Decentralized Finance in general

Thank you

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ia.cr/2020/269