Towards Formal Verification of HotStuff-Based Byzantine Fault Tolerant Consensus in Agda

NASA Formal Methods 2022

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Agenda

1. Problem and contributions
2. Abstract model and definitions
3. Key theorem, relating it to an implementation
4. Remarks about approach
5. Concluding remarks

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Byzantine Fault Tolerant Consensus

- **Consensus: distributed peers (repeatedly) agree on proposed values**
- **Fault tolerant: even if some are “faulty” (e.g., crash)**
- **Byzantine: even if some peers actively and maliciously misbehave**
- **Many proposed BFT consensus solutions in literature, with various properties**
  - Notoriously difficult to get right
  - Many examples of incorrect “solutions”
  - None with fully formal, machine checked proofs
- **New solutions emerging and being adopted**
  - HotStuff (Yin et al., PODC 2019)
  - LibraBFT / DiemBFT (based on HotStuff)
- **Context: we have developed a Haskell implementation based on LibraBFT, and we are working towards formally verifying its correctness**

Contributions

- **Defined abstract model of core protocol underlying HotStuff/LibraBFT**
- **Precisely formulated assumptions**
  - Limits on combined power of dishonest peers
  - Rules that honest peers obey
- **Precisely stated correctness (safety) properties (liveness would be proved for specific implementations, not the abstract model)**
  - Informally, “honest peers agree”
- **Formal, machine-checked proofs**
- **Development is in Agda**
- **Available in open source**
  - https://github.com/oracle/bft-consensus-agda/releases/tag/nasafm2022

Power of abstraction

- **Abstract model knows nothing of message formats, validation, implementation data structures and logic, etc.**
- **Focusing on core protocol enables verifying a range of implementations, without repeating hard work of verifying underlying protocol**
- **LibraBFT under development during verification effort, no need to repeat abstract work when updating our implementation**

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Growing a chain of Records

- **Start with initial (genesis) record I**

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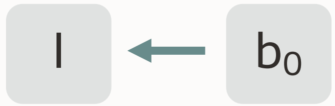
- **Extend with alternating Block proposals and Quorum Certificates (QCs) to “certify” them**



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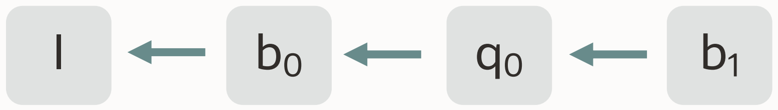

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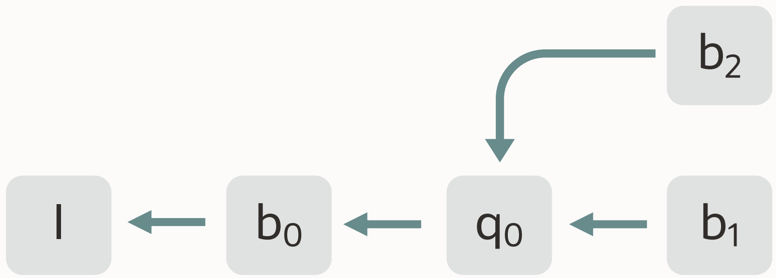

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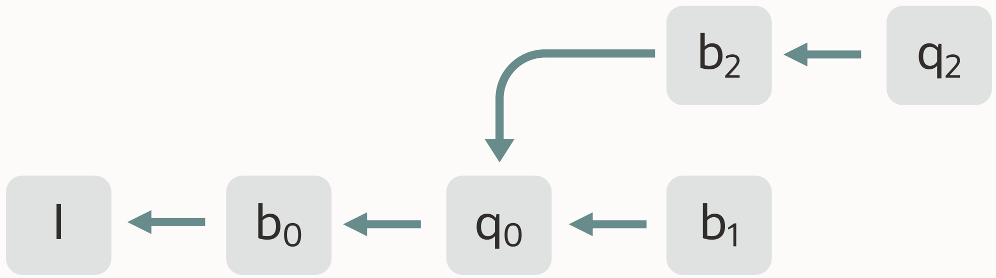

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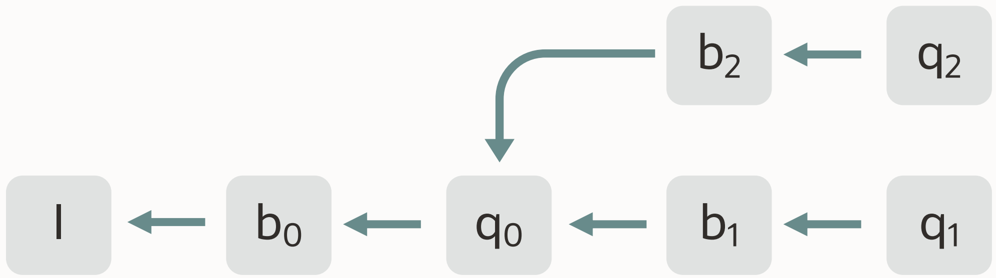

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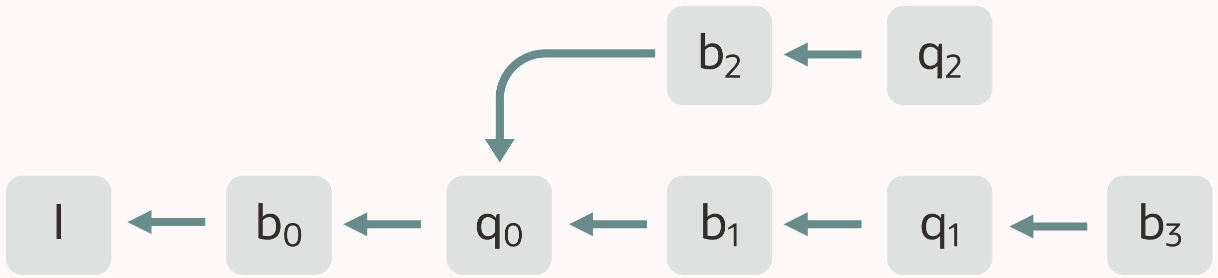

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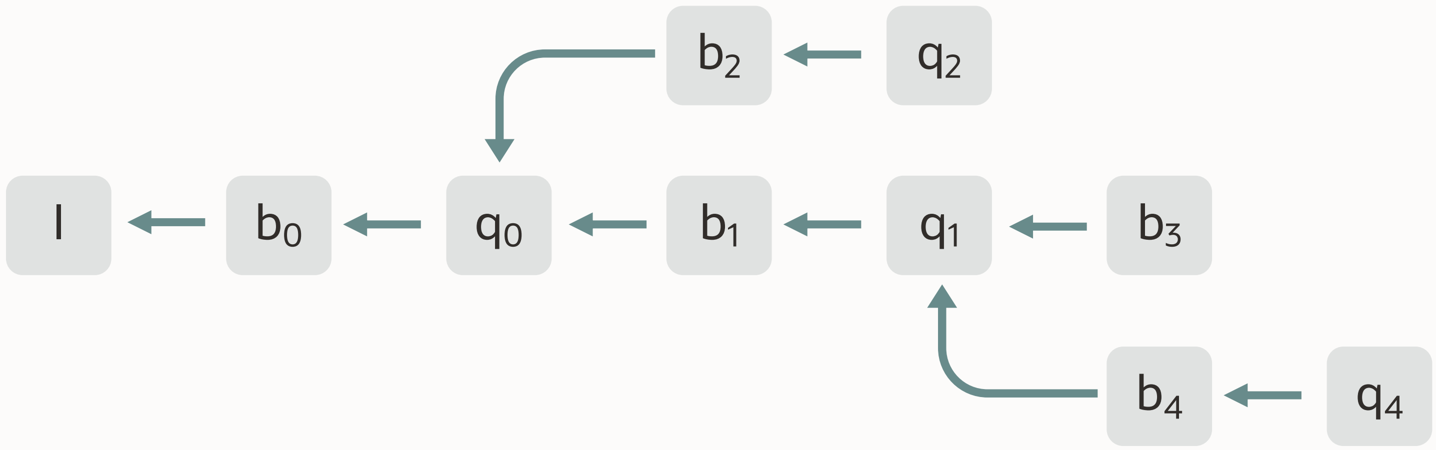

Growing a chain of Records

- Start with initial (genesis) record **I**
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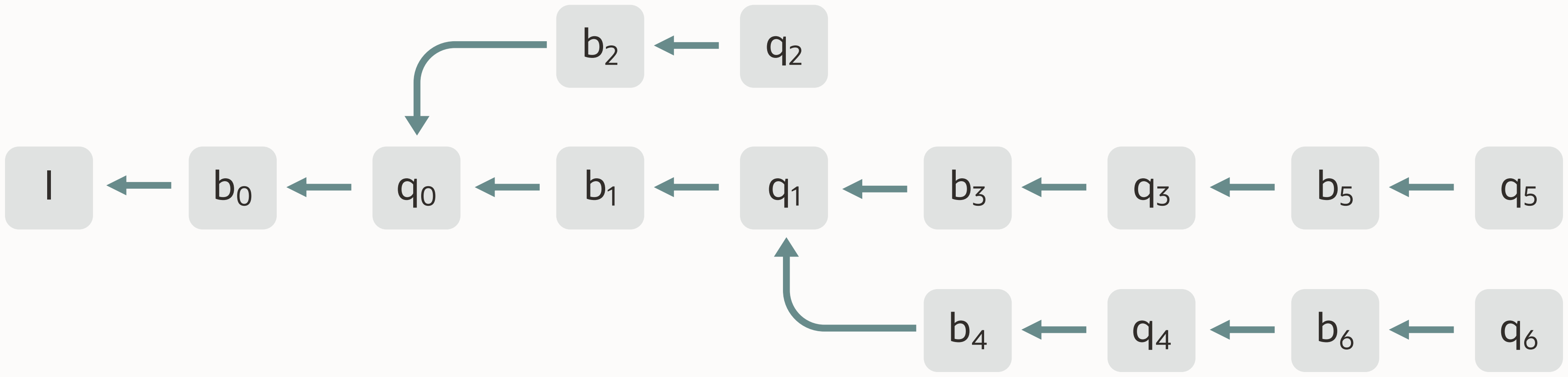

Growing a ~~chain~~ tree of Records

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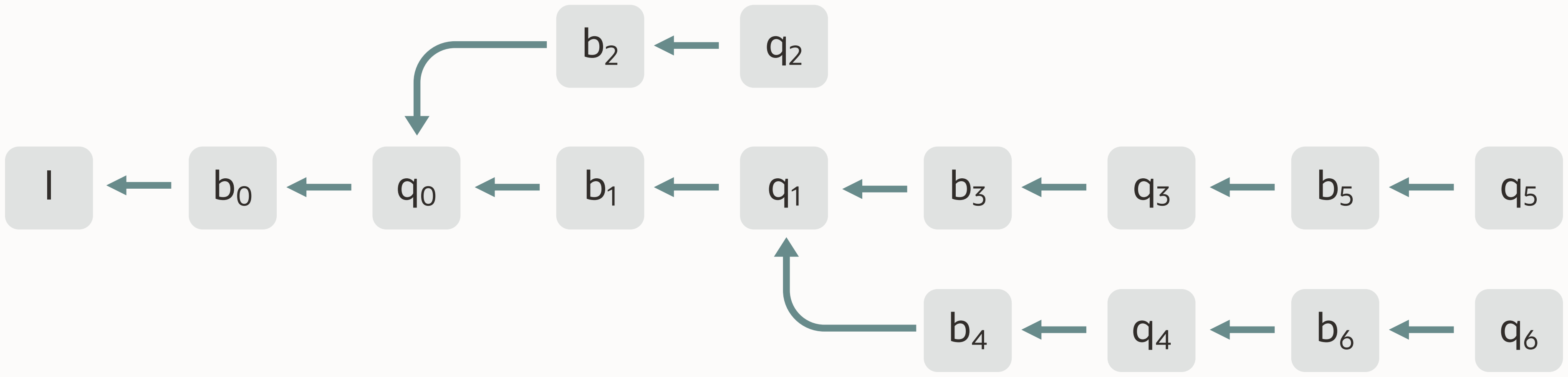

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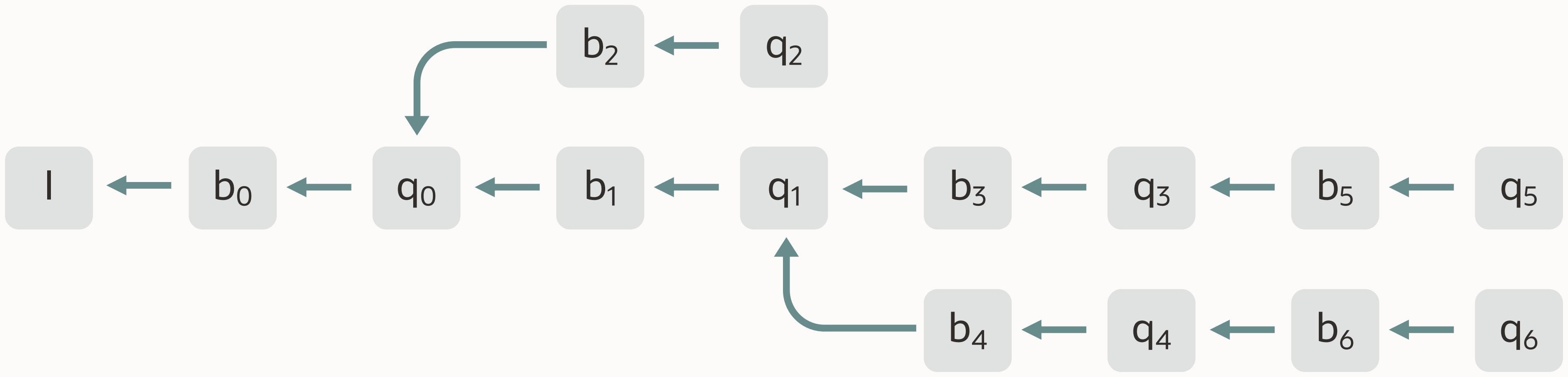
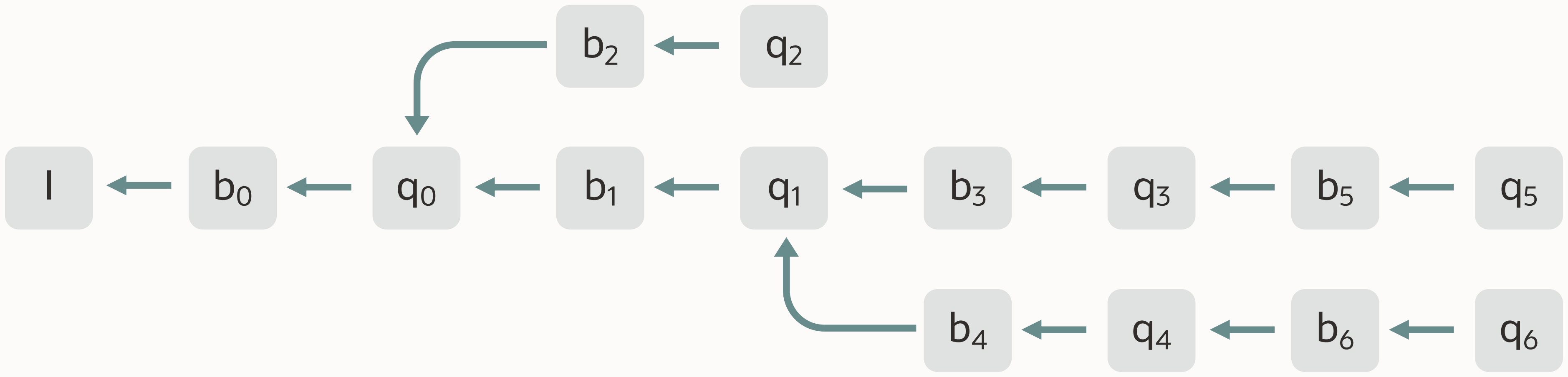
- If QC not formed/known, time out and propose alternative Block
- What if QC does emerge for b_1?
- Must model a <u>tree</u> of Records
- How to ensure honest peers agree on decisions?



Desired property, less informally

- **If two honest peers each commit (decide on) a Block, then the Blocks do not "conflict": there is a single path in the tree that contains them both:**
  - Commit b_1 and b_6: no problem
  - Commit b_2 and b_6: conflict!



Abstract records

- **QCs indicate UID and round of Blocks they certify**
- **To enable specifying rules to ensure consistent decisions Blocks have round numbers**
- **QCs and Votes they contain indicate the Round of the voted-for Block**

```
data Record : Set where
  I  :                Record
  B : Block     → Record
  Q : QC         → Record
```

```
record Block  : Set where
  field
    bRound   : Round
    bId         : UID
    bPrevQC  : Maybe UID
```

```
record QC : Set where
  field
    qRound          : Round
    qCertBlockId  : UID
    qVotes           : List Vote
    …
```

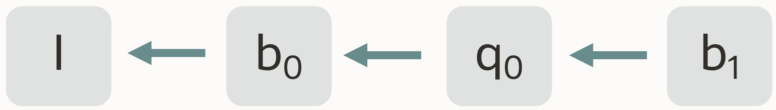
```
record Vote : Set where
  field
    abs-vRound       : Round
    abs-vMember    : …
    abs-vBlockUID  : UID
```

Extends relation (_←_)

- _←_ imposes constraints on rounds
- **QC** is for same round as **Block** it extends
- **Block** is for higher round than **Block** it extends (via a **QC**)

```
data _←_ : Record → Record → Set where
  I←B : {b : Block}
      → 0 < getRound b
      → bPrevQC b ≡ nothing
      → I ← B b
  B←Q : {b : Block} {q : QC}
      → getRound q ≡ getRound b
      → bId b ≡ qCertBlockId q
      → B b ← Q q
  Q←B : {q : QC} {b : Block}
      → getRound q < getRound b
      → just (qCertBlockId q) ≡ bPrevQC b
      → Q q ← B b
```

Defining RecordChains



RecordChain (B b_1)

```
data RecordChainFrom (o : Record) :
          Record → Set where
  empty : RecordChainFrom o o
  step   : ∀ {r r'}
           → (rc : RecordChainFrom o r)
           → r ← r'
           → RecordChainFrom o r'

RecordChain : Record → Set
RecordChain = RecordChainFrom I
```

Defining 𝕂-Chains

```
data 𝕂-chain (R : ℕ → Record → Record → Set)
    : (k : ℕ){o r : Record} → RecordChainFrom o r → Set where
  0-chain : ∀{o r}   {rc : RecordChainFrom o r} → 𝕂-chain R 0 rc
  s-chain  : ∀{k o r}{rc : RecordChainFrom o r}{b : Block}{q : QC}
         → (r←b  : r   ← B b)
         → (prf   : R k r (B b))
         → (b←q : B b ← Q q)
         → 𝕂-chain R k rc
         → 𝕂-chain R (suc k) (step (step rc r←b) b←q)

-- Contiguous 𝕂-chains are those in which all adjacent pairs of
-- Records have contiguous rounds.
 Contig : ℕ → Record → Record → Set
 Contig 0          _ _ = Unit
 Contig (suc _) r  r' = round r' ≡ suc (round r)
```

Roughly speaking,

𝕂-Chain Contig k rc

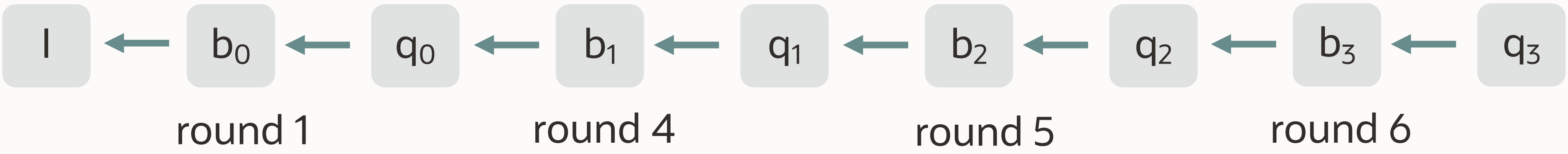
Says that rc contains at least k Blocks, such that the Rounds of the last k Blocks are consecutive

How to decide a Block is committed?

```
data CommitRuleFrom {o r : Record}(rc : RecordChainFrom o r)(b : Block) : Set where
  commit-rule : (c3 : 𝕂-chain Contig 3 rc)
                → b ≡ c3 b⟦ suc (suc zero) ⟧
                → CommitRuleFrom rc b

CommitRule : ∀{r} → RecordChain r → Block → Set
CommitRule = CommitRuleFrom
```

rc : RecordChain (Q q_3)



CommitRule rc b_1

Block b_1 is now committed (and all Blocks before it, i.e., b_0)

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Key theorem: thmS5

- **If we have CommitRules for Blocks b and b' enabling commiting both Blocks, then the one of the Blocks is in the RecordChain of the other's CommitRule (i.e., there is no conflict in committing them both)…**

```
thmS5 : ∀ {q q'}
      → {rc  : RecordChain (Q q )} → All-InSys rc
      → {rc' : RecordChain (Q q')} → All-InSys rc'
      → {b b' : Block}
      → CommitRule rc  b
      → CommitRule rc' b'
      → NonInjective-≡-pred (InSys ∘ B) bId
      ⊎ (B b) ∈RC rc'
      ⊎ (B b') ∈RC rc
```

- **…unless there are two different Blocks "in the system" with the same block ID.**

Relating thmS5 to an implementation

- **To invoke thmS5 for a particular implementation, we must instantiate these module parameters:**

```
module LibraBFT.Abstract.RecordChain.Properties
  (UID    : Set)                                      -- type for Block ids
  …
  …
  (𝓔                    : EpochConfig UID …)          -- specifies peers, assumptions, …
  …
  (InSys                : Record → Set …)             -- which abstract Records are represented
                                                          (e.g., in messages that have been sent)
  (votes-only-once      : VotesOnlyOnceRule InSys)    -- honest peers obey two rules
  (preferred-round-rule : PreferredRoundRule InSys)
where
  …
  thmS5 : …
  … proof of thmS5
```

Rules for honest peers (1/2)

- **An honest peer does not send inconsistent Votes for the same Round:**

```
VotesOnlyOnceRule : Set …
VotesOnlyOnceRule
  = (α : Member) → Meta-Honest-Member α
    → ∀{q q'} → InSys (Q q) → InSys (Q q’)
    → (v  : α ∈QC q) (v' : α ∈QC q')
    → abs-vRound (∈QC-Vote q v) ≡ abs-vRound (∈QC-Vote q’ v’)
    → ∈QC-Vote q v ≡ ∈QC-Vote q' v'
```

- **Manual proof in an early LibraBFT paper required “Increasing Round” constraint:**
  An honest node that voted once for B in the past may only vote for B’ if round (B) < round (B’)
- **One contribution is making rules *precise* enough to enable rigorous (machine-checked) proofs**

Rules for honest peers (2/2)

```
PreferredRoundRule : Set …
PreferredRoundRule
    = ∀(α : Member) → Meta-Honest-Member α
    → ∀{q q'}
    → {rc : RecordChain (Q q)} → All-InSys rc
    → {n : ℕ} (c3 : 𝕂-chain Contig (3 + n) rc)
    → (v : α ∈QC q)
    → {rc' : RecordChain (Q q')} → All-InSys rc'
    → (v' : α ∈QC q')
    → abs-vRound (∈QC-Vote q v) < abs-vRound (∈QC-Vote q' v')
    → NonInjective-≡-pred (InSys ∘ B) bId
    ⊎ (getRound (kchainBlock (suc (suc zero)) c3) ≤ prevRound rc')
```

- **The key rule that honest peers must follow to avoid contributing to QCs that could result in committing conflicting Blocks**
- **Key implementation requirement for invoking thmS5**
- **Again, result required only if there is no injectivity failure among Blocks "in the system"**

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Block id injectivity

- Abstract model and proofs know nothing about UID, how Block ids are assigned, etc.
- Typical implementations use cryptographic hash functions (e.g., SHA256)
- Standard to assume that a computationally bounded adversary cannot find two different values (e.g., Blocks) that hash to the same value
- Most related work implicitly or explicitly assumes that such hash collisions do not exist, which is false by an easy counting argument (hash results are of fixed size)
- False implies anything. Danger!
- We don't assume hash functions are injective. Instead, we ensure that our results hold unless and until there is a collision between Blocks that the implementation considers "in the system" (e.g., messages containing them have been sent).
- ToyChain (Pîrlea and Sergey, CPP 2018) work to address this issue required changes to every proof, one ballooned from 10 lines to 150!

Power of abstraction

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- **Focusing on core protocol enables verifying a range of implementations, without repeating hard work of verifying underlying protocol**
- **LibraBFT under development during verification effort, no need to repeat abstract work when updating our implementation**

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- **That said, recently LibraBFT changed to a** CommitRule **based on 2-chains. That implementation does not ensure the** PreferredRoundRule **defined in our development**
- **Does not mean it is not correct, but that it cannot be proved correct using our abstract model**
- **Updating our work for a 2-chain-based** CommitRule **is future work**

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Concluding remarks

- **Byzantine Fault Tolerant consensus is notoriously difficult to get right**
- **Formal, machine-checked verification is important, but difficult and time consuming**
- **Our approach separates correctness of underlying protocol from details of a range of (but not all) implementations**
- **We avoid the dangerous assumption that hash collisions do not exist (they do!) by tying hash collisions to specific values actually encountered in an execution**
- **Results for a single "epoch", epoch change / reconfiguration is future work**
- **Broader project includes:**
  - Agda translation of our Haskell implementation
  - Syntax and library support to keep Agda close to Haskell implementation
  - System Model and machinery for modeling and proving properties about a distributed system in which honest peers follow implementation, dishonest ones unconstrained other than inability to forge honest signatures
  - Significant progress towards verifying that our implementation satisfies requirements to instantiate abstract results
  - Open source: https://github.com/oracle/bft-consensus-agda/releases/tag/nasafm2022

Questions?

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