Formal specifications of systems for fun and profit

Stefan Nožinić (stefan@lugons.org)

October 29, 2023

Agenda

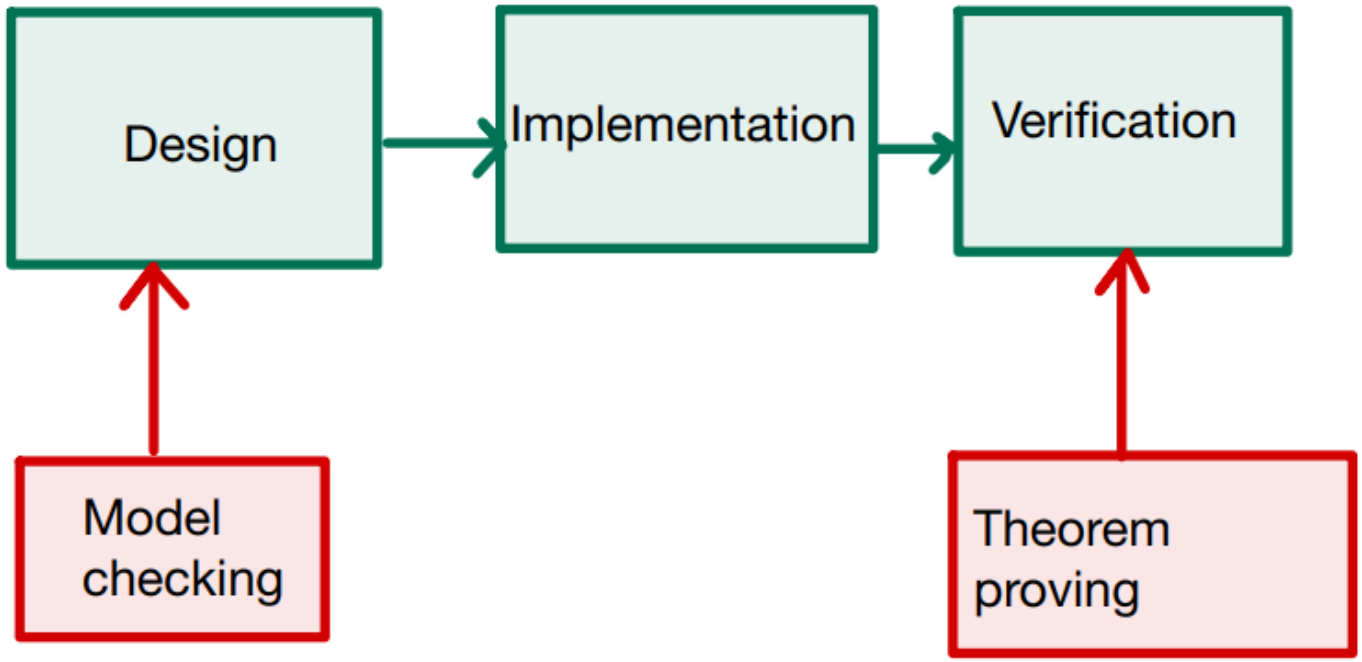
- Motivating example
- What are formal specs?
- TLA+ and PlusCal
- One real world example
- Proof systems
- Conclusion

System

Specification

Formal language

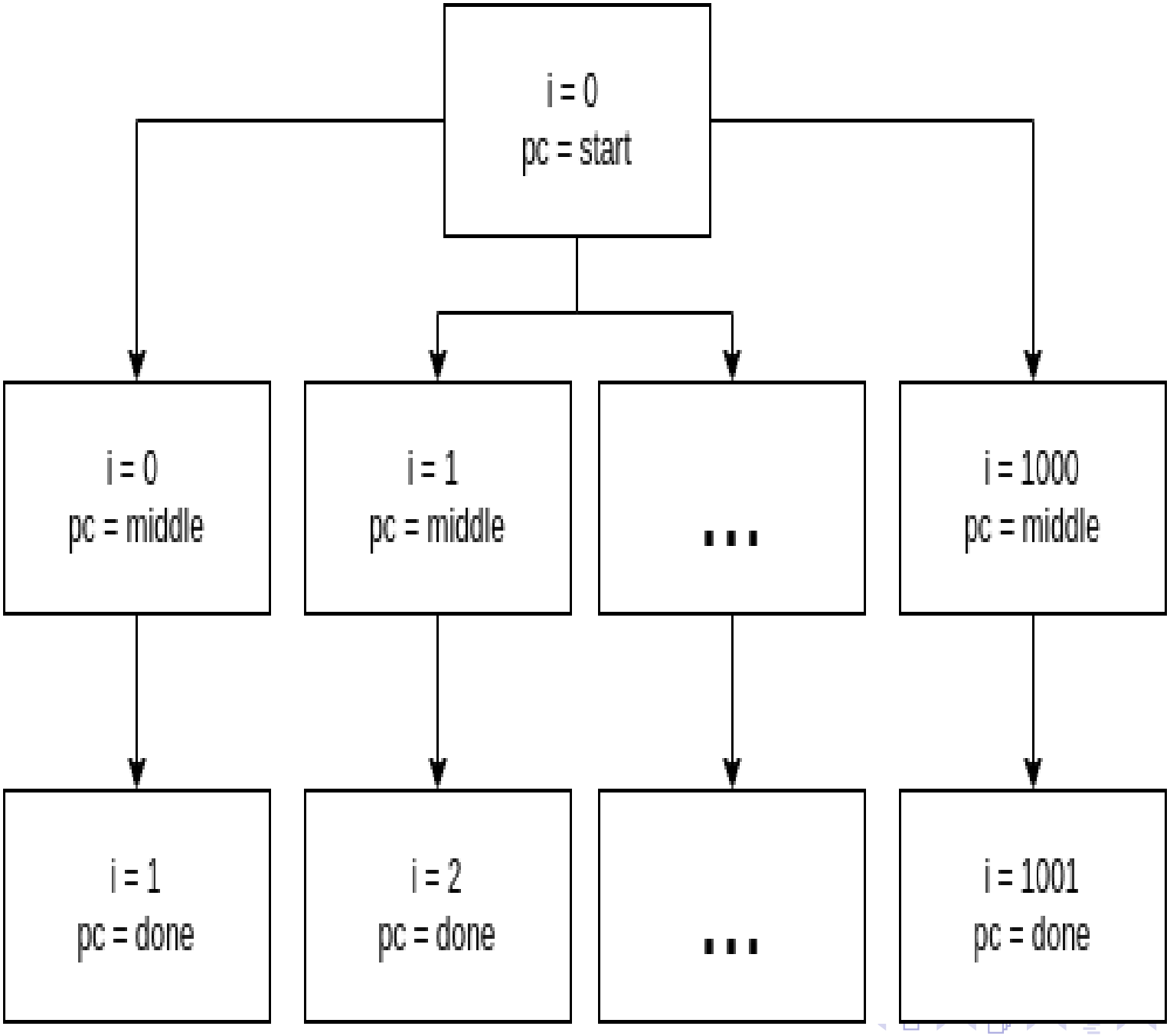
Process


Design
Implementation
Verification
Model checking
Theorem proving

```
void main() {
    int i = getValue(); // start
    i++; // middle
    setValue(i); // done
}
```

How to model this simple program formally as state machine?

State diagram



```
void thread2() {
    int i = getValue();
    i++;
    setValue(i);
}

void thread1() {
    int i = getValue();
    i++;
    setValue(i);
}
```

Networked program

```
void processRequest() {
    Message *msg = receiveMessage();
    if (msg->type == CLIENT_REQUEST) {
        ...
    } else {
        ...
    }
    for (auto node : getNodes()) {
        node->sendMessage(NODE_REQUEST);
    }
}
```

TLA+

- Essentially we specify state machine and its properties
  - State variables
  - What are valid initial states
  - What are valid next states, given current state
  - Properties
- TLC is used for model checking

Die Hard

```
void main() {
    int i = getValue(); // start
    i++; // middle
    setValue(i); // done
}
```

MODULE *simple_increment_sm*

EXTENDS TLC, $Integers$

VARIABLES i, pc

$$init \triangleq i = 0 \land pc = \text{“start”}$$

$$next \triangleq \text{IF } pc = \text{“start”} \text{ THEN } (i' \in 0 \,..\, 1000) \land (pc' = \text{“middle”}) \text{ ELSE IF } pc = \text{“middle”} \text{ THEN } (i' = i + 1) \land (pc' = \text{“done”}) \text{ ELSE FALSE}$$

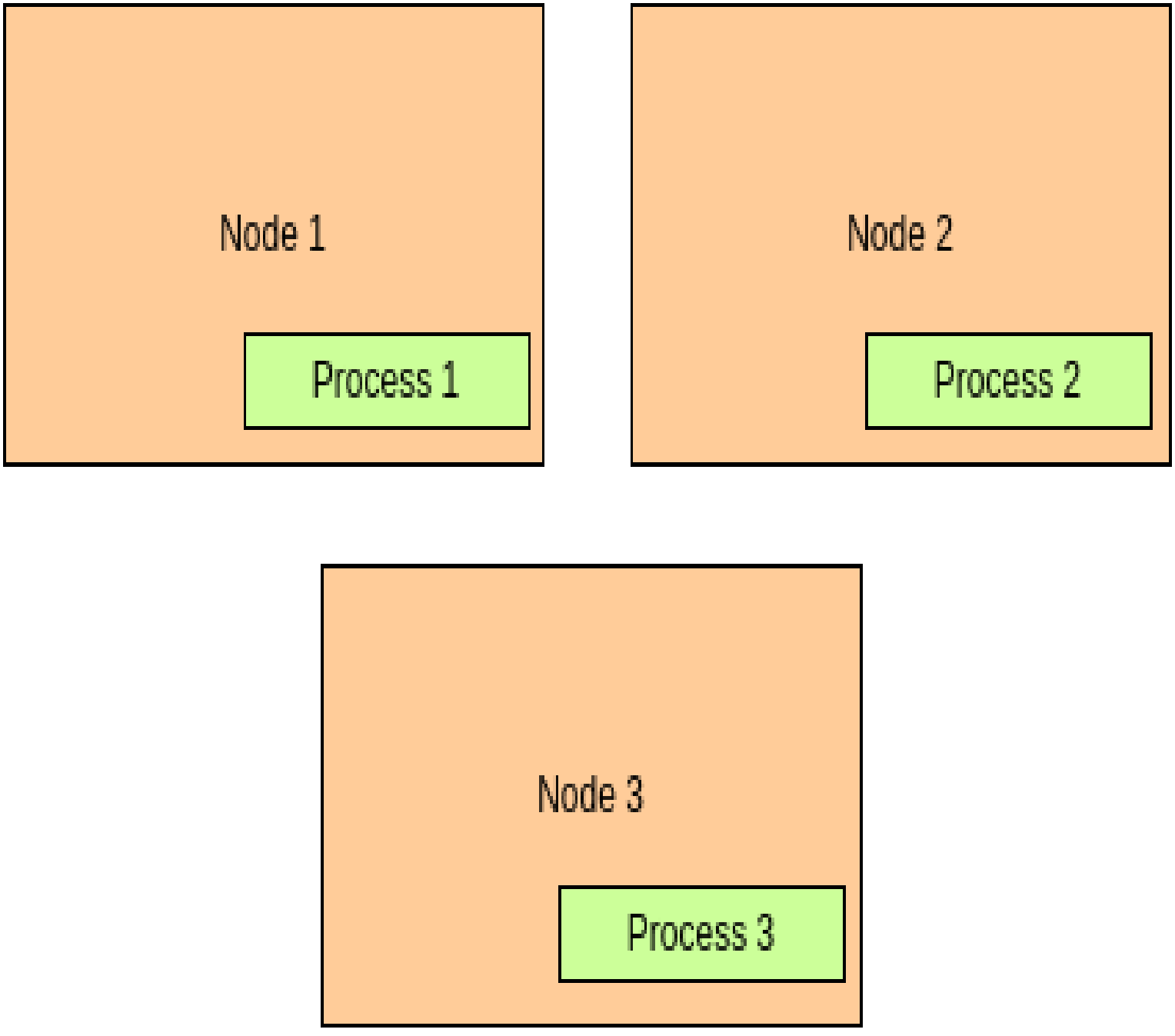
$$TerminationProperty \triangleq \Box(pc = \text{“done”} \Rightarrow i > 0)$$

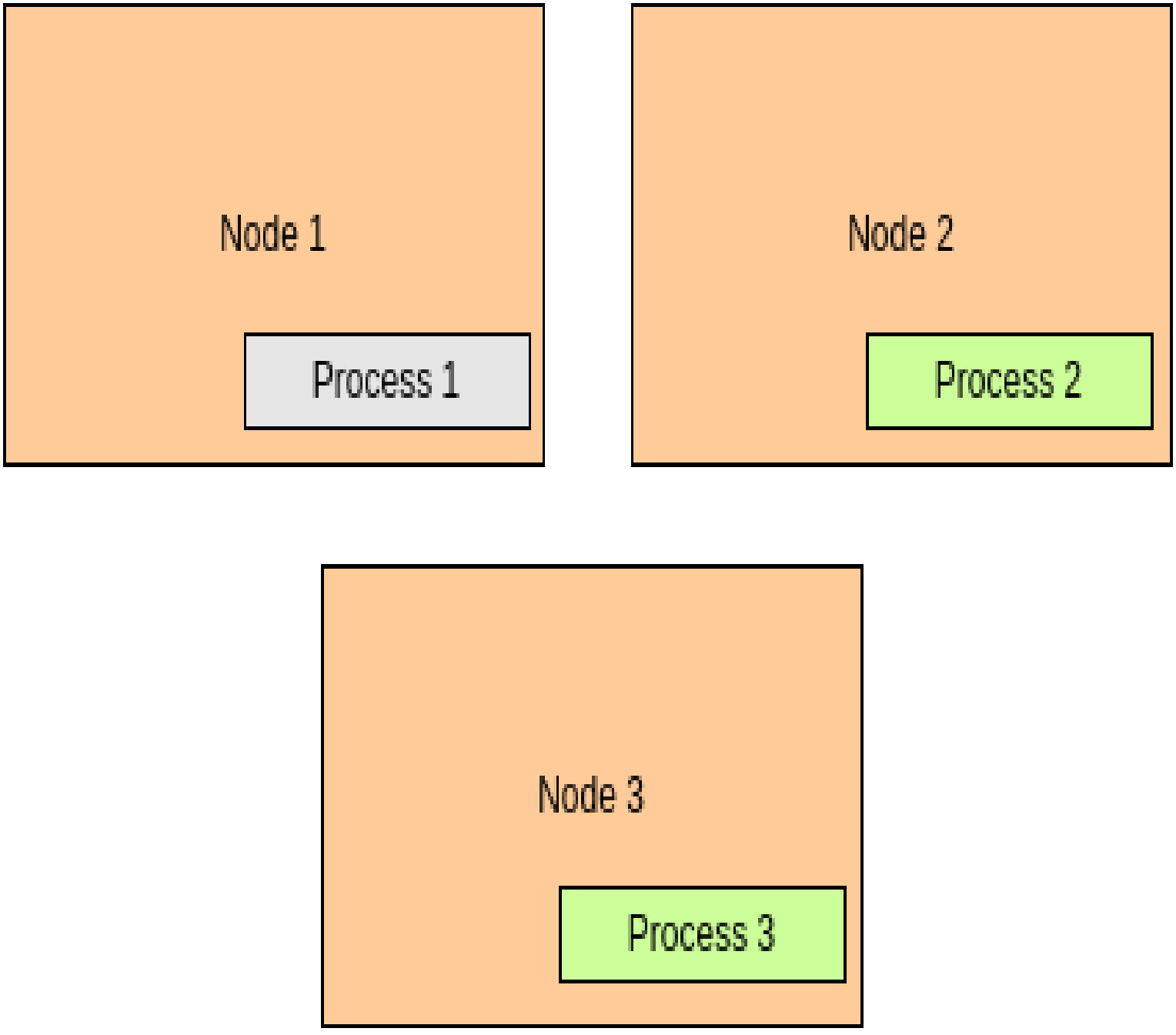
PlusCal

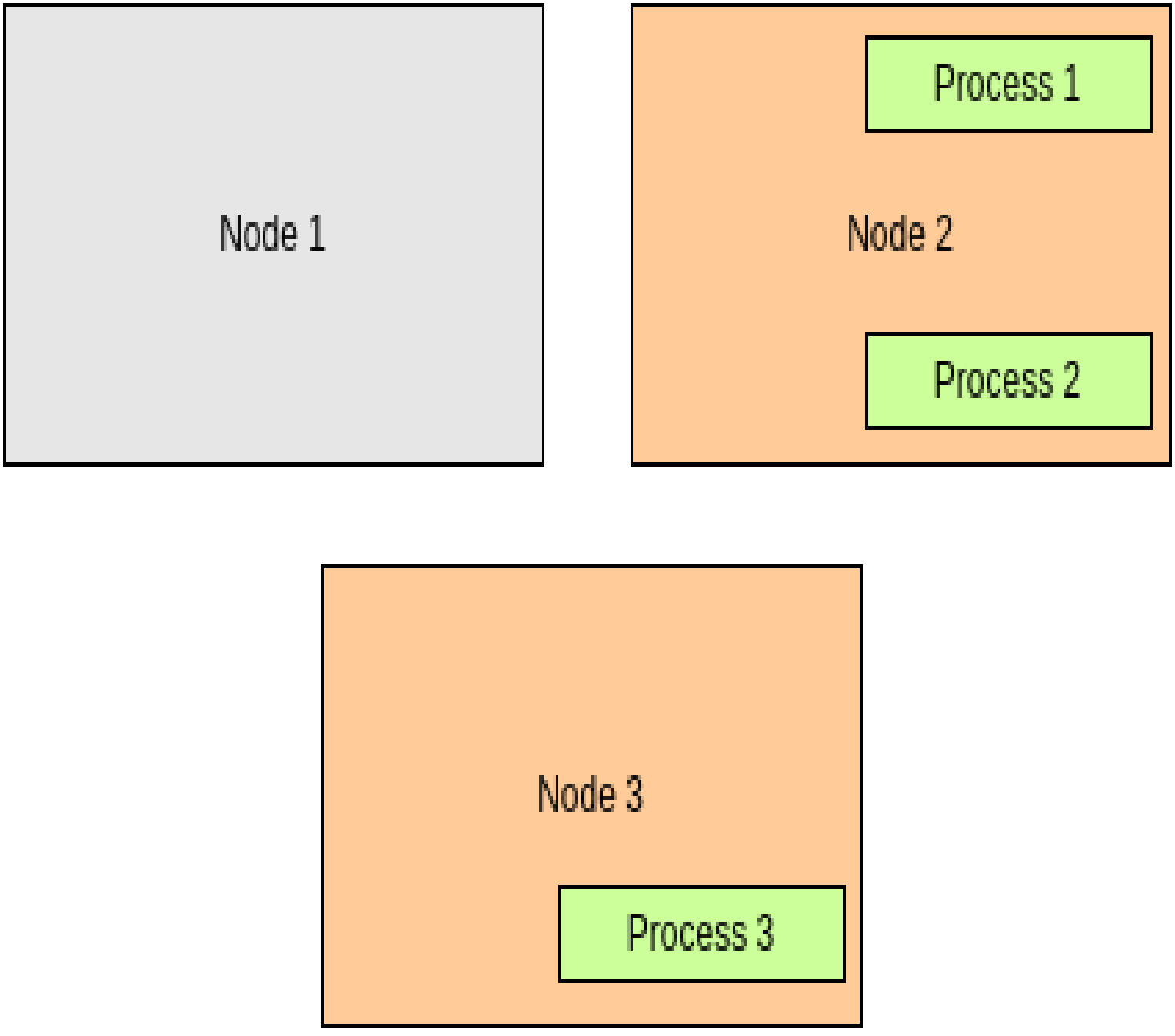
- A little more programmer-friendly
- We specify processes and TLC will check all behaviours

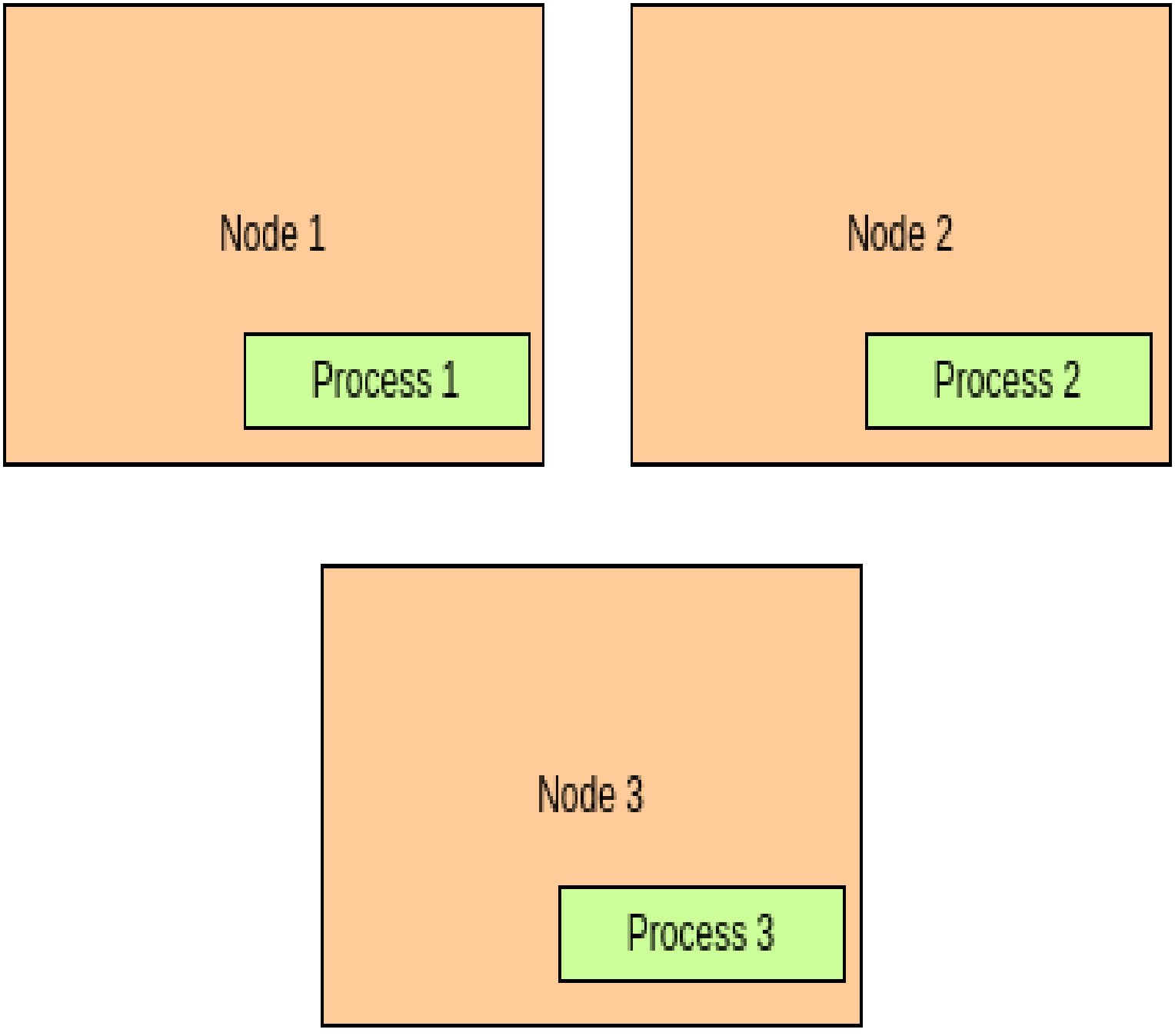
Real world example - health monitor

- We have several nodes (lets say nodes are 1, 2 and 3)
- Every node can reboot and recover later on
- Every node has one instance of service
- When node is down, its service instance gets transferred to another node which is up to serve additional traffic
- When we detect that service instance is stuck, we kill it and restart it
- We state that eventually if service is stuck, this will lead to either it being killed or recovered by itself


Node 1
Process 1
Node 2
Process 2
Node 3
Process 3


Node 1
Process 1
Node 2
Process 2
Node 3
Process 3


Node 1
Process 1
Node 2
Process 2
Node 3
Process 3


Node 1
Process 1
Node 2
Process 2
Node 3
Process 3

Demo

▼ **14: Orchestrator in heartbeat >>**

► alive (1)	{3}
killed (0)	{}
► pc (4) M	(0 :> "RebootNode" @@ 1 :> "NodeDown" @@ 2 :> "NodeDown" …
► replOwner (3)	<<2, 3, 3>>
► replStuck (3)	<<TRUE, TRUE, FALSE>>

▼ **15: RestartReplicator in heartbeat >>**

► alive (1)	{3}
killed (0)	{}
► pc (4) M	(0 :> "RebootNode" @@ 1 :> "NodeDown" @@ 2 :> "NodeDown" …
► replOwner (3)	<<2, 3, 3>>
► replStuck (3)	<<TRUE, TRUE, FALSE>>

▼ **16: RebootNode in heartbeat >>**

► alive (1)	{3}
killed (0)	{}
► pc (4) M	(0 :> "Orchestrator" @@ 1 :> "NodeDown" @@ 2 :> "NodeDown" …
► replOwner (3)	<<2, 3, 3>>
► replStuck (3)	<<TRUE, TRUE, FALSE>>

▼ **17: Orchestrator in heartbeat >>**

► alive (1)	{3}
killed (0)	{}
► pc (4) M	(0 :> "RebootNode" @@ 1 :> "NodeDown" @@ 2 :> "NodeDown" …
► replOwner (3)	<<2, 3, 3>>
► replStuck (3)	<<TRUE, TRUE, FALSE>>

▼ **18: P in heartbeat >>**

► alive (1)	{3}
killed (0)	{}
► pc (4) M	(0 :> "RebootNode" @@ 1 :> "NodeDown" @@ 2 :> "NodeDown" …
► replOwner (3)	<<2, 3, 3>>
► replStuck (3)	<<TRUE, TRUE, FALSE>>

► **15: Back to state >>**

Status

Check again Full output

Checking heartbeat.tla / heartbeat.cfg

Success : Fingerprint collision probability: 4.4E-11

Start: 13:23:48 (Jul 4), end: 13:23:55 (Jul 4)

States

Time	Diameter	Found	Distinct	Queue
00:00:00	0	1	1	1
00:00:03	13	36 691	9 543	2 062
00:00:05	21	69 801	14 637	0
00:00:06	21	69 801	14 637	0

Coverage

Module	Action	Total	Distinct
heartbeat	Init	1	1
heartbeat	P	11 895	5 256
heartbeat	CheckIfStuck	11 004	4 365
heartbeat	RestartReplicator	15 465	570
heartbeat	NodeDown	0	0
heartbeat	Orchestrator	9 894	2 964
heartbeat	RebootNode	7 245	208
heartbeat	MakeReplicatorStuck	14 637	1 273
heartbeat	Terminating	0	0

TLAPS

- Language extension on top of TLA+ for proving theorems about system formal specs
- Limited on temporal logic (and not whole temporal logic)
- Still in development
- Translates to Isabelle which is generic theoremprover

Conclusion

- Formal specification can help us reason about systems and communicate better in teams
- There are tools to help us formally specify systems and to check its validity
- More granular we go, more validation we get
- We can specify various kinds of systems and check various kinds of things
  - Termination
  - Security
  - Correctness for given level of granularity

Gossip session