Formal Modeling of Distributed Systems

Modeling the Raft Distributed Consensus Protocol in LNT

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MARS’22

Munich, 2 April 2022

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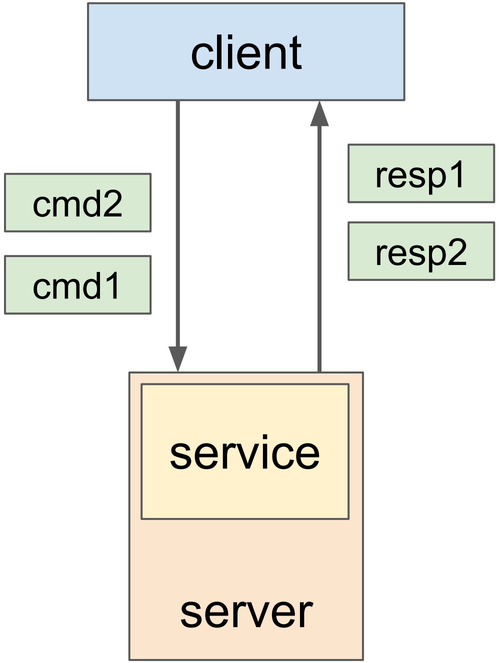
Opinions are my own and not the views of my employer

Agenda

- Distributed consensus
- Raft protocol
- Modeling with LNT
- Modeling distributed systems

A crash-proof service



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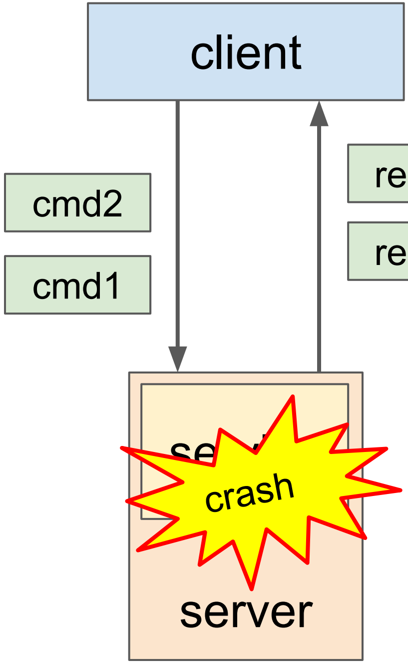
A crash-proof service



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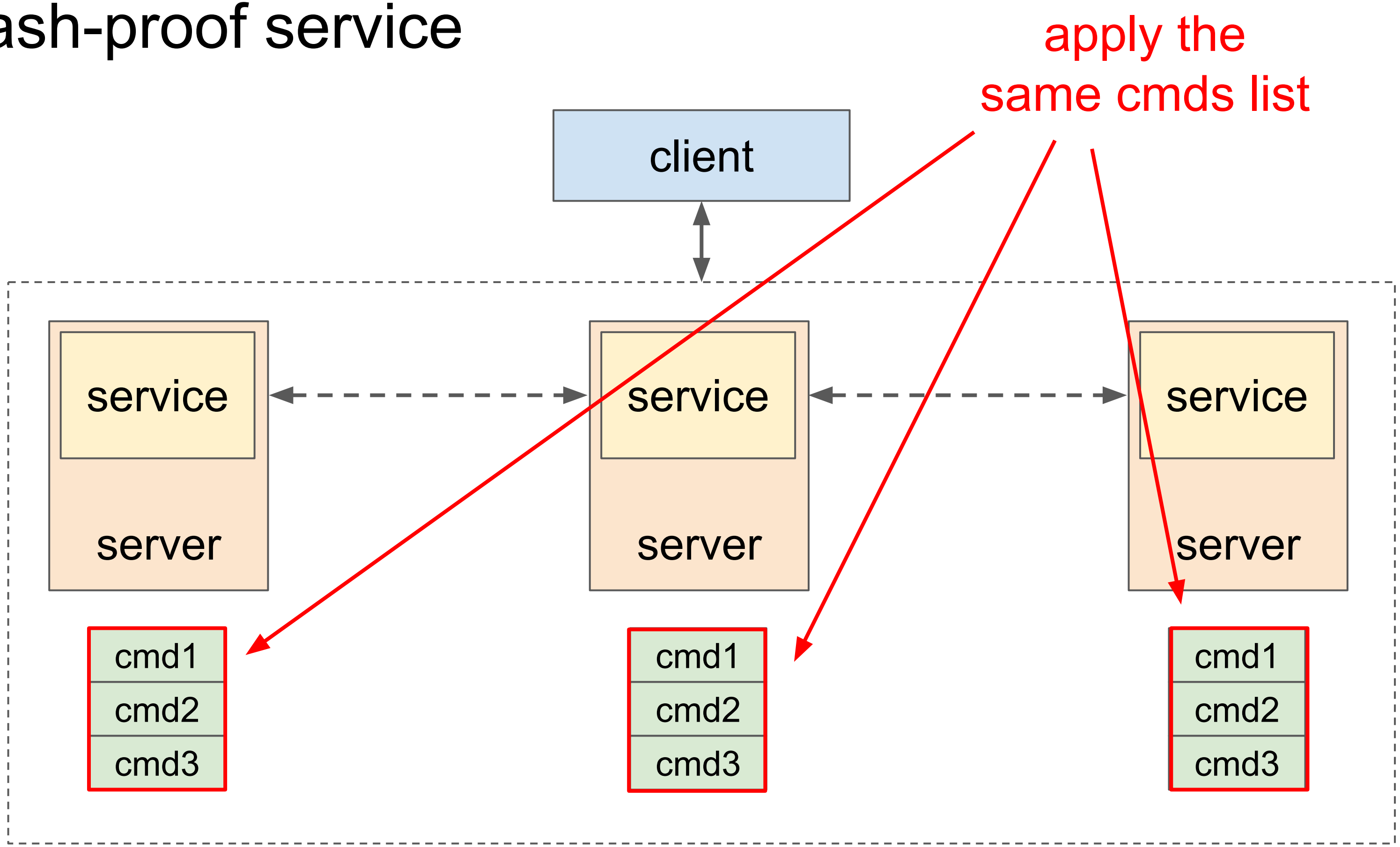

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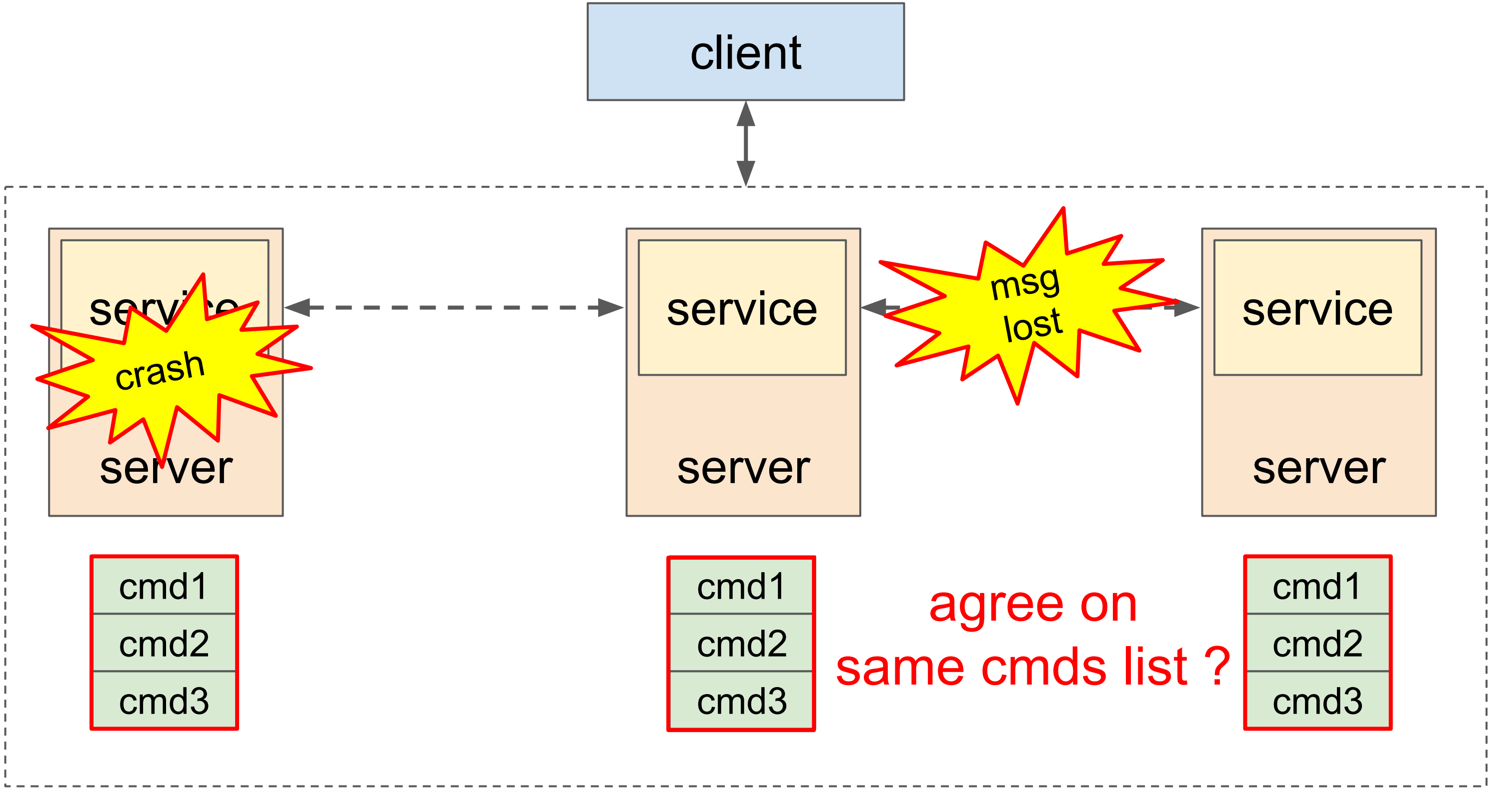

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Distributed consensus

- Distributed: several **nodes**
- Nodes may **crash**
- Nodes communicate via **asynchronous messages**
- **Unreliable channels:** messages can be ***dropped, duplicated, reordered***

Consensus: **can nodes agree on something?**

Distributed consensus

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Consensus: **can nodes agree on something?**

If using a deterministic protocol, then it's **impossible** (*FLP* impossibility)

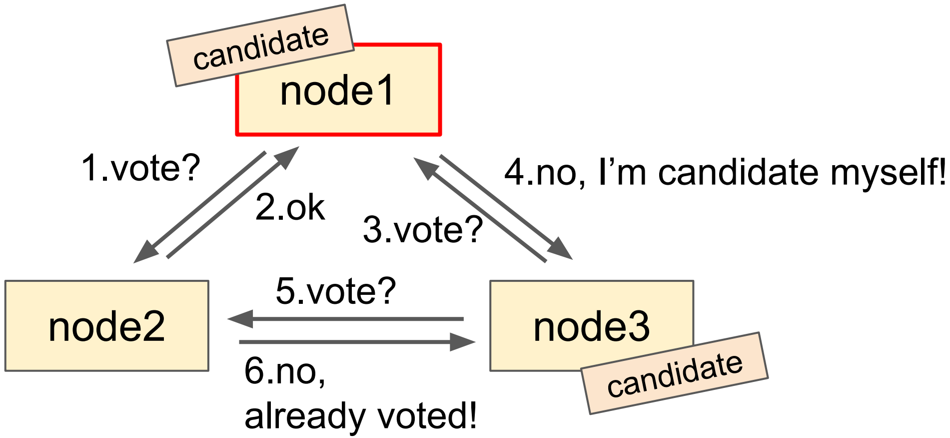
[**F**ischer-**L**ynch-**P**aterson-85] *Impossibility of distributed consensus with one faulty process*

Distributed consensus: (non-deterministic) protocols

- Paxos: [Lamport-90-98] *The Part-Time Parliament*
- Rich literature:
    - Multi-Paxos
    - “Paxos made easy”
    - …
- Raft: [Ongaro-Ousterhout-13] *In Search of an Understandable Consensus Algorithm*
    - https://raft.github.io/
    - Focus on **clarity** and **understandability**
    - Specification in TLA
    - Manual proof

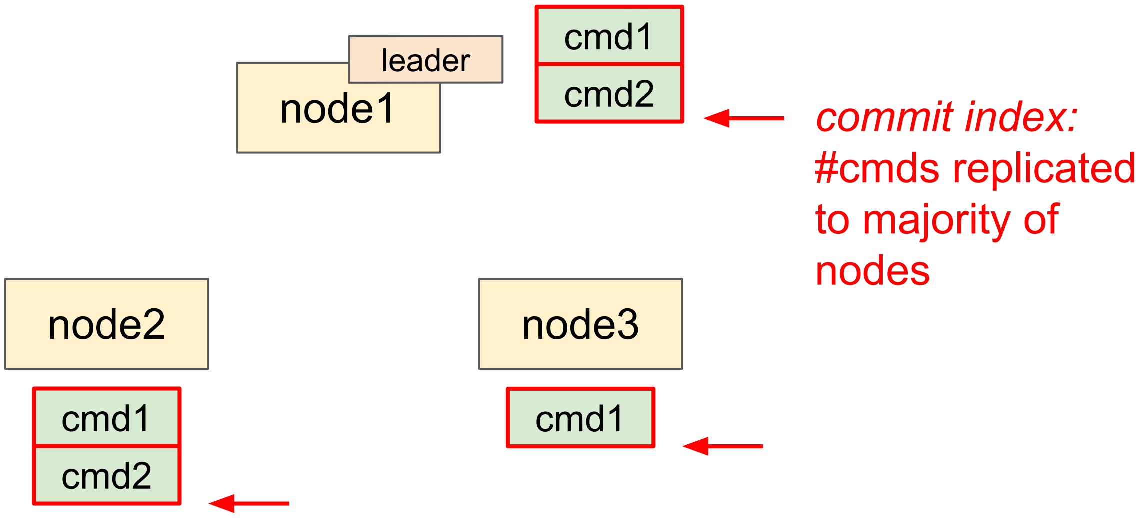
Raft in a nutshell (1)

- Time divided in **terms**
- At each term:
  - 1. **Leader election:** elect one leader among nodes



Raft in a nutshell (2)

- Time divided in **terms**
- At each term:
  - 1. **Leader election:** elect one leader among nodes
  - 2. **Append log entries:** leader replicates log entries to quorum of followers



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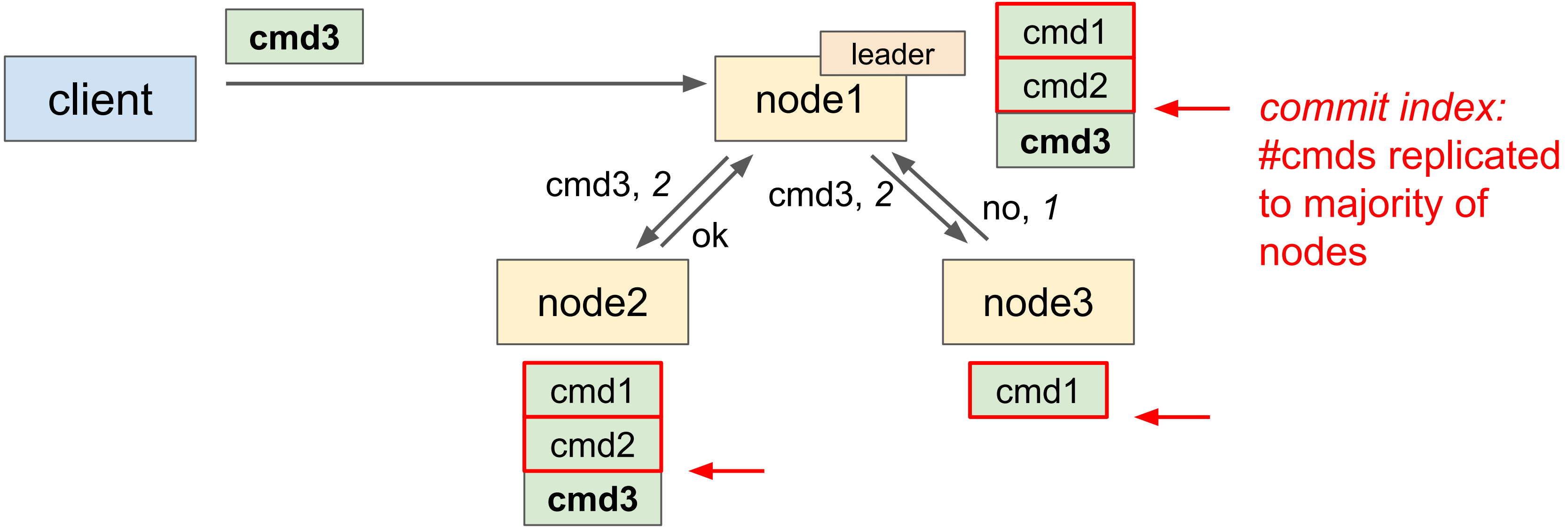

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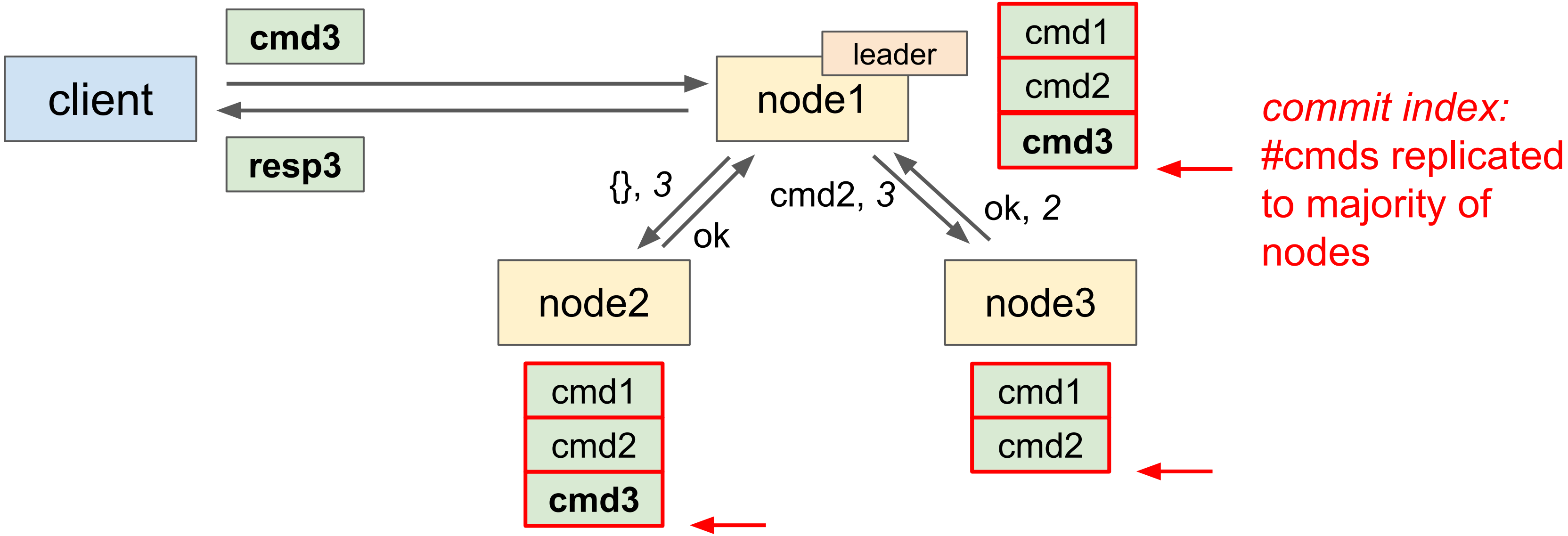


Raft in a nutshell (3)

- Time divided in **terms**
- At each term:
  - 1. **Leader election:** elect one leader among nodes
  - 2. **Append log entries:** leader replicates log entries to quorum of followers

- Only the leader interacts with the client
- Any node can timeout and start a new election
- Leader sends heartbeat messages to prevent timeouts

- Used in the industry
  - e.g. Hashicorp’s Consul, etcd (Kubernetes)

Verification? Start with **formal model**

Formal modeling with LNT: a primer

```
module primer is

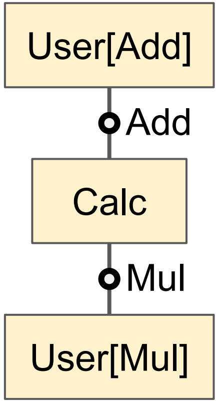
channel CalcOp is
  (op1, op2, res: nat)
end channel

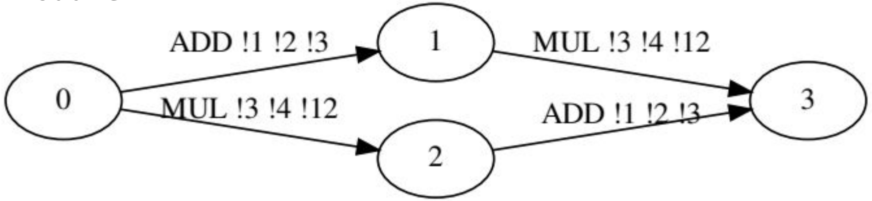
process Calc [Add, Mul: CalcOp] is
  var op1, op2, res: nat in
    loop
      select
         Add(?op1, ?op2, ?res)
           where res == (op1 + op2)
      [] Mul(?op1, ?op2, ?res)
           where res == (op1 * op2)
      end select
    end loop
  end var
end process
```

```
process User [Op: CalcOp] (a, b: nat)  is
  var result: nat in
    Op(a, b, ?result)
  end var
end process

process Main [Add, Mul: CalcOp] is
  par
    Add -> User[Add](1, 2)
  ||
    Mul -> User[Mul](3, 4)
  ||
    Add, Mul -> Calc[Add, Mul]
  end par
end process

end module
```



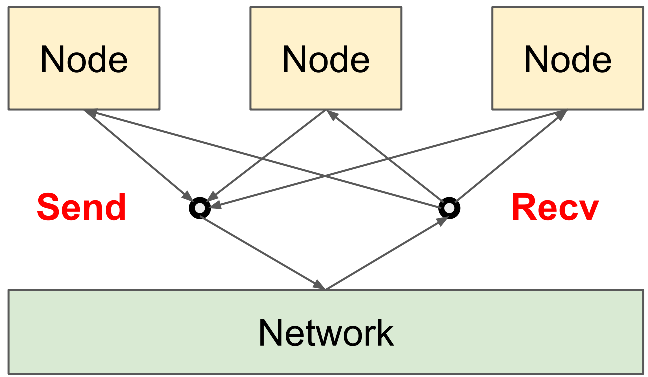


State space as LTS: *Labelled Transition System*

Modeling Raft in LNT (1): top-level parallel composition

```
par Send, Recv in
     par
       Node
     ||
       Node
     ||
       Node
     ||
       ...
     end par
||
     Network
end par
```

replicated server nodes



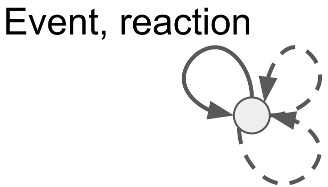
Modeling Raft in LNT (2): Network

```
process Network is
  var bag: MsgSet := {} in
    loop
      select
         Send(?msg);
         bag := insert(msg, bag)                 good reception
      []
         Send(?msg);                             msg lost (not stored in bag)
      []
         Recv(msg) where member(msg, bag);
         bag := remove(msg, bag)                 transmit, possible reordering
      []
         Recv(msg) where member(msg, bag);       msg duplication: transmit & keep in bag
      end select
    end loop
  end var
end process
```

Modeling Raft in LNT (3): Node with Crash in select

```
process Node is
  (* init … *)
    loop
      select
         Recv(?msg);
         case msg in
           VoteRequest -> … Send(msg) …
         | AppendEntries -> … Send(msg) …
         end case
      []
          Timeout;
          (* start election or send heartbeat *)
      []
          Client(?cmd) where state == Leader;
          (* add client command in local log *)
      []
          Crash;
          break
      end select
    end loop
end process
```

Simplified LTS



Modeling Raft in LNT (3): Node with Crash in select

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```

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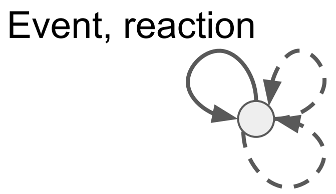
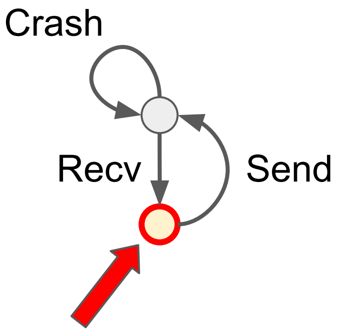


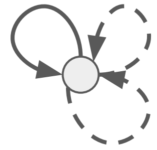


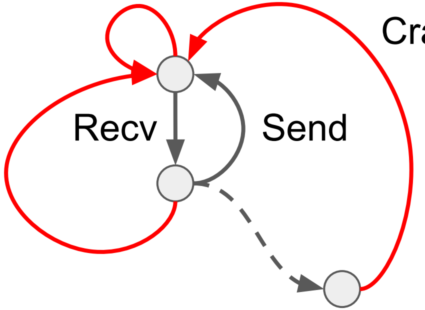
Cannot crash here?

Modeling Raft in LNT (4): Node with Crash in disrupt

```
process Node is
  (* init … *)
  disrupt
    loop
      select
         Recv(?msg);
         case msg in
           VoteRequest -> … Send(msg) …
         | AppendEntries -> … Send(msg) …
         end case
      []
          Timeout;
          (* start election or send heartbeat *)
      []
          …
      end select
    end loop
  by
    Crash
  end disrupt
end process
```

Simplified LTS





Issues found in the original TLA specification

- Typo-style error
  - missing apostrophe denoting future state
- Missing node state transition: candidate did not step down
  - Different from the behavior described in plain English in the paper
  - Did not jeopardize the manual proof

- Both have been fixed since.
- **Pretty hard to get a spec right!**

Modeling distributed systems

LNT / CADP formal development environment

- Writing a formal specification ~= writing a program
- Want a **quick feedback loop**
  - like REPL or fast edit-compile-run cycles
- LNT + CADP offers:
  - LNT: Mainstream programming language syntax
  - Strong typing, good error messages
  - Very powerful parallel composition and inter-process communication
    [Garavel-Serwe-17] *The Unheralded Value of the Multiway Rendezvous*
  - Fast compile time
  - "`assert`" keyword to fail early at state-space generation time
    - debug: can still inspect the state space generated so far
  - generate *implicit* state space
    - manual step-by-step exploration to inspect/debug the spec

Generic models for distributed systems

```
process Node is
  (* init local state … *)
  disrupt
    loop
      select

         Recv(?msg);
         (* update local state, send messages *)

      []

         LocalEvent; (* e.g. timeout, read sensor, … *)
         (* update local state, send messages *)

      end select
    end loop
  by
    Crash (* local failure *)
  end disrupt
end process
```

generic skeleton
(like Erlang's gen_server)

A library of network models

- Network oblivious to protocol details
  - Just transfer messages
- Can write various network semantics
  - synchronous/asynchronous
  - drop message, or not
  - reorder message, or not
- Can switch between network modules with no change anywhere else in the spec!

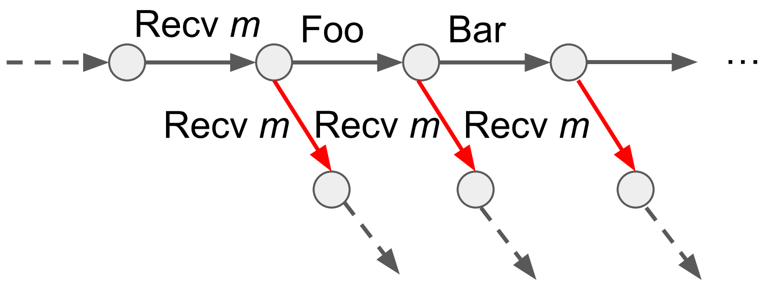
```
(* Transfer any message immediately *)
process ReliableSynchronousNetwork is
  loop
       Send(?msg);
       Recv(msg)
  end loop
end process
```

Modeling choices

- Want to keep state space size under control
- Model only the necessary, but no less
  - Distributed systems: inter-node communication, outstanding local events
  - Hide the rest as much as feasible
- Some examples in our Raft model:
  - A candidate directly votes for itself, rather than sending itself a vote request
  - Do not respond to stale RPC requests
    - The TLA spec does, to promptly inform a node that it is outdated
  - Append only one entry at a time (i.e. do not batch entries)
  - Force the order in which VoteRequests are broadcasted
    - Rely on network semantics to model reordering

Possible generic shortcut: duplicated messages

- Most distributed protocol are robust to message duplication
  - Have idempotent messages
  - Receive it once, then drop duplicates
- Assume this robustness: no need to model message duplication
- This can typically save a lot of state space size!



Modeling shortcuts: watchout for pitfalls!

- **Taking shortcuts in modeling is a very slippery slope!**
- It is **very easy** to make wrong assumptions there
    - Better be safe than sorry!

Formal model and implementation: bridging the gap

- You've got a verified model, now what?
- Implement. And introduce bugs ☹️
- Direct formal-model-to-implementation approaches
  - [Evrard-15] Distributed LNT Compiler: LNT to distributed C with TCP sockets
  - [Wilcox-et-al-15] Verdi: distributed system proof framework, Coq-OCaml
  - [deMoura-et-al-15] Lean: both theorem prover & compiler to Javascript
  - …
- Need **good tooling**
  - debugger, profiler, package manager, etc
- Wild request: next gen language's specification is ***formally*** defined
  - Avoid/reduce undefined behaviors
  - Sane basis for FM: stop reverse-eng/afterthought FM once the language is out!
  - Also formalize the ISAs (See e.g. Alastair Reid's work on ARM ISA)

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Quoting https://doc.rust-lang.org/reference/:

Finally, this book is not normative. It may include details that are specific to rustc itself, and ***should not be taken as a specification for the Rust language.*** *We intend to produce such a book someday, and until then, the reference is the closest thing we have to one.*

-
    - Sane basis for FM: stop reverse-eng/afterthought FM once the language is out!
    - Also formalize the ISAs (See e.g. Alastair Reid’s work on ARM ISA)

Conclusion

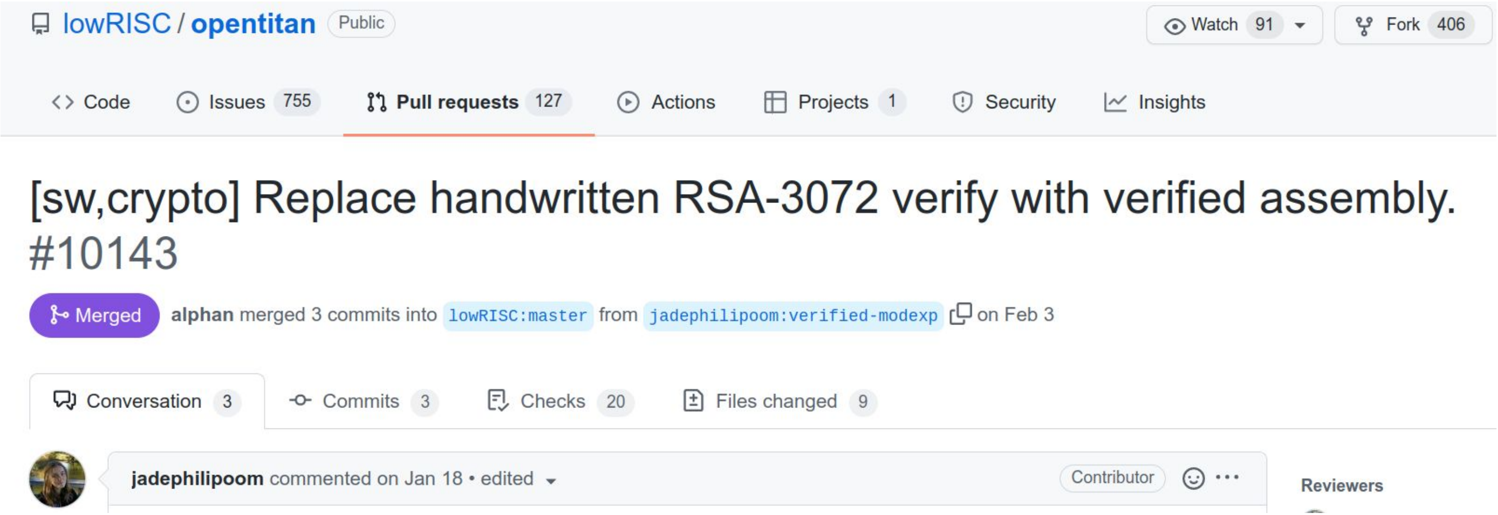
- Modeling Raft in LNT
- Formal modeling of distributed systems in general
- Modeling approaches to keep state space size small
  - Powerful, but watchout for semantics pitfalls!
- Bridge the gap with between formal models and implementation

Thanks!

- Questions?

Formal methods at Google? Some examples:

- pKVM (Android Hypervisor): formal semantics of ARM-v8a, see e.g. Peter Sewell's recent papers
- OpenTitan: code verified via Dafny https://github.com/lowRISC/opentitan/pull/10143



- BoringSSL has code verified via Fiat (MIT) https://boringssl.googlesource.com/boringssl/+/refs/heads/master/crypto/curve25519/curve25519.c#2015

```
// The following implementation was transcribed to Coq and proven to
// correspond to unary scalar multiplication in affine coordinates given that
// x1 != 0 is the x coordinate of some point on the curve. It was also checked
// in Coq that doing a ladderstep with x1 = x3 = 0 gives z2' = z3' = 0, and z2
// = z3 = 0 gives z2' = z3' = 0. The statement was quantified over the
// underlying field, so it applies to Curve25519 itself and the quadratic
// twist of Curve25519. It was not proven in Coq that prime-field arithmetic
```