Consensus

Via the information theoretic lens
(Part 1)

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Group blog: Decentralized Thoughts

Consensus

Via the information theoretic lens

A fundamental problem that captures the essence of coordination in the face of failures

- Multi Party Computation
- Used in many large-scale compute infrastructures
- Cryptocurrency and blockchain disruption

Deep connections between (information theoretic) cryptography and (information theoretic) distributed computing

- Lower bounds for consensus are lower bounds for MPC
- Broadcast (consensus) is used for MPC
- MPC techniques are used for obtaining efficient (randomized) consensus protocols

My background:

- I do research in algorithms and distributed computing
- Wannabe Cryptographer

“The proof-of-work chain is a solution to the Byzantine Generals’ Problem. I’ll try to rephrase it in that context”

Satoshi Nakamo, email archive, 2008

"Bitcoin is the first practical solution to a longstanding problem in computer science called the Byzantine Generals Problem"

Marc Andreessen, Why Bitcoin Matters, NYT, 2014

Consensus: Approach for today and tomorrow

Traditional way to learn distributed computing and fault tolerance: learning isolated Islands

Today: a foundational view on traditional (and new) protocols

- Not a historical survey
- Not islands, highlight connections
- Understanding the connections allows better abstractions, theory, protocols, systems

Why via the information theoretic lens?

- Everything should be made as simple as possible, but not simpler

On Learning

- First via intuition then via rigor
- Learning by asking
- Learning by doing (no shortcuts)

Consensus: plan for today and tomorrow

Focus on information theoretic solutions

A call for multidisciplinary research

Adversary and Network Models

Consensus: definitions, upper and lower bounds

Paxos (Synchrony) → Paxos (Partial Synchrony)

↓ GradeCast

Byzantine Paxos (Synchrony)

↓ Multiword + MVSS + RandElect

O(1) exp time Byzantine Paxos (Synchrony)

Paxos (Partial Synchrony)

↓ Reliable Broadcast

Byzantine Paxos (Partial Synchrony)

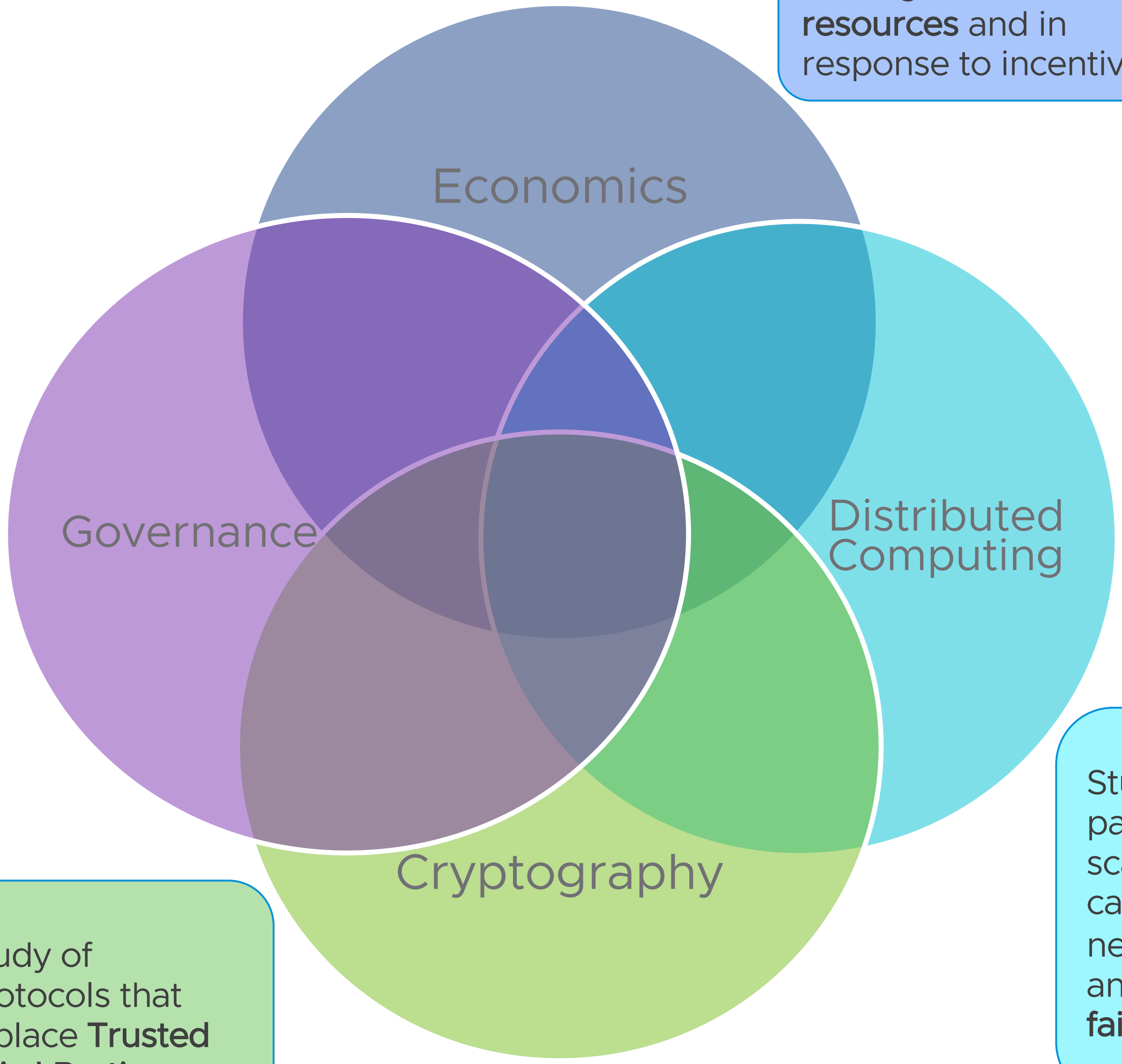
↓ A-MW + A-VSS + ARandElect

O(1) exp time Byzantine Paxos (Asynchrony)

Study of decision making with **scarce resources** and in response to incentives

Political science, Public policy, Law

Study social norms, institutions, regulations



Study how multi party and large-scale systems can overcome network delays and **tolerate failures**

Study of protocols that replace **Trusted Third Parties**

Distributed Computing 101

Synchrony, Asynchrony and Partial synchrony and flavors of Partial Synchrony

Asynchrony: adversary can delay messages by any finite amount

Synchrony: adversary can delay messages by some known Δ

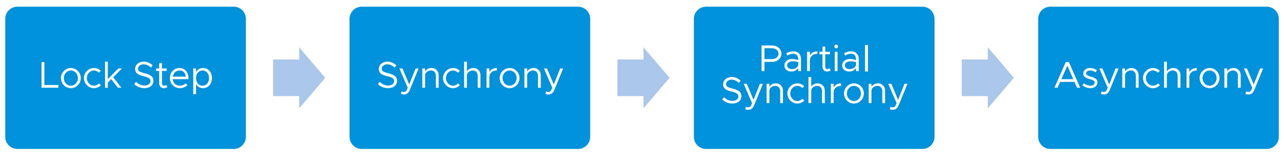
- lock step: all messages take exactly $\Delta=1$

[DLS88]: Partial Synchrony (Global Stabilization Time):

- adversary can delay messages by any finite amount
- until some unknown finite point in time called GST (Global Stabilization Time)
- adversary can delay messages by some known Δ

[DLS88]: Partial Synchrony (Unknown Latency):

- adversary must set Δ at the beginning of the execution



Power of the Adversary

Blog post

Passive adversary (semi honest, honest-but-curious)

Crash failure

Omission failure (“bubble adversary”)

Byzantine failure (malicious)

- Covert (malicious but does not want to be detected)
- **ε**-covert (malicious but only if probability of detection is low)

Passive → Crash → Omission → Covert → Byzantine

Consensus [Lamport etal 78]

Parties have initial input

Can send messages via point-to-point channels

Termination (Liveness): In the end of the protocol each party must *decide* on a value

Safety: No two non-malicious parties decide on different values

Trivial: Always decide a default value

Make the problem not trivial:

- *Validity:* If all the non-faulty have the same input, then this must be the decision value
- *Fair Validity*: With constant probability an input of a non-faulty server is decided upon

Nor required:

- *Security*: that the view of the adversary in the ideal world is indistinguishable from a simulated view generated from the view of the adversary in the real world

Consensus: Broadcast vs Agreement

Safety: all non-malicious parties decide the same value

Liveness: all non-faulty parties eventually decide

Broadcast:

- Designated sender P*
- Validity: if the sender is non-faulty with input m then m is the decision value

Agreement:

- *Validity* :If all the non-faulty have the same input, then this must be the decision value
- *Fair Validity*: With constant probability an input of a non-faulty server is decided upon

Broadcast from Agreement (in synchrony):

- Given agreement, sender sends to to all, then parties run agreement

Agreement from Broadcast (in synchrony):

- Given broadcast (and $f<n/2$), each party broadcasts its input, then use say majority

Goal:

- Upper bounds for Agreement
- Lower bounds for Broadcast

Consensus results in one slide: deterministic

	Synchrony		Partial Synchrony	
Crash		$n>f$ (primary backup)	$n \leqq 2f$ (DLS “split”)	
Ommision	$n \leqq 2f$ (uniform)	$n>2f$ (Sync Paxos)		$n>2f$ (Paxos)
Byzantine (cannot simulate)		$n>2f$ (Auth Byz)	$n \leqq 3f$ (DLS “split”)	
Byzantine (unbounded)	$n \leqq 3f$ (FLM the “hexagon”)	$n>3f$ (Sync Byz)		$n>3f$ (PBFT)

FLP85: every protocol solving asynchronous consensus for 1 crash must have an infinite execution

LF82: every protocol solving synchronous consensus for f crashes must have a f+1 round execution

DR82: deterministic consensus needs Ω(f^2) messages

Consensus results in one slide: randomized, with private channels

	Synchrony		Partial Synchrony		Asynchrony	
Crash		n>f (primary backup)	n≦2f (DLS88 "split brain")			
Ommision	n≦2f (uniform)	n>2f, O(1) expected time		n>2f, O(1) expected time		n>2f, O(1) expected "time"
Byzantine (cannot simulate)		n>2f, Auth, O(1) exp. Time (KK06)	n≦3f (DLS88 "split brain")			
Byzantine (unbounded)	n≦3f (FLM86 the "hexagon")	n>3f, O(1) expected time (MF88, KK06)		n>3f, O(1) expected time	VSS n≦4f must have error (BKR94)	1. n>4f, O(1) exp. "time" (BCG93) 2. n>3f, error, O(1) (CR93) 3. n>3f, no error, poly exp. "time" (ADH)

Primary-Backup in the omission model [Lamport, Oki Liskov, DLS,]

The omission model

- There are *n* replicas
- The adversary corrupts *f* replicas which can fail by not receiving or not sending each message

Systems works in *views*, in each view

- One replica is designated as Primary
- All the rest of the replicas are Backups

For simplicity: in view *i* the primary is *(i mod n)*

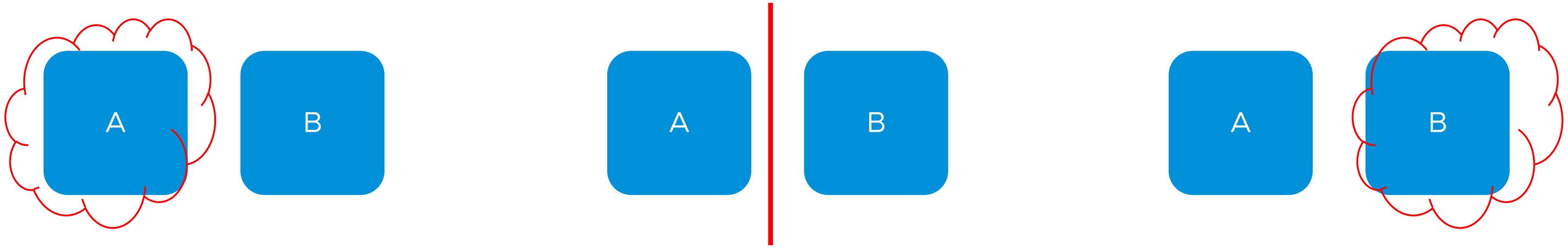
Many other options:

- Randomized leader election
- Back-off protocols

Primary-Backup in the omission model: Lower bound for $n \leq 2f$ (DLS 88)

n=2 and one omission failure

1. In Partial synchrony
2. In Synchrony, assuming *uniform* consensus
   - Safety for omission faulty parties



Learning by Doing

3 parties, each with input in {0,1}

Adversary controls one party (ommision)

Write a protocol for consensus:

- (Uniform) Safety: no two decide different vlaues
- Liveness: All non-fualty parties dedcide
- Validity: If all the non-faulty have the same input x, then x is the decision value

Primary-Backup in the omission model: Foundations

The only math you will need:

- Quorum intersection (pigeonhole principle)
- Given a set of n elements: two sub-sets of $n-f$ elements must intersect at $n-2f$ elements
- For $n=2f+1$, any two sets of $f+1$ must intersect at one element
- For $n=3f+1$, any two sets of $2f+1$ must intersect at $f+1$ elements

Primary-Backup in the omission model: What could possibly go wrong?

Primary chooses its input: *x*

- decide *x*
- Sends *<decide x>* to all replicas

Primary chooses its input: *x*

- Sends *<propose x>* to all replicas
- decide *x*

Main challenge: the first primary may decide *x*, but the next primary decides *x'*

Primary-Backup in the omission model: View Change protocol

Use a **view change** protocol to guarantee safety:

- Before a new primary starts, it runs a view change protocol
- If there is any possibility that some value was previously decided, the new primary must *adopt* that value

Three challenges:

1. Only decide a value after you are sure later primaries can recover and adopt this value
2. Make the view change safe: only choose safe values to adopt
3. Make the view change live: don't get stuck waiting

Primary-Backup:
Algorithm structure – three simple parts!

1. Normal case protocol
   – allow the primary to decide
2. View change trigger protocol
   – trigger the replacement of a primary
3. View change protocol
   – a way for a new primary to make safe choices

Primary-Backup in the omission model: Normal case

1. Send:
    - Primary (of view v) sends <propose x in view v> to all replicas
2. Ack:
    - Replica sends <ack x in view v> to all
        - Unless it has moved to a higher view
3. Decide:
    - Replica wait for n-f messages of <ack x in view v> to *decide x*

View Change Trigger: Revolving coordinator, random leader, stable leader

View change to replace a failed primary

- Use synchronized heartbeat mechanisms to have all replicas move to the next view
- For now: simple revolving coordinator
- Later: random leader election
- In practice: use a stable leader for many consensus decisions

View Change

Maybe the previous primary caused a decision?

Maybe one of the previous primary caused a decision?

New primary may need to adopt a value instead of choosing its own

Quorum intersection to the rescue:

- If some primary decided, then it used a write quorum (of n-f)
- So reading from a quorum of n-f:
  - Is safe: primary will see intersection (since n-2f>0)
  - Is live: can always be done

Primary-Backup in the omission model: Normal case

1. Send:
   - Primary (of view v) sends <propose x in view v> to all replicas
2. Ack:
   - Replica sends <ack x in view v> to all
     - Unless it has moved to a higher view
3. Decide:
   - Replica wait for n-f messages of <ack x in view v> to *decide x*

View Change: from view v to view $v+1$

New primary for view $v+1$:

- (Send message *<view change for view v+1> to all)*
- A replica responds with *<my maximal propose is x' at view v'>*
  - –Using the *propose* with maximal view v' it heard
  - –Or send *<null at view 0>* if heard no propose

Primary waits for $n-f=f+1$ responses:

- **Adopts** the proposed value associated with the *maximal view number*, or
- Uses its own value if every message is *<null at view 0>*

Primary-Backup in the omission model for n>2f

Three simple parts

1. Normal case protocol
   - Send: Primary (of view v) sends <propose x in view v> to all replicas
   - Ack: Replicas send <ack x in view v> to all (update their maximal propose)
     - Unless it has moved to a higher view
   - Decide: Replicas wait for n-f messages of <ack x in view v> to decide x
2. View change trigger protocol
   - Revolving coordinator: wait for enough time (4 rounds) to replace primary with next primary
3. View change protocol
   - Each replica sends to new primary <my maximal propose is x’ at view v’>
     - Using the propose with maximal view v’ it heard
     - Or send <null at view 0> if heard no propose
   - Primary waits for n-f responses:
     - Adopts the proposed value associated with the maximal view number; or
     - Uses its own value if every message is <null at view 0>

Safety

Let v^* be the first view that some replica decides, say on value x

Base case: all decisions in view v^* must be to x

By induction on $v>v^*$: any primary must adopt the value x

- Set G of f+1:
  - Each member of G: maximal propose is on value x
  - Each member outside of G: has an equal or higher maximal propose than any member of G, then it must be on value x

This argument does not use synchrony! It works for asynchrony

Termination (liveness)

Claim: Eventually all non-faulty replicas will learn the decision value

Any faulty primary that does not make progress will eventually be replaced

A non-faulty primary will cause termination

(here we use synchrony)

Primary-Backup in Partial Synchrony

Asynchrony: adversary can delay messages by any finite amount

Synchrony: adversary can delay messages by some known finite value Δ

Partial Synchrony:

- adversary can delay messages by any finite amount
- until some unknown finite point in time called GST (Global Stabilization Time)
- adversary can delay messages by some known finite value Δ

The Partial Synchrony paradigm:

- Safety holds in asynchrony
- Termination holds in synchrony
- Extremely successful in industry
- Gateway to asynchrony

Byzantine Adversaries!

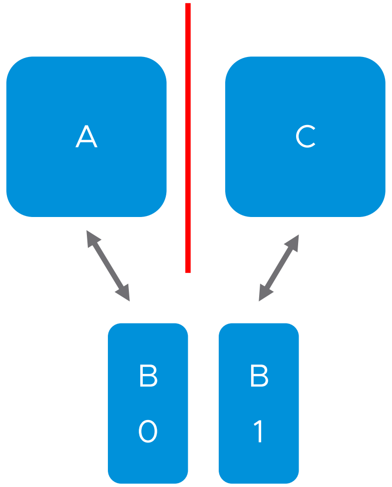
Can we reach agreement in synchrony for $n=2f+1$?

Can we reach agreement in partial synchrony for $n=2f+1$?

Byzantine adversaries

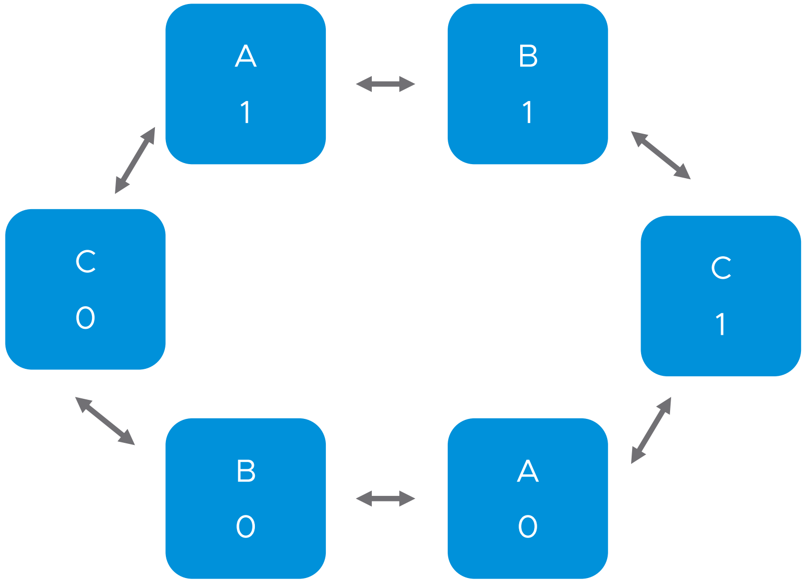
n=3, f=1 is impossible

In partial synchrony, the split-brain attack [DLS]:



In synchrony, the hexagon [FLM]:

- Any edge defines a legal world with two non-faulty parties around edge
- Non-faulty party decide the same for left edge and right edge worlds



Byzantine Model in Partial Synchrony

Two primary attacks:

- Equivocate: tell different replicas different things
- Unsafe: adopt a non-safe value after view change
  - Invent a value
  - Choose a non-maximal value

Solution approach:

- Add a sub-protocol to force primary to act like omission (no equivocation)
- Add a sub-protocol to guarantee the primary will fail if using un-safe values
  - Key idea: replica that sent a value *lock* on it, primary has to prove value is real

Byzantine Primary-Backup (at view v):

Straw Man 1: with n=3f+1, what could possibly go wrong?

Primary can send different values to different replicas ☹, need to block equivocation

1. Primary sends *<send, (value, v)>* to all
2. Replica accepts *<send, (value, v)>, then*
   - Set lock:=v; lock value:=value
   - Sends *<lock, (value, v)>* to all
3. Replica gathers *n-f <lock, (value, v)>, then*
   - Decide (value)

The good: cannot decide different values

The bad: If non-faulty commits, there may be conflicting locks for the view change

- How do we choose which one?
- Want all the locks to be the same

Non-Equivocation:

Goal: given a (potentially) Byzantine primary, **transform** its send-to-all to a (potentially) omission fault primary send-to-all

n>3f

1. Primary sends *<send (value,v)>* to all
2. Replica sends *<echo (value,v)>* to all for the *first <send (value,v)>* it hears from primary
3. If a replica sees n-f *<echo (value,v) ,proof> from different replicas,*
    - *then* it **accepts** *<send (value,v)>*

Non-Equivocation: Proof

Claim: If a replica accepts *<send (value,v) >* then no replica will accept *<send,(value',v)>* with $value \neq value'$

Proof by contradiction:

1. One replica sees *n-f <echo* (*value,v)>* and another sees *n-f <echo* (*value',v)>*
2. The intersection is at least *f+1*, so at least one non-faulty in the intersection
3. Non-faulty will send at most one echo per view

Byzantine Primary-Backup (at view v):

Straw Man 2: with equvocation

Primary can send any value it wants ☹, how can we protect a decision value?

1. Primary sends *<send, (value, v)>* to all
2. Replica receives *<send, (value, v)>,* then
   - If first send from primary in view v, then
   - sends : *<echo, (value, v)>* to all
3. Replica gathers *n-f <echo, (value, v)>, then*
   - Set lock:=v; lock value:=value
   - Sends *<lock, (value, v)>* to all
4. Replica gathers *n-f <lock, (value, v)>, then*
   - Decide (value)

The good: all locks will be the same

The bad: how do we force the new primary to choose the highest lock?

Recall: View Change from view *v* to view *v+1*

New primary for view *v+1*:

- A replica responds with *<my maximal propose is x' at view v'>*
  - Using the *propose* with maximal view *v'* it heard
  - Or send *<null at view 0>* if heard no propose

Primary waits for *n-f* responses:

- **Adopts** the proposed value associated with the *maximal view number*, or
- Uses its own value if every message is *<null at view 0>*

Can we force new primary to adopt the maximum value?

- Information theoretically possible, a PBFT type view change (see Castro's thesis)

Can Primary prove the (value) its using was indeed sent in some view u<v?

- Yes, this will allow a Tendermint, HotStuff type view change

Safety:

- Replica that is locked on (value, v) will Ignore primary with (value',v') if v'<v
- f+1 locked replicas will block a malicious primary

Force primary to prove: the (value) its using was indeed sent in some view u<v

Primary of view u could sign its message!
- We don't have signatures ☹

We have non-equivocation on primary, would like stronger property:
- If I **accept** the primary message then all parties **weakly accept** (and eventually **accept** it)
- Bracha's Reliable Broadcast, (Micali and Feldmans's Gradecast)

1. Primary sends *<send (value,v)>* to all
2. Replica sends *<echo1 (value,v)>* to all for *first <send (value,v)>* it hears from primary
3. If a replica sees n-f *<echo1 (value,v) ,proof> from different replicas,*
   - *then* it sends *<echo2 (value,v)> to all*
4. If a replica sees n-f *<echo2 (value,v) ,proof> from different replicas,*
   - *then* it accepts *<send (value,v)>*
5. If a replica sees f+1 *<echo2 (value,v) ,proof> from different replicas,*
   - *then* it weakly accepts and sends *<echo2 (value,v)> to all*

Reliable Broadcast (at view v):

1. Primary sends *<send (value,v)>* to all
2. Replica sends *<echo1 (value,v)>* to all for *first <send (value,v)>* it hears in view v from Primary
3. If a replica sees n-f *<echo1 (value,v) ,proof> from different replicas,*
   - *then* it sends *<echo2 (value,v)> to all*
4. If a replica sees n-f *<echo2 (value,v) ,proof> from different replicas,*
   - *then* it accepts *<send (value,v)>*
5. If a replica sees f+1 *<echo2 (value,v) ,proof> from different replicas,*
   - *then* it weakly accepts and sends *<echo2 (value,v)> to all*

Claim 0: all accepted values are the same (non-equivocation)

Claim 1: If a non-fualty accepts (in synchrony), then all non-fauty will at least weakly accept

Claim 2: If a non-fauty accepts (in asynchrony), then all non-fualty will eventually accept

Byzantine Primary-Backup (at view v):

Straw Man 3: with Reliable Boradcast

Primary can prove its using a real value

1. Primary sends *<send, (value, v)>* to all
2. Replica receives *<send, (value, v)>*, then
   - If first send from primary in view v, then
   - sends : *<echo1, (value, v)>* to all
3. Replica gathers *n-f <echo1, (value, v)>, then*
   - Sends *<echo2, (value, v)>* to all
4. Replica gathers *n-f <echo2 (value, v)>, then (at view v)*
   - Set lock:=v; lock value:=value
   - Sends *<lock, (value, v)>* to all
5. Replica gathers *n-f <lock, (value, v)>, then*
   - Decide (value)

Replica gathers *f+1 <echo2, (value, v)>, then*
- If did not send echo2
- Sends *<echo2, (value, v)>* to all

View change:
- **Replica**:
- Sends its lock and lock value

- **Primary**:
- accept a lock (value',v') if also n-f *<echo2, (value, v)>* arrive
- Wait for n-f such locks
- Choose the value with the highest lock (view)

Byzantine Primary-Backup (at view v):

with Reliable Boradcast and locking

1. Primary sends *<send, (value, v, u)>* to all
2. Replica receives *<send, (value, v, u)>*,
   - If u>=lock, n-f *<echo2, (value, u)>* arrive, and first send from primary in view v, then
     - sends : *<echo1, (value, v)>* to all
3. Replica gathers *n-f <echo1, (value, v)>, then*
   - Sends *<echo2, (value, v)>* to all
4. Replica gathers *n-f <echo2 (value, v)>, then (at view v)*
   - Set lock:=v; lock value:=value
   - Sends *<lock, (value, v)>* to all
5. Replica gathers *n-f <lock, (value, v)>, then*
   - Decide (value)

Replica gathers *f+1 <echo2, (value, v)>, then*

- If did not send echo2
- Sends *<echo2, (value, v)>* to all

View change:

- **Replica**:
- Sends its lock and lock value

- **Primary**:
- accept a lock (value',v') if also n-f *<echo2, (value, v)>* arrive
- Wait for n-f such locks
- Choose the value with the highest lock (view)

Safety

Let v^* be the first view that any replica decided (value X, view v^*)

Prove by induction that any accepted send of view $v \geq v^*$ must be consistent with value X

- for base case due to non-equivocation

Induction argument:

- Existence of a *core* of *f+1* non-faulty that have a lock on view at least v* with value X
  - Base case: core is the n-2f out of the n-f that sent a lock to decider
- Any accepted value from a primary of view at least v* must be X
  - By induction, core will block any other value
  - Core members can only gain a higher lock but then primary uses the same value.

Liveness

If a non-faulty primary is elected and the system is synchronous

Primary will hear locks from *all* non-faulty and will choose the maximum one

All non-faulty replicas will also see same lock and hence will echo1 the primary

vmware®

Responsivness: liveness in asynchrony

In asynchrony the non-faulty primary can wit for n-f responses during view change

May miss a lock of a non-fualty

- Will casue a livenss problem!

Solution: add one more round ☺

- After seeing n-f echo2, send ***key***
- After seeing n-f keys, send ***lock***
- If I have a lock then there are at least f+1 non-faulty that have a key
- During view change, ask for keys

Responsive Byzantine Primary-Backup (at view v):

Information Theoretic HotStuff

1. Primary sends *<send, (value, v, u)>* to all
2. Replica receives *<send, (value, v, u)>*,
   - If u>=lock, n-f *<echo2, (value, u)>* arrive, and first send from primary in view v, then
     - sends : *<echo1, (value, v)>* to all
3. Replica gathers *n-f <echo1, (value, v)>, then*
   - Sends *<echo2, (value, v)>* to all
4. Replica gathers *n-f <echo2 (value, v)>, then (at view v)*
   - Set key:=v; key value:=value
   - Sends *<key, (value, v)>* to all
5. Replica gathers *n-f <key, (value, v)> and n-f <echo2 (value, v)>, then (at view v)*
   - Set lock:=v
   - Sends *<lock, (value, v)>* to all
6. Replica gathers *n-f <lock, (value, v)>, then* Decide (value)

Replica gathers *f+1 <echo2, (value, v)>, then*
- If did not send echo2
- Sends *<echo2, (value, v)>* to all

View change:
- **Replica**:
- Sends its key and key value

- **Primary**:
- accept a key (value',v') if also n-f *<echo2, (value, v)>* arrive
- Wait for n-f such key
- Choose the value with the highest key (view)

Byzantine Paxos: adding randomness

Elect a random primary

Revolving coordinator

- After f view changes (O(f) rounds) a non-faulty primary will be elected

Assume we have a *oblivious leader election* functionality

- At least f+1 honest must request for functionality to start
- Each party i outputs a leader L(i)=j
- With probabilty at least ½ (can use any constant) :
  - –all non-fualty output the same value j and,
  - –j was non-faulty before functionality started

Good for a static adversary

Adaptive adversary will adaptivly corrupt that chosen primary ☹

Byzantine Paxos: adaptive adversaries

Everyone is a Priamry ☺

Adaptive adversary will shoot down the primary

Solution:

- Let everyone be a primary
- Then choose who the real primary is in hindsight (and all other are just decoys)

Liveness: with constant probability a good primary is chosen

Safety:

- In hindsight, looks like a single primary each view
- If a faulty primary or a confusion of primaries is chosen then this is just like a faulty primary
  - Safety is maintained!

Responsive Byzantine Primary-Backup (at view v):

Determinstic version

1. Primary sends *<send, (value, v, u)>* to all
2. Replica receives *<send, (value, v, u)>,*
   - If u>=lock, n-f *<echo2, (value, u)>* arrive, and first send from primary in view v, then
     - sends : *<echo1, (value, v)>* to all
3. Replica gathers *n-f <echo1, (value, v)>, then*
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4. Replica gathers *n-f <echo2 (value, v)>, then (at view v)*
   - Set key:=v; key value:=value
   - Sends *<key, (value, v)>* to all
5. Replica gathers *n-f <key, (value, v)> and n-f <echo2 (value, v)>, then (at view v)*
   - Set lock:=v
   - Sends *<lock, (value, v)>* to all
6. Replica gathers *n-f <lock, (value, v)>, then*
   - Decide (value)

Replica gathers *f+1 <echo2, (value, v)>, then*

- If did not send echo2
- Sends *<echo2, (value, v)>* to all

View change:

- **Replica**:
- Sends its key and key value
- **Primary**:
- accept a key (value',v') if also n-f *<echo2, (value, v)>* arrive
- Wait for n-f such key
- Choose the value with the highest key (view)

Responsive Byzantine Primary-Backup (at view v):

with random leader election

1. Each party as Primary, sends *<send, (value, v, u)>* to all
2. Run oblivious leader election to decide who to listen to
3. Replica receives *<send, (value, v, u)>*,
   - If u>=lock, n-f *<echo2, (value, u)>* arrive, and first send from primary in view v, then
     - sends : *<echo1, (value, v)>* to all
4. Replica gathers *n-f <echo1, (value, v)>, then*
   - Sends *<echo2, (value, v)>* to all
5. Replica gathers *n-f <echo2 (value, v)>, then (at view v)*
   - Set key:=v; key value:=value
   - Sends *<key, (value, v)>* to all
6. Replica gathers *n-f <key, (value, v)> and n-f <echo2 (value, v)>, then (at view v)*
   - Set lock:=v
   - Sends *<lock, (value, v)>* to all
7. Replica gathers *n-f <lock, (value, v)>, then*
   - Decide (value)

Replica gathers *f+1 <echo2, (value, v)>, then*

- If did not send echo2
- Sends *<echo2, (value, v)>* to all

View change:

- **Replica**:
- Sends its key and key value

- **Primary**:
- accept a key (value’,v’) if also n-f *<echo2, (value, v)>* arrive
- Wait for n-f such key
- Choose the value with the highest key (view)

Oblivious Leader Election

Choosing a random leader is a simple MPC protocol

But MPC uses VSS, and VSS requires broadcast ☹

Solution:

- a notion that is weaker than VSS but strong enough for OLE
- Moderated VSS (KK06) and Graded VSS (MF88)
- Tailor made MPC (with a constnat error probabilty)

Gradecast -> MVSS ->OLE ->O(1) time expected Byzantine Agreement

Gradecast (MF88, D81)

Dealer P* has inoput m

Each party outputs a vlaue m and a grade in {0,1,2}

If the dealer is no-fualty then all non-fualty output (m,2)

If a non-fualty outputs (m’,2) then all non-fulaty output (m’,g) with g>0

(If two non-faulty have grade 1 then have same value)

Gradecast protocol (MF88)

round 1: Dealer P* <sends m> to all

round 2: Party sends <echo1 m> to the first message it recives from the primary

round 3: If party gathers n-f echo1 it sends <echo2 m>

End of round 3:

- Grade 2: If party gatheres n-f echo2; otherwise
- Grade 1: if party gathers f+1 echo2; otherwise
- Gread 0 (default value)

Gradecast proof (MF88)

round 1: Dealer P* <sends m> to all

round 2: Party sends <echo1 m> to the first message it recives from the primary

round 3: If party gathers n-f echo1 it sends <echo2 m>

End of round 3:

- Grade 2: If party gatheres n-f echo2; otherwise
- Grade 1: if party gathers f+1 echo2; otherwise
- Gread 0 (default value)

Echo1 causes non-equivocation -> any two grade 1 must have same value

Non-fualty dealer -> all non-fulty have (m,2)

Non-fualty has (m’,2) -> all nonfaulty have at lesT f+1 echo2 -> all non-fualty have (m,g) with g>0

Moderated VSS [KK06]

MVSS from VSS

Dealer P*

Moderator P**

Take any VSS that uses broadcast only in share phase

Replace <broadcast m by party j> with:

- Party j runs gradecast (m)
- The moderator P** takes the value m' of the gradecast and runs gradecast (m')

Outcome for party i:

- Let (m,g) be the outcome of the first gradecast
- Let (m',g') be the outcome of the first gradecast
- If g'<2 or (g'=2 and g=2 and m≠m') then set OK=false

Proof for Moderated VSS

If OK=true for any non-faulty then VSS properties hold

- Because all see the moderator's value and the moderator's value is consistent with any non-faulty broadcaster

If the moderator is non-faulty then all non-faulty have OK=true

- From the grade cast properties of an honest sender

Oblivious Leader Eelection

OLE from MVSS

For each i,j, do a MVSS with dealer i and moderator j (say random value in n^4)

The secret ballot for j will be the sum mod n^4 of all the VSS where j is a moderator

Reveal all the secret ballots for all parties

But if for some moderator j you see OK=false in any MVSS then set secret ballot to 0

Choose the leader to be the party with the highest secret ballot

With large probability there are no collisions, and then with constant probability a non-faulty is elected

Moving to asynchrony

Responsivness: we added a key round

MVSS does not work:

- n>4f, costnat time [MF]
- AVSS constnat time, but has non-zero deadlock [CR]
- ShunningAVSS no deadlock but polynomial time [ADH]

Attach f+1 secrets. Honest attach only after the RB works

Liveness even in asynchrony ?

Primary-Backup and Byzantine Primary-Backup:

- Always safe; live when system is synchronous

Problems with asynchrony:

- Adversary can attack the primary
- Adversary can delay the primary
- Cannot tell the difference
- Choose a random leader?
- Works for a static adversary
- Replace leaders quickly: works for an adaptive adversary that is slow
- What about an adaptive adversary that is not slow?

Asynchrony: Lower bounds and solutions

1985: Fischer, Lynch and Patterson:

- Impossible to decide on one command even with f=1 crash failure
- For any safe protocol there is an adversary strategy (on delays) that forces the protocol to make an infinite number of steps (never terminate)

Solutions:

- Assume eventually the system is synchronous (so no progress in DDoS)
- Use randomization so the infinite execution have probability (measure) 0
- In fact O(1) expected rounds!

Building State Machine Replication

- Weak validity: is not enough assuming asynchronous client communication
- Binary agreement is not enough (can be a building block)
- External Validity [CKPS 01] is key for SMR implementation

Start the election after *n-f* are done [AMS PODC19]

Primary i gets a proof that *n-f* learned it's commit decision

- call this a *done-proof*, sends singed *<**done** (done-proof)>*$_i$

Barrier: Start leader election after seeing *n-f* valid *<done (*)>* messages

Safety does not change

Liveness:

- With constant probability we chose a primary that made progress!

Thank you