CSCI 7000-001 Distributed Systems Verification

Lec 1: Introduction

CUPLV
CU Programming Languages
& Verification

Introductions

- About me: Gowtham Kaki

- Assistant Professor, Dept. of Computer Science
- New to CU Boulder - Joined Fall 2020
- PhD from Purdue University, 2019.
  - Thesis: Automatic Reasoning Techniques for Non-Serializable Data-Intensive Applications
- Research: Programming Languages and Formal Methods. Applications in Concurrent and Distributed Systems.
- Best known for Quelea (PLDI 2015) and MRDTs (OOPSLA 2019).
- Enjoy reading pop-science books (recent: Emperor of All Maladies) and biographies/memoirs (recent: Hillbilly Elegy). Amateur cartoonist and racquetball player. Maker of terrible puns.

- About you?
  - Name
  - Academic program
  - Research interests
  - Other interests

About the course

- Key learning objective is to appreciate and internalize a scientific approach to building and reasoning about distributed systems.
- We shall learn formal mathematics to reason about distributed systems, and apply it to design novel systems.
- Why do we need formal mathematics?

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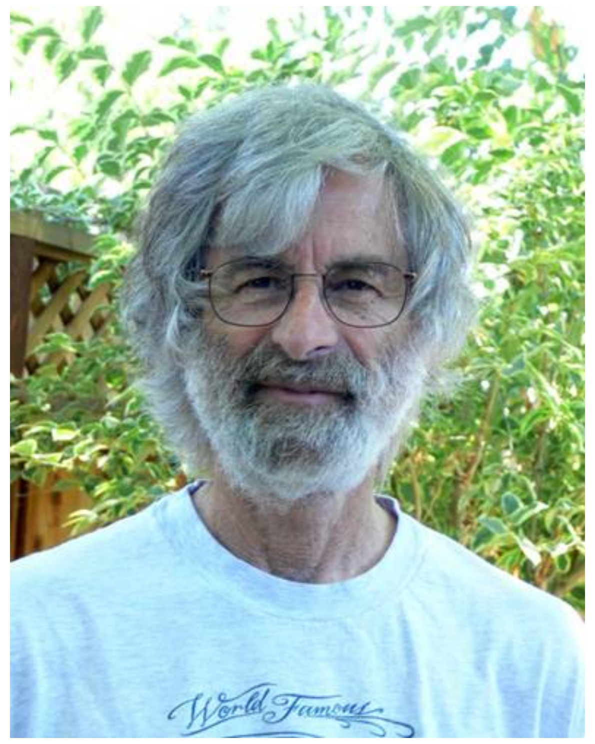

Leslie Lamport

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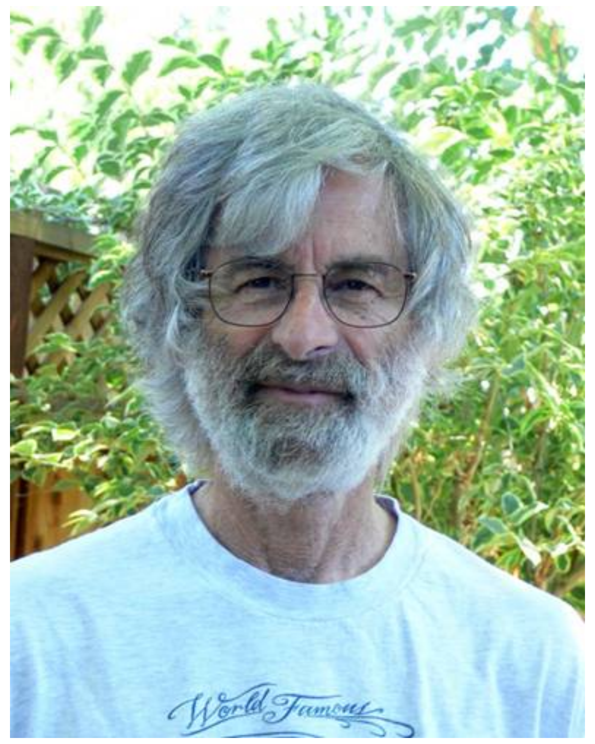

Leslie Lamport

- Distributed systems are complex beasts.
  - Sloppy thinking is easy.
  - Sloppy thinking $\Longrightarrow$ terrible systems.

Course structure

- Seminar-style course:
  - Part 1: Instructor-led lectures (10-12).
  - Part 2: Student-led paper presentations and discussions (≥ 2×#students).
- Lectures review the foundations of distributed systems; introduce relevant formal methods & tools.
  - Asynchronicity
  - Logical Time & Vector Clocks
  - Consensus
  - Fault tolerance
  - Safety and Liveness
  - FLP & CAP Impossibilities
  - Paxos, Raft etc
  - Byzantine faults
  - State transition systems
  - Temporal Logic of Actions
  - Inductive reasoning
  - Program Logics
  - Refinement Proof Technique
  - TLA+/PlusCal
  - IVy
- Papers presentations review the state-of-the-art in scientific approach to building distributed systems.
  - Tentative list of papers is posted on the course website. List evolves as the semester progresses.

Grading

Item	Weight
Programming assignment (TLA/PlusCal or IVy)	25%
Research paper presentations	30%
Exploratory project based on a research paper	30%
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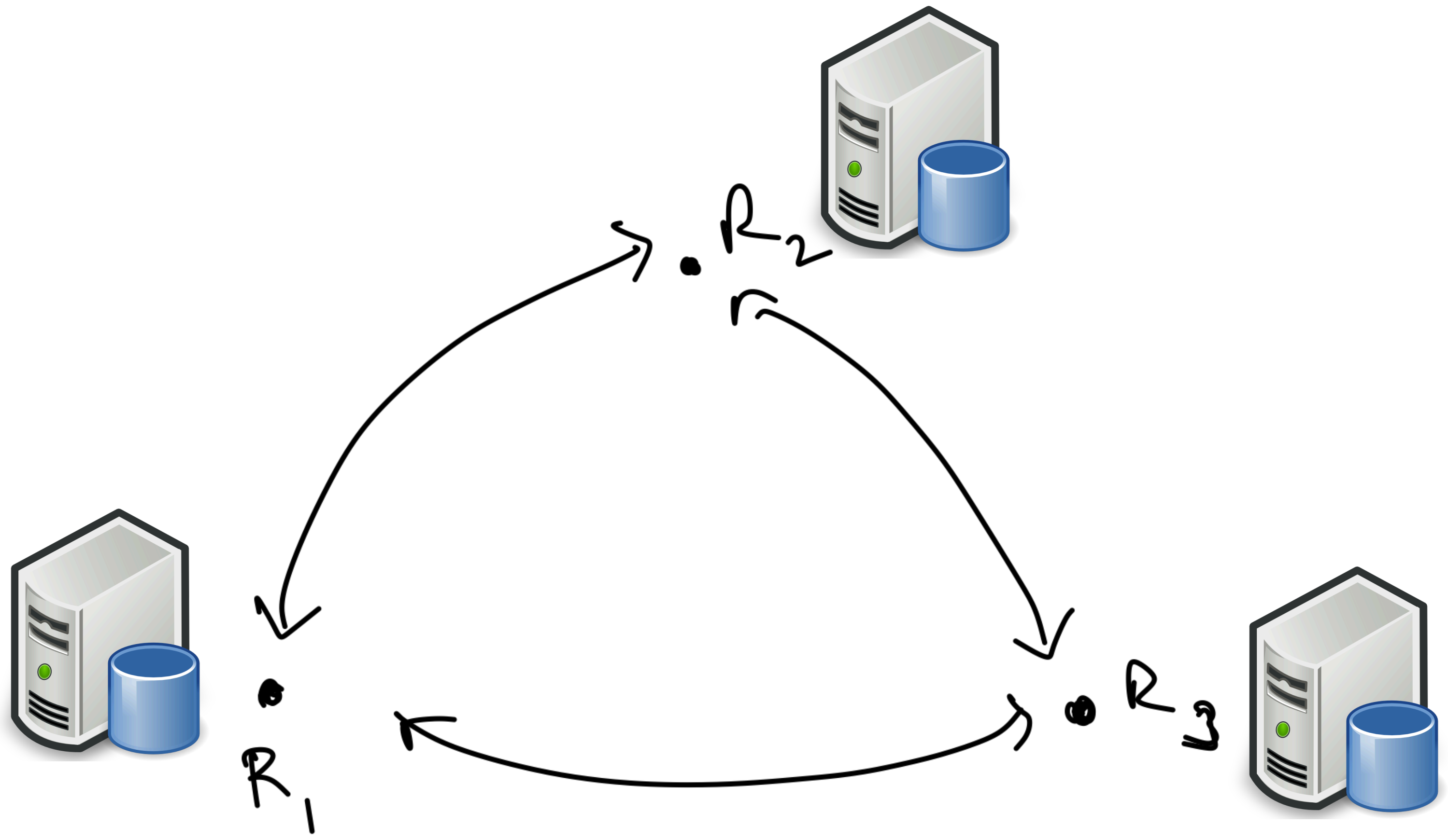
- Important: the intent of grading is *not* to evaluate you, but to incentivize learning.
- Partial credit shall be awarded wherever possible.
- Efforts to think creatively and try something new shall be rewarded even if the outcome is not a total success.
- Let’s learn together and have fun!

Introduction to distributed systems & formal reasoning

Distributed System

- System of interconnected computers coordinating to execute a computational task.



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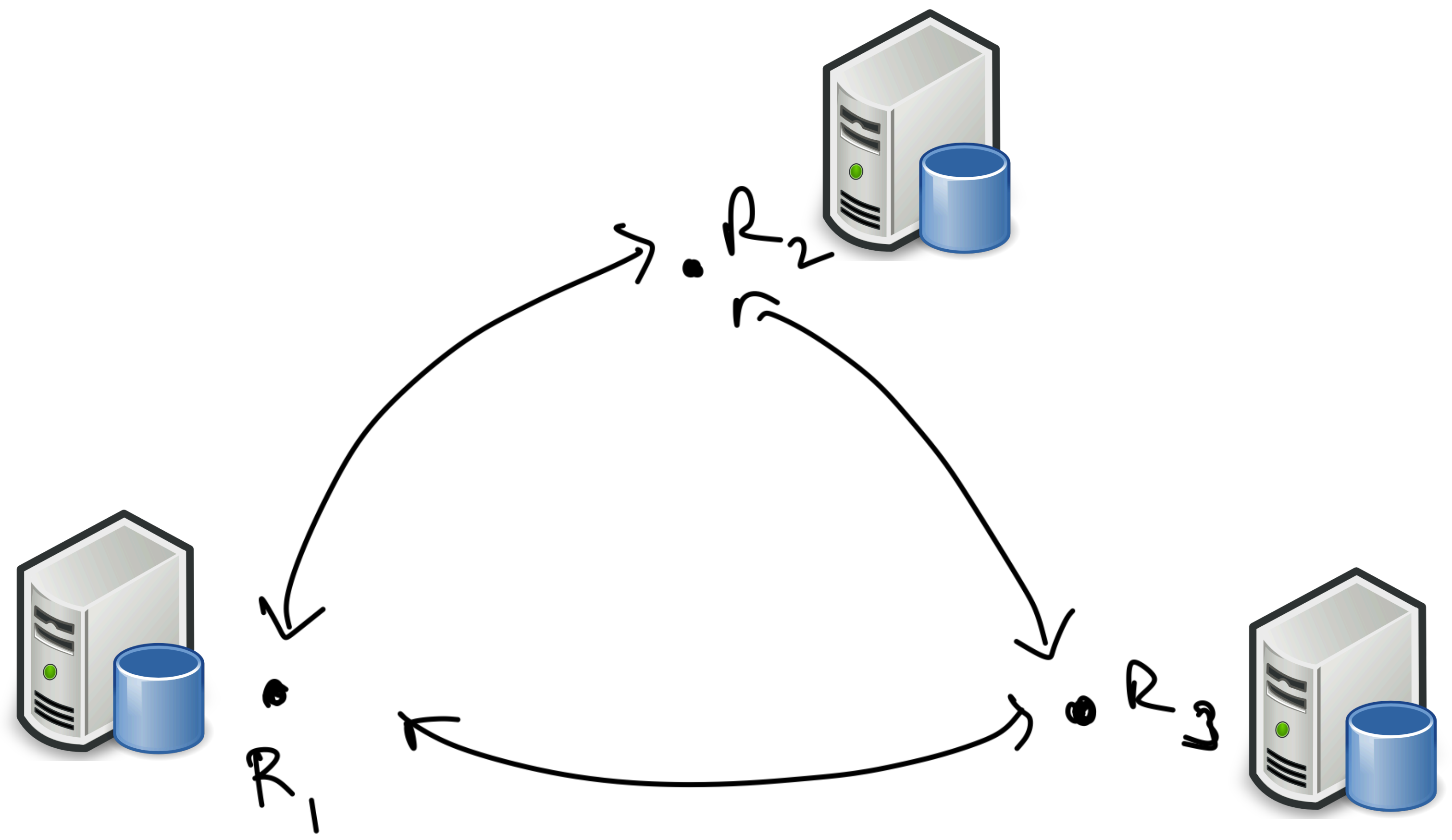

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  - Network never fails (latency is finite and known).
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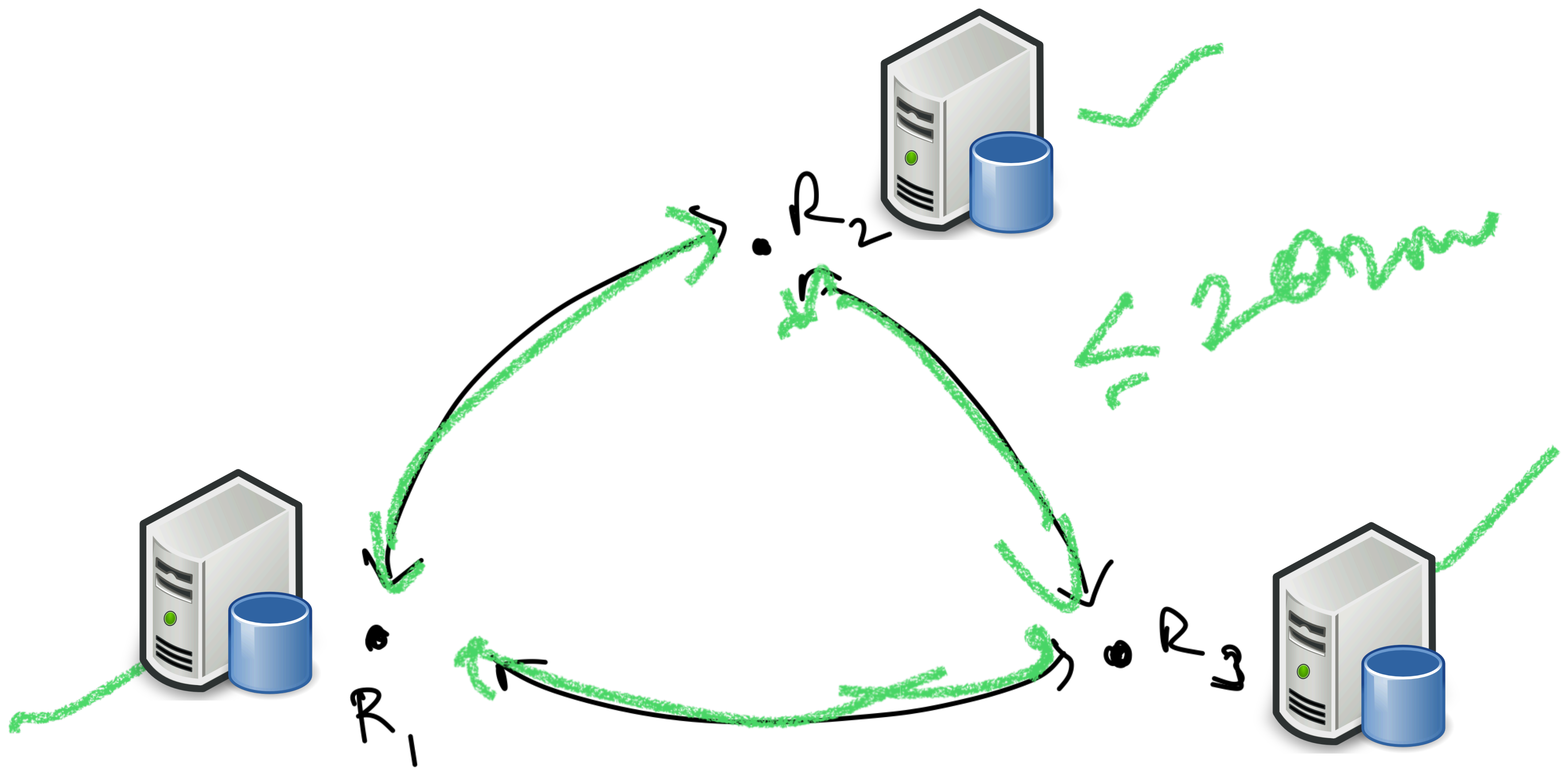

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  - Sub-components can fail independently.
  - Worse: It’s impossible to reliably detect failures!

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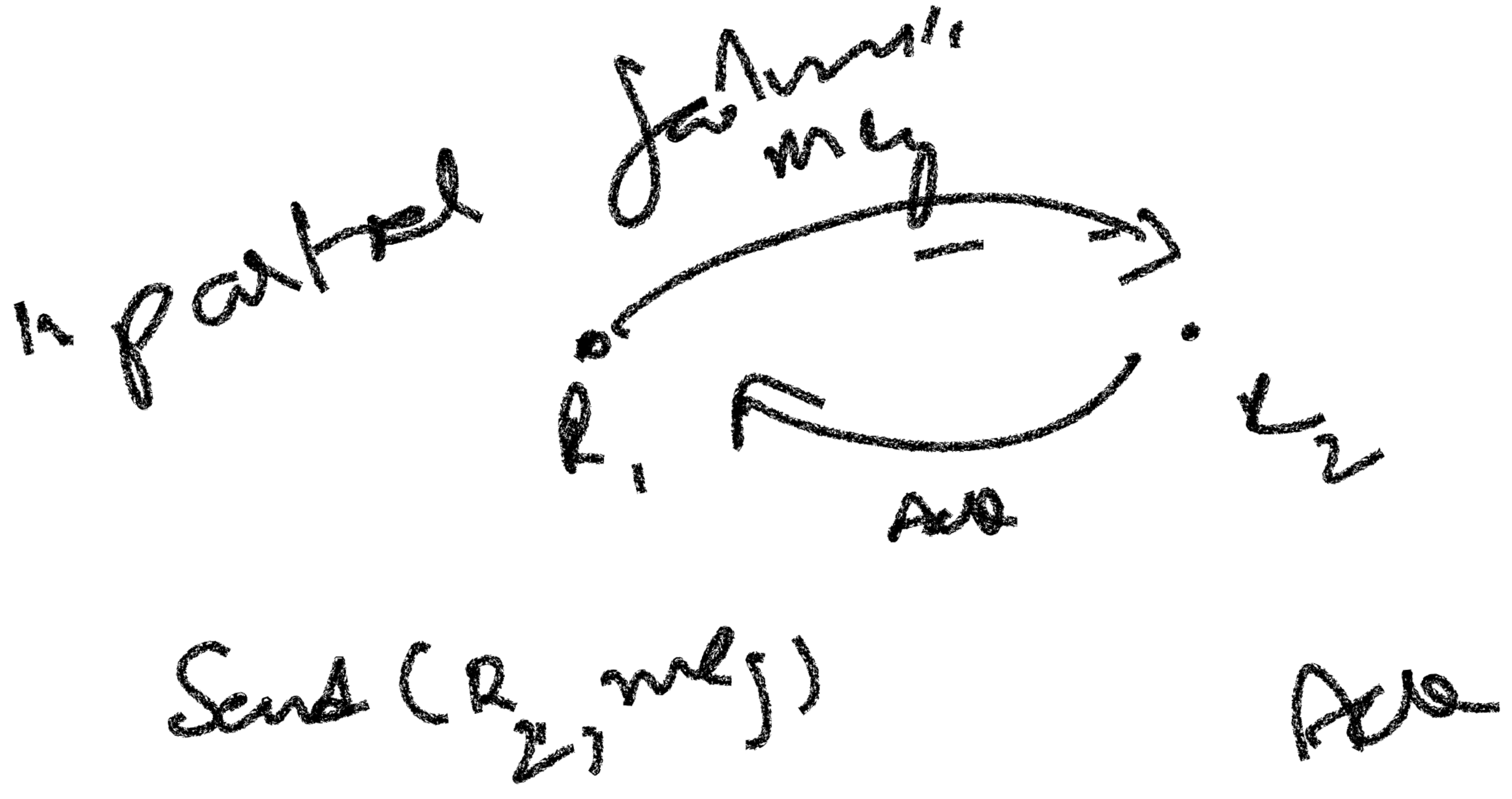

* Server can might fail. because internal error

* Network might fail.

* Network may lose the message.

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Non answer: terminate the program on every failure.

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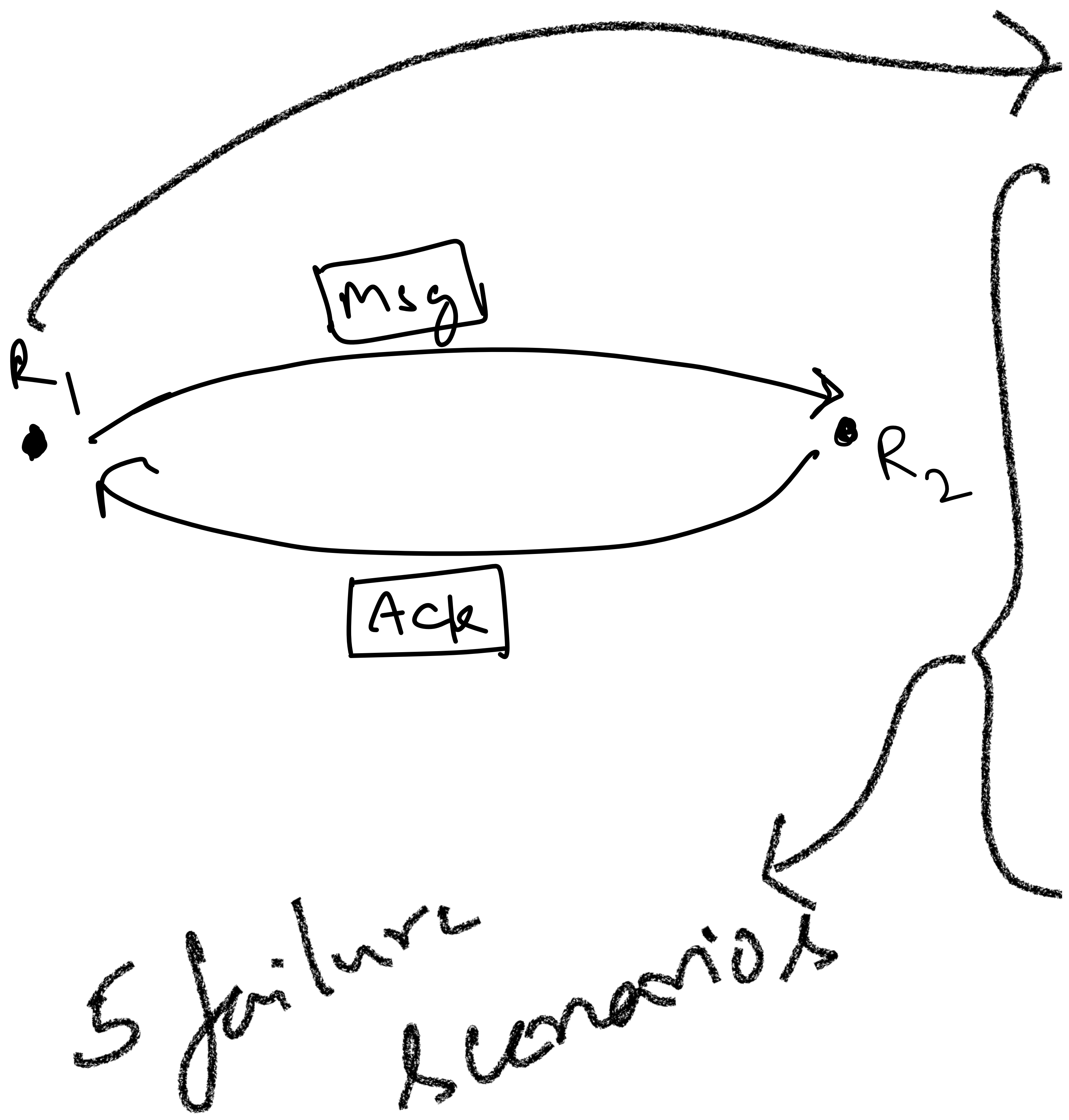

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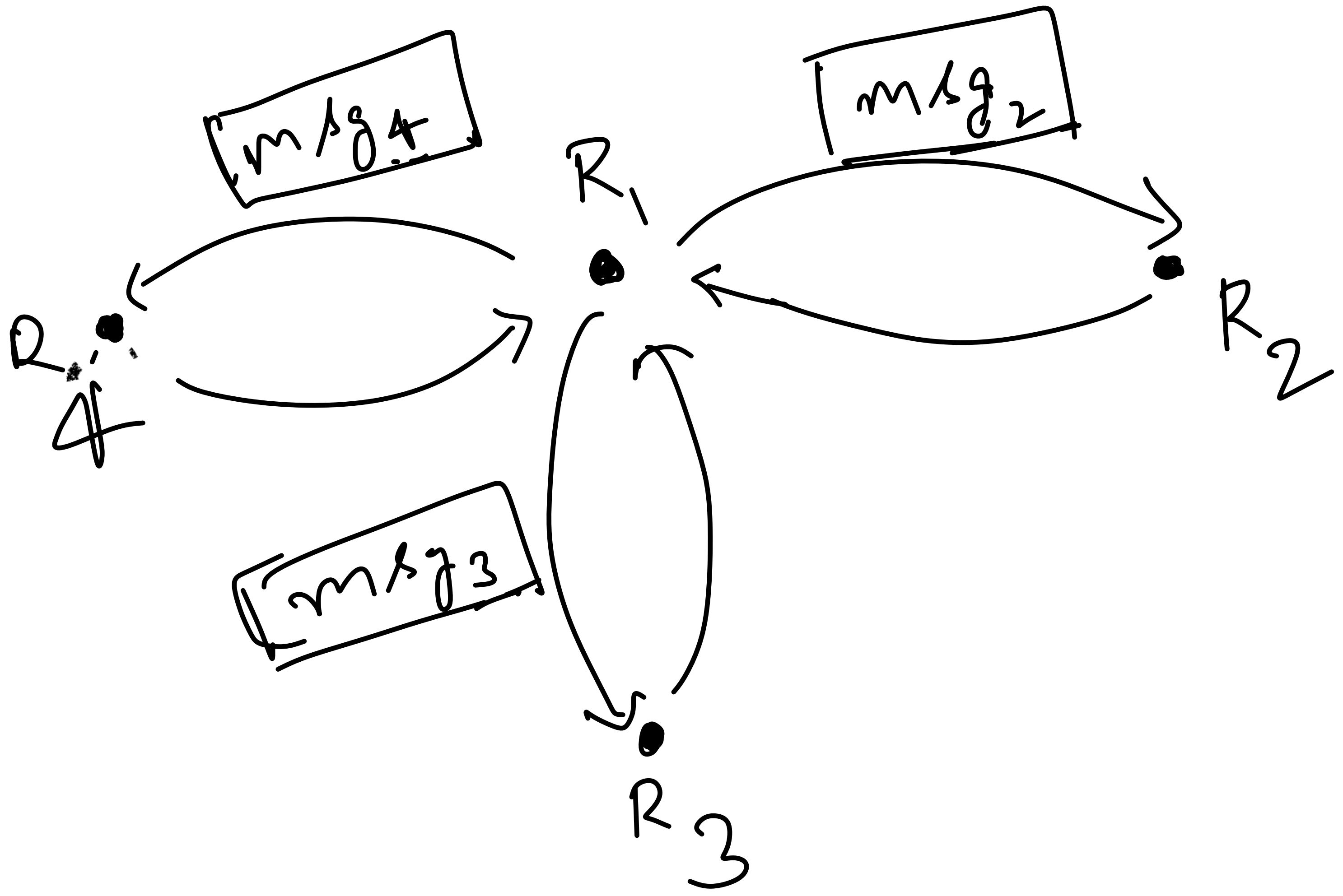
Failure scenarios accumulate



```
for(i=2; i<5; i++) {
    resp[i] = send(R[i], msg[i]);
    //....
}
```

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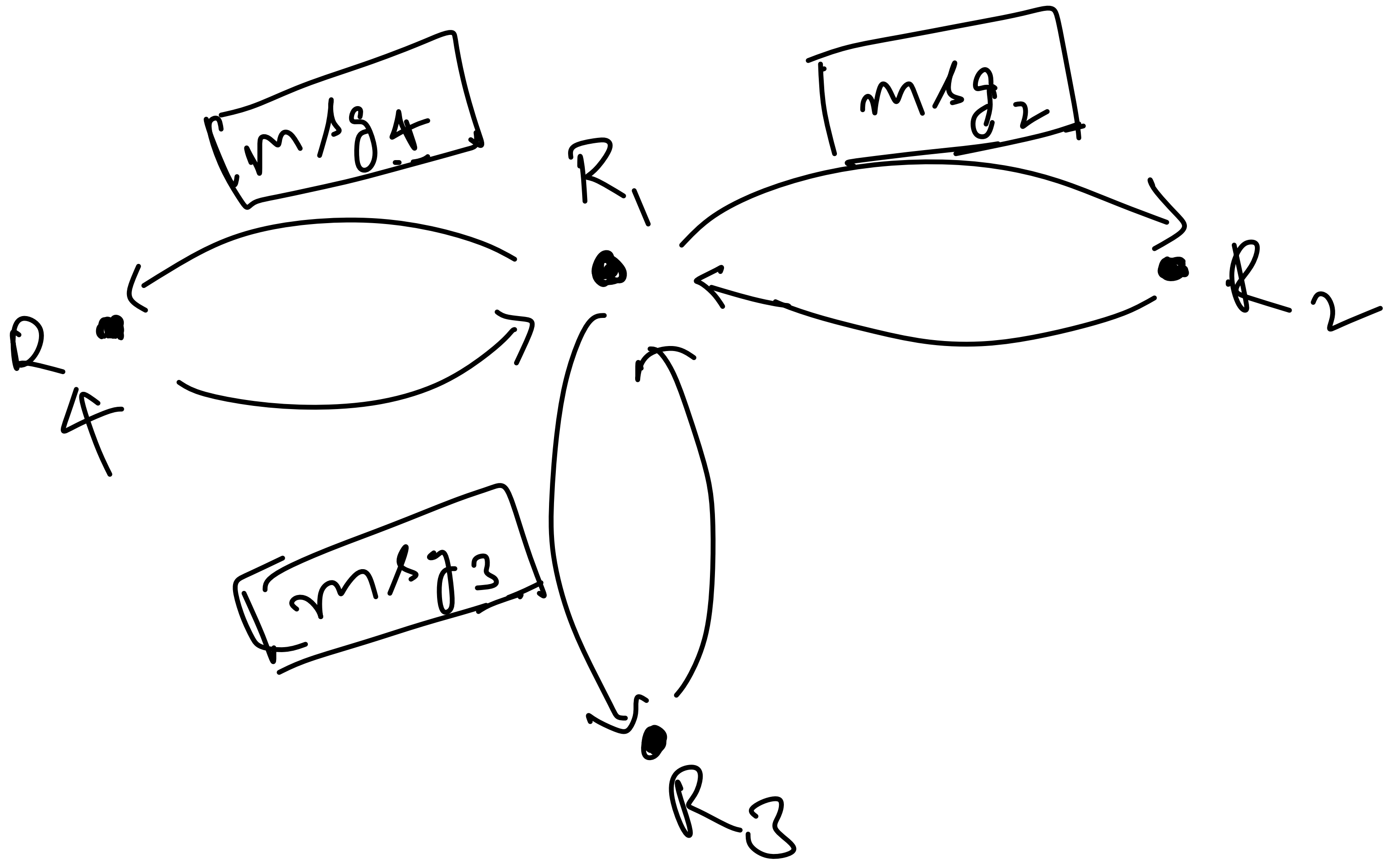

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```

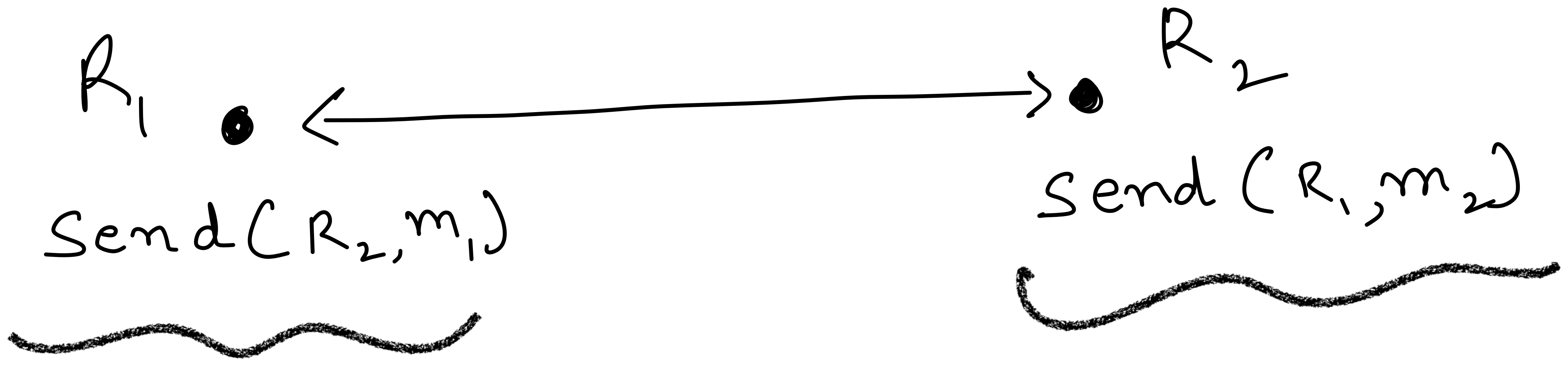
Scenarios:

- `send(R2,..)` fails.
- `send(R2,..)` succeeds, but `send(R3,..)` fails
- `send(R2,..)` and `send(R3,..)` succeed, but `send(R4,..)` fails.

5
+ 5
+ 5

15 failure scenarios

Failure scenarios multiply



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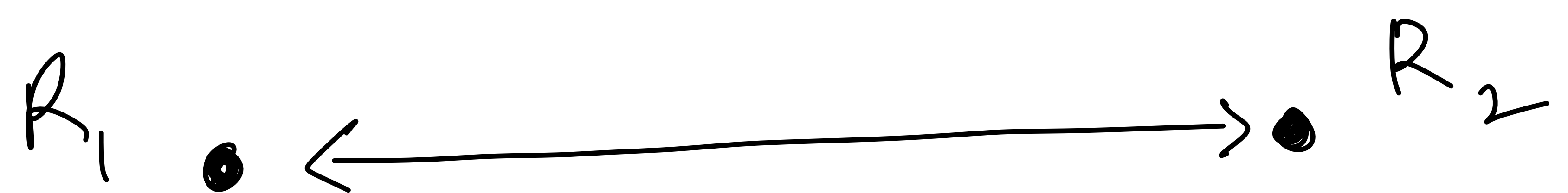

send(R2,m1)

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$\underbrace{5 \times 5}$

25 failure scenarios

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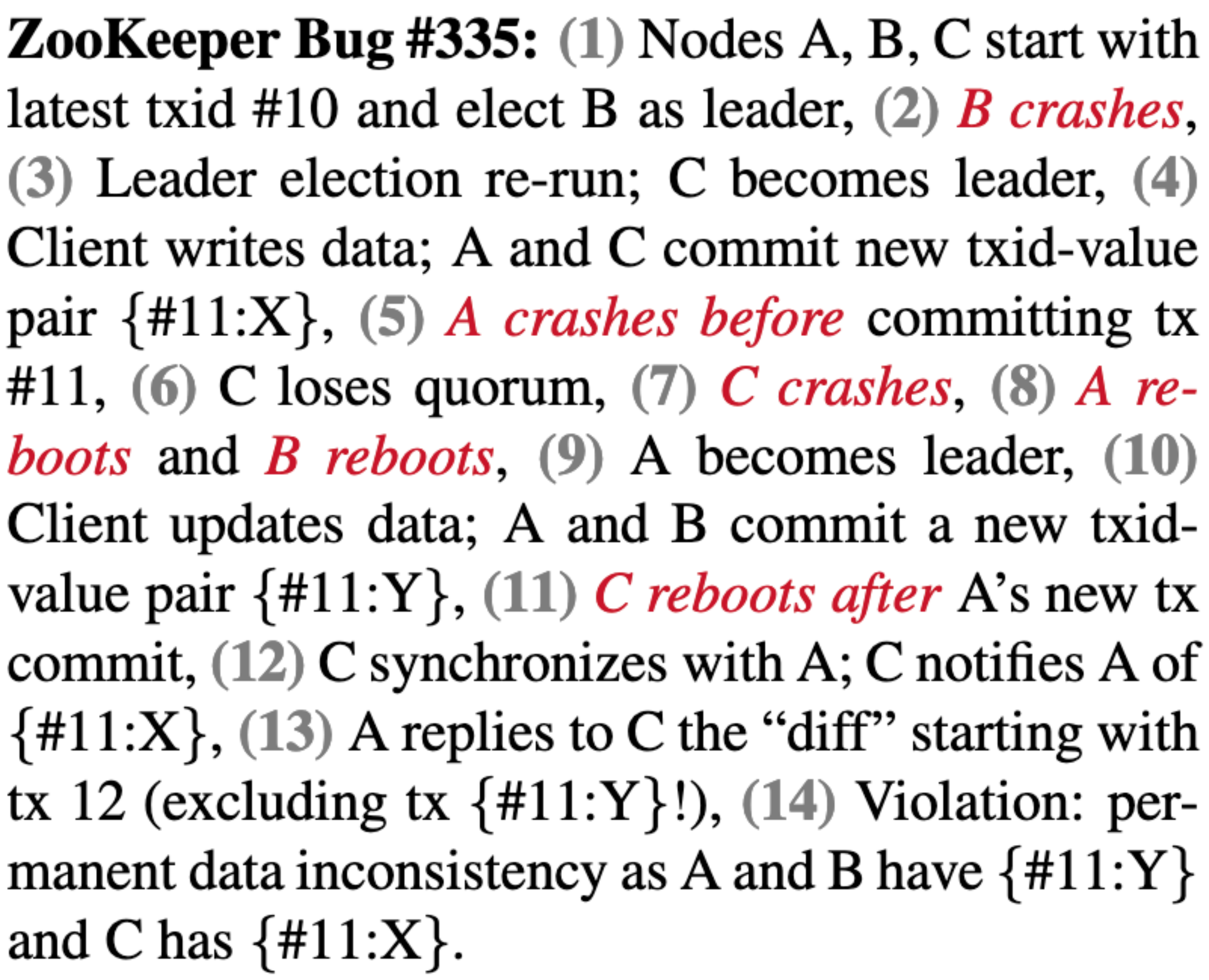
Failure scenarios multiply

- Exhaustively testing a non-trivial distributed system is practically impossible!

Failure scenarios multiply

- Exhaustively testing a non-trivial distributed system is practically impossible!
- Debugging is nightmarish!

From Leesatapornwongsa et al, OSDI’14:



ZooKeeper Bug #335: (1) Nodes A, B, C start with latest txid #10 and elect B as leader, (2) *B crashes*, (3) Leader election re-run; C becomes leader, (4) Client writes data; A and C commit new txid-value pair {#11:X}, (5) *A crashes before* committing tx #11, (6) C loses quorum, (7) *C crashes*, (8) *A reboots* and *B reboots*, (9) A becomes leader, (10) Client updates data; A and B commit a new txid-value pair {#11:Y}, (11) *C reboots after* A’s new tx commit, (12) C synchronizes with A; C notifies A of {#11:X}, (13) A replies to C the “diff” starting with tx 12 (excluding tx {#11:Y}!), (14) Violation: permanent data inconsistency as A and B have {#11:Y} and C has {#11:X}.

14 steps!

Testing vs Formal Verification

- E.g., “slow” multiplication.

```
// Assume m>=0 and n>=0
int slow_multiply(int m, int n) {
    int s = 0, i = 0;
    while(i<n){
        s = s + m;
        i = i + 1;
    }
    return s;
}
```

32 bit int

$2^{32} \times 2^{32} = 2^{64}$

~

18 quintillion.

Combinations of unique test inputs!

- `slow_multiply(m,n) = m×n`

Testing vs Formal Verification

- E.g., “slow” multiplication.

we assume m & n are non negative to begin with

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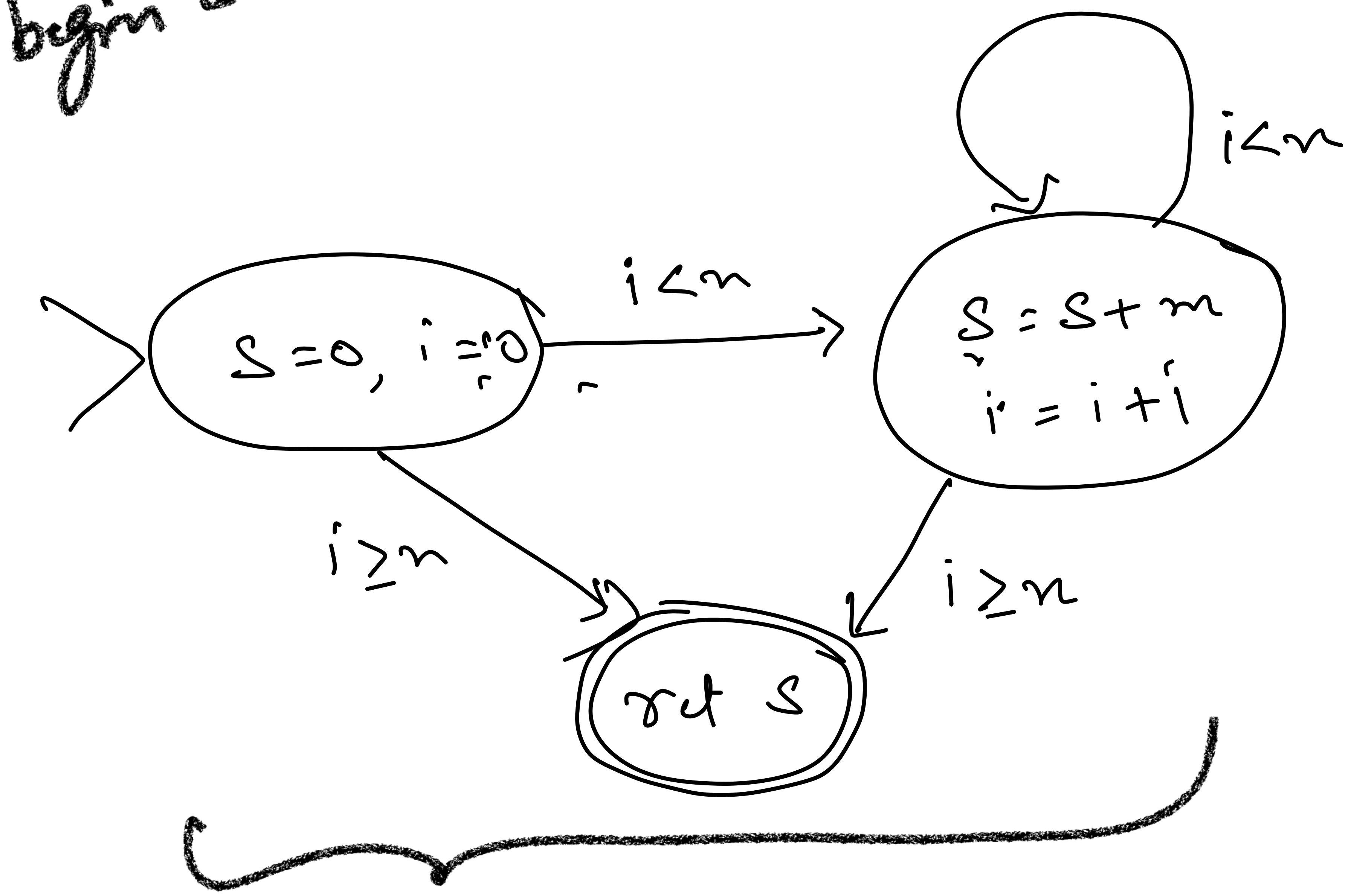
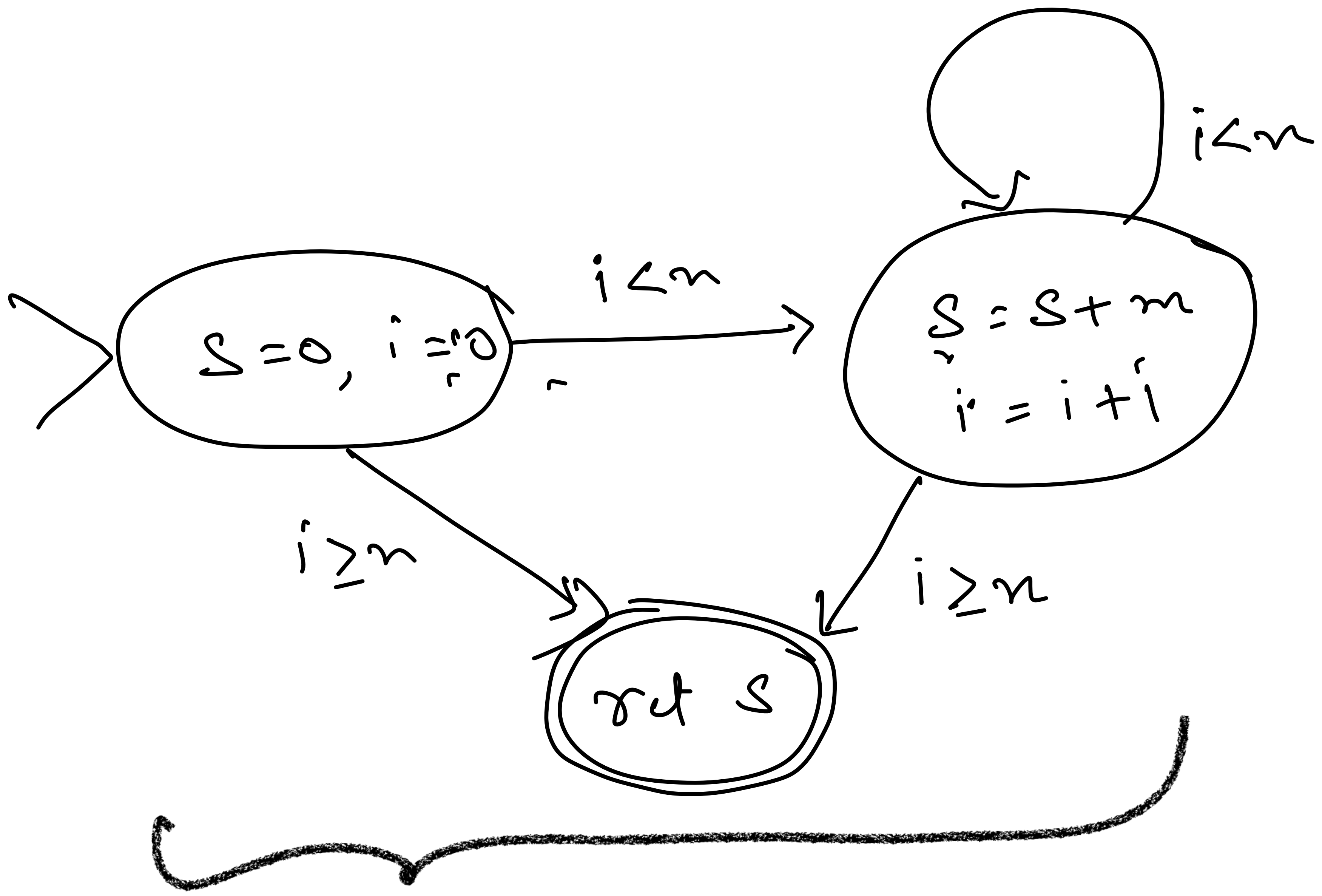
- `slow_multiply(m,n) = m×n`



Let's use a Control-Flow Automaton (CFA) as a mathematical model of the program. We would like to prove that in the final state, s=m×n

Testing vs Formal Verification



Let's use a Control-Flow Automaton (CFA) as a mathematical model of the program. We would like to prove that in the final state, $\underline{s=m\times n}$

Final state has two incoming transitions. If we know the values of s & i before each transition, we can then assert something about their values after the transition. However, we only know the values at initial state, so we can only do this for 1 transition directly.

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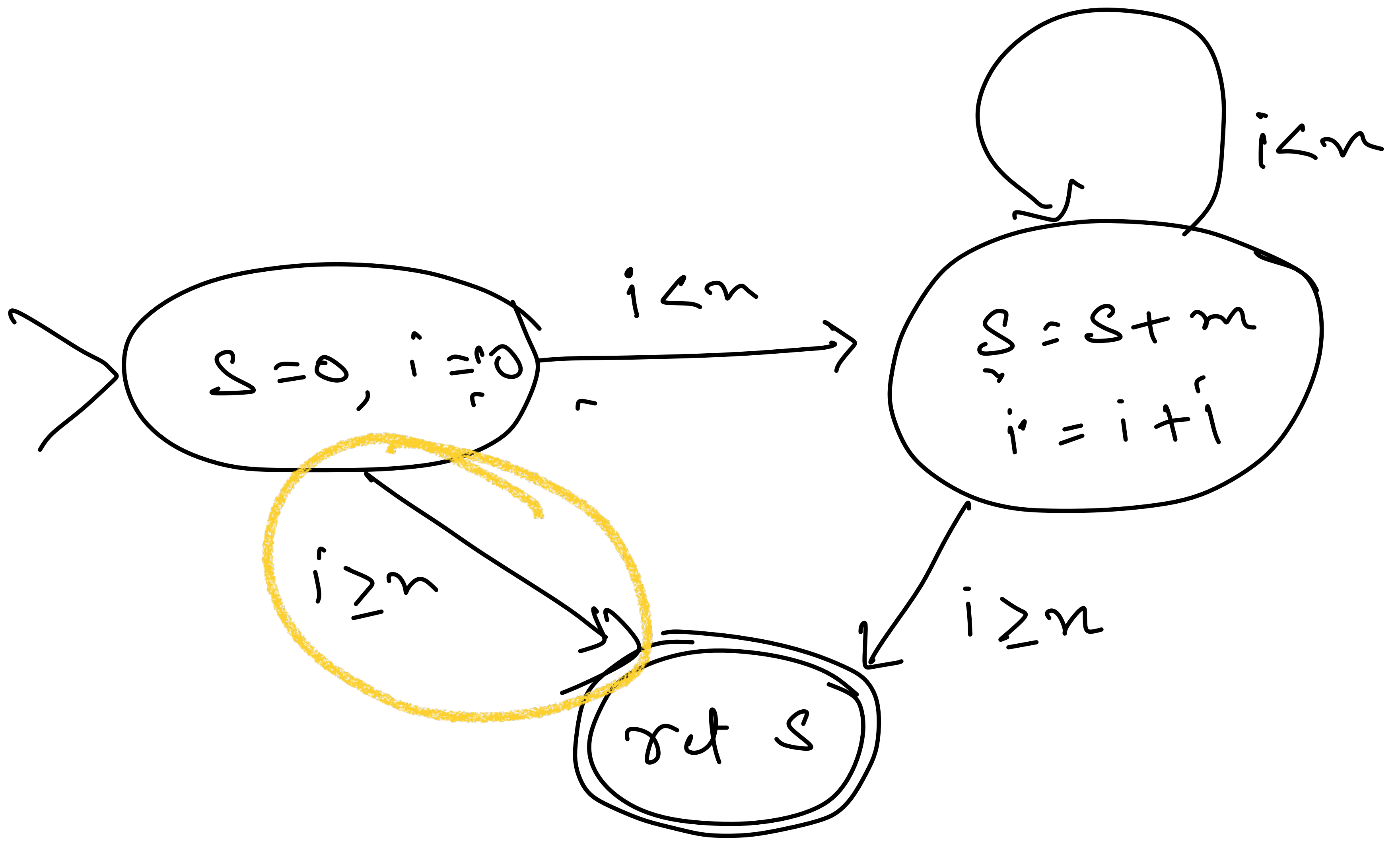


For this transition;

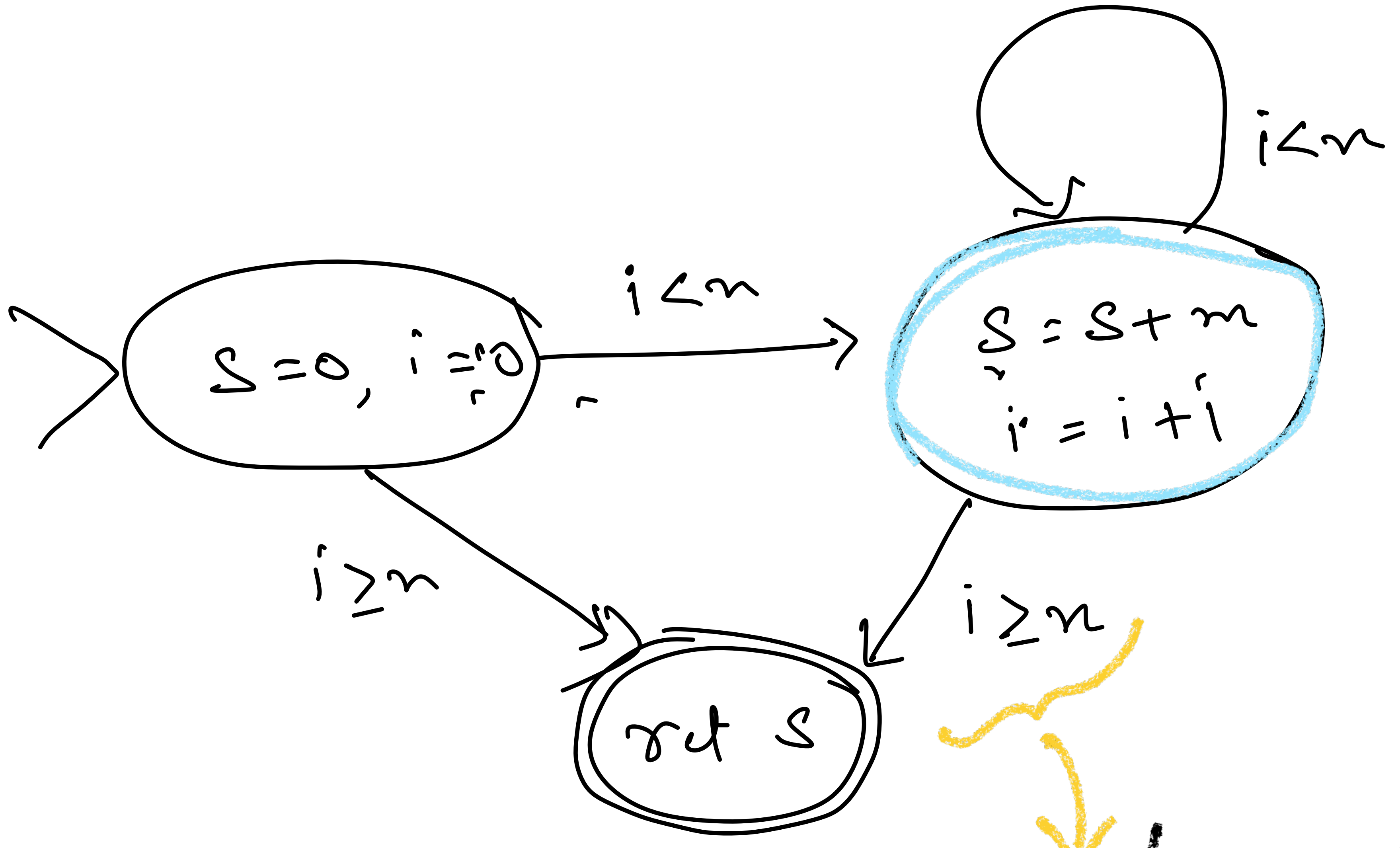
$m \geq 0 \wedge n \geq 0$ (precondition)

$s = 0 \wedge i = 0$ (initial values)

$i \geq n$ (transition condition)

$$\Rightarrow n = 0 \Rightarrow \underline{\underline{s = m \times n}}$$

Testing vs Formal Verification



what about the other transition?

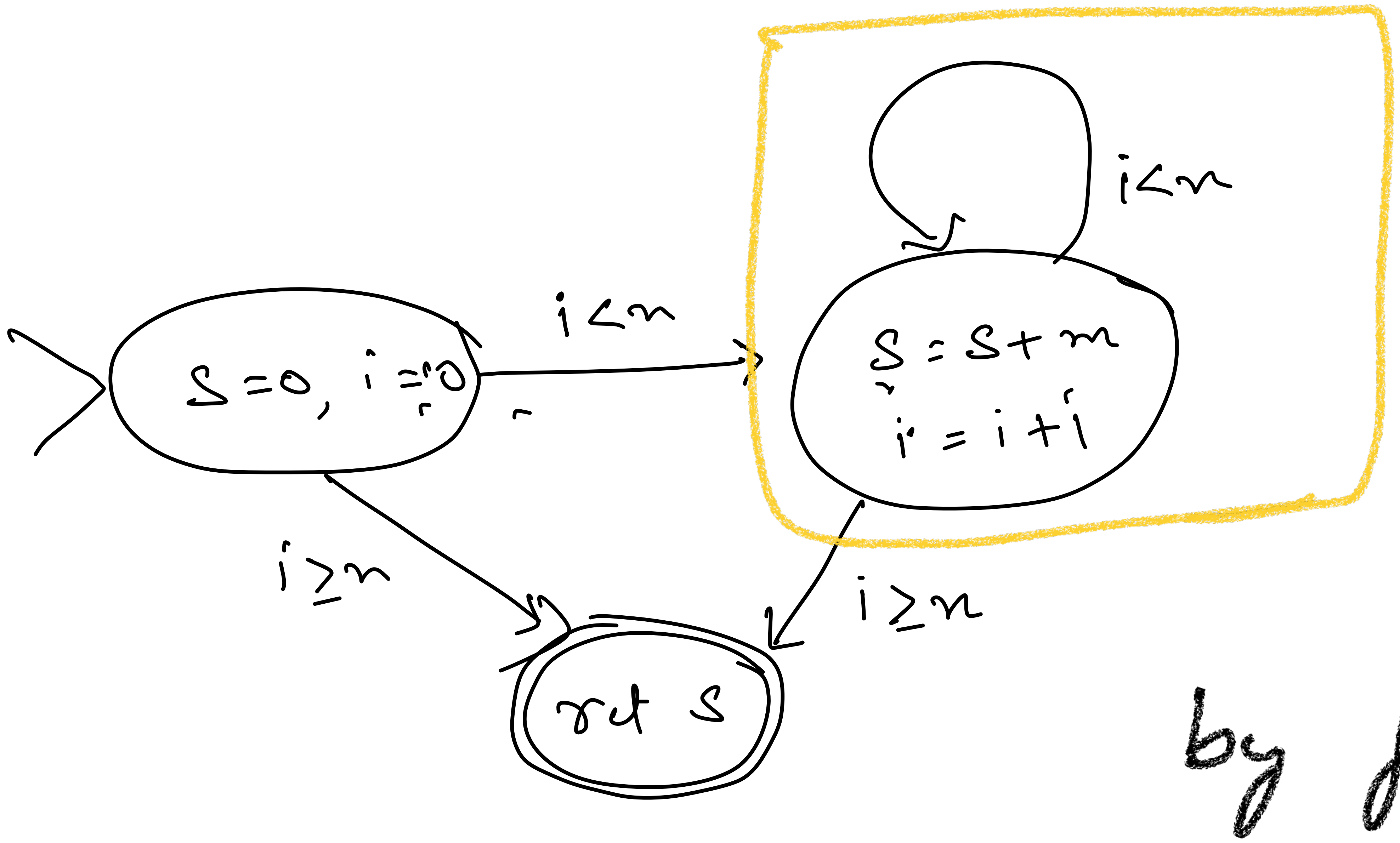
Unfortunately, here we don't know the precise values of s & i in the pre-state. The values are defined "recursively" in terms of themselves

For proof to work, we have to "untangle" this recursion and come up with a formula Φ s.t. Φ is true as long as the control is at the intermediate state (pre-state for final transition; circled in blue)

I claim $\Phi = i \leq n \wedge s = m \times i$

How did I come up with this Φ? purely based on the intuition, but there are automatic methods for this (lookup research on "inductive invariant inference").

Testing vs Formal Verification



Can be replaced by
$i \leq n \wedge s = m \times i$

With the intermediate state replaced by formula $\Phi = i \leq n \wedge s = m \times i$, let's see if we can now reason about second transition.

For the second transition:

$m \geq 0 \wedge n \geq 0$ (Pre condition)

$i \leq n \wedge s = m \times i$ (property of pre-state)

$i \geq n$ (transition condition)

$\Rightarrow i = n \Rightarrow \underline{\underline{s = m \times n}}$

Testing vs Formal Verification

- E.g., "slow" multiplication.

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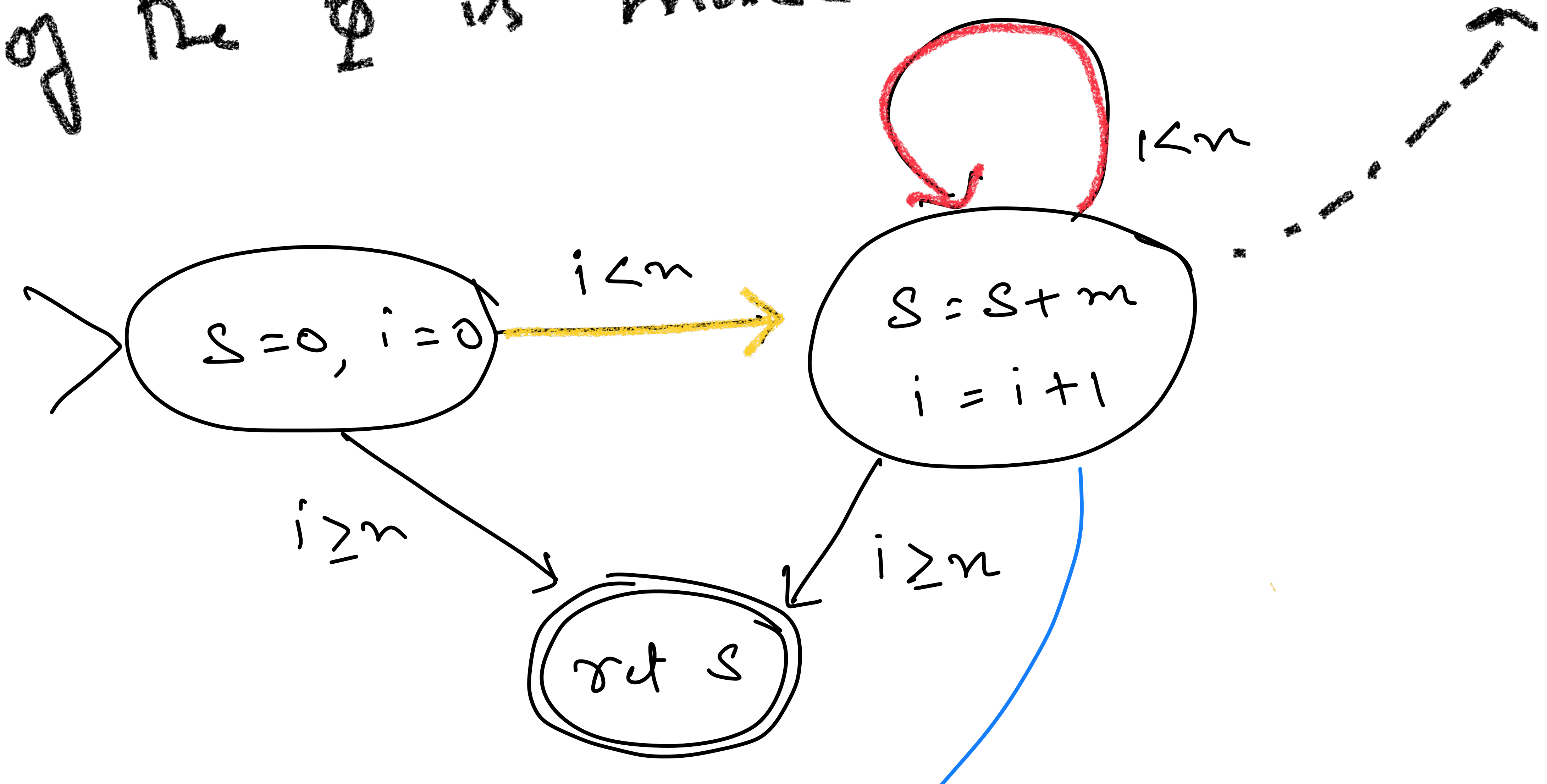
- Prove `slow_multiply(m,n)` = m×n

Prove the Φ is indeed true in this state



Claim: As long as we are in this state, $i \leq n \wedge s = m \times i$

(1) Base Case: $m \geq 0 \wedge n \geq 0 \wedge s = 0 \wedge i = 0 \wedge i < n$

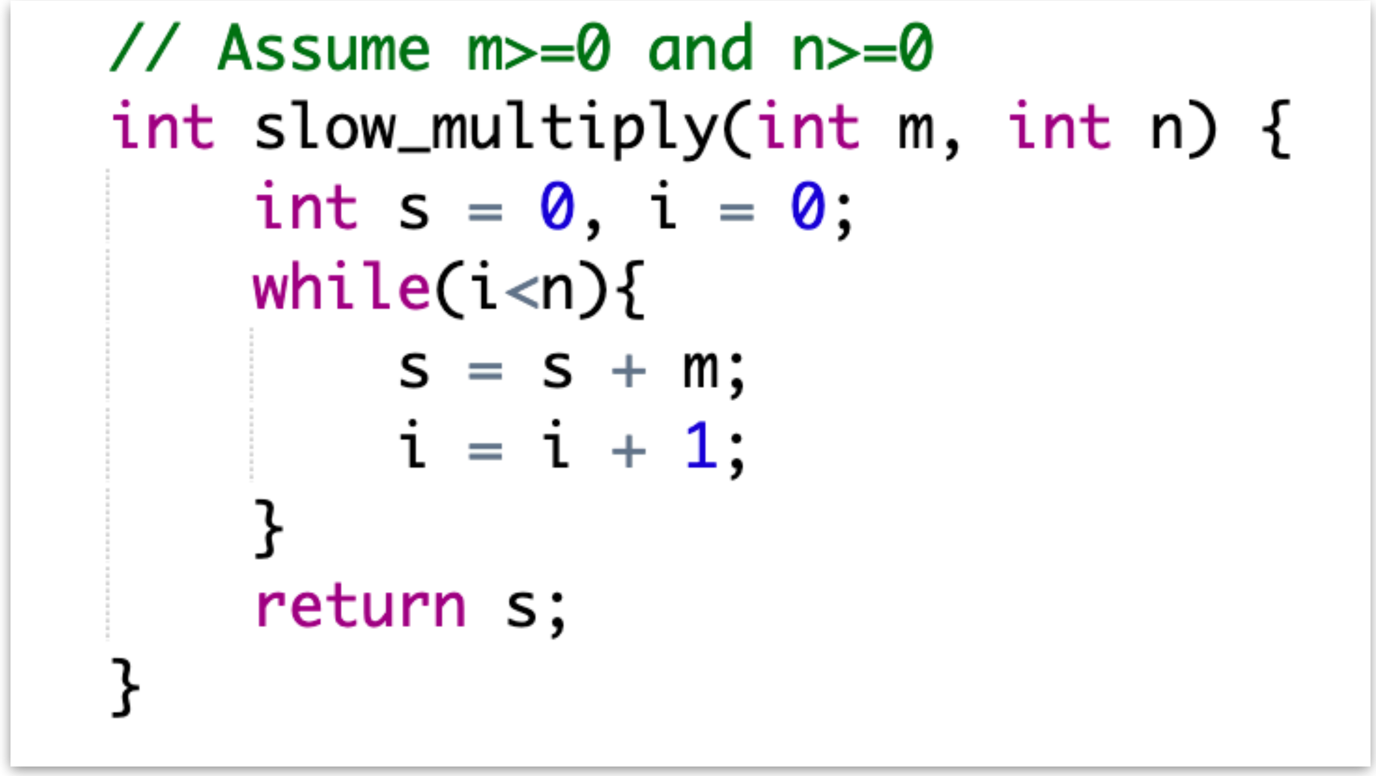
(Yellow transition) $\Rightarrow i \leq n \wedge s = m \times i$

(2) Inductive Case. $i \leq n \wedge s = m \times i \wedge i < n$

(red transition) $\Rightarrow i+1 \leq n \wedge s+m = m \times (i+1)$

Formal Verification for Distributed Systems

- How do we formalize a distributed system/program?



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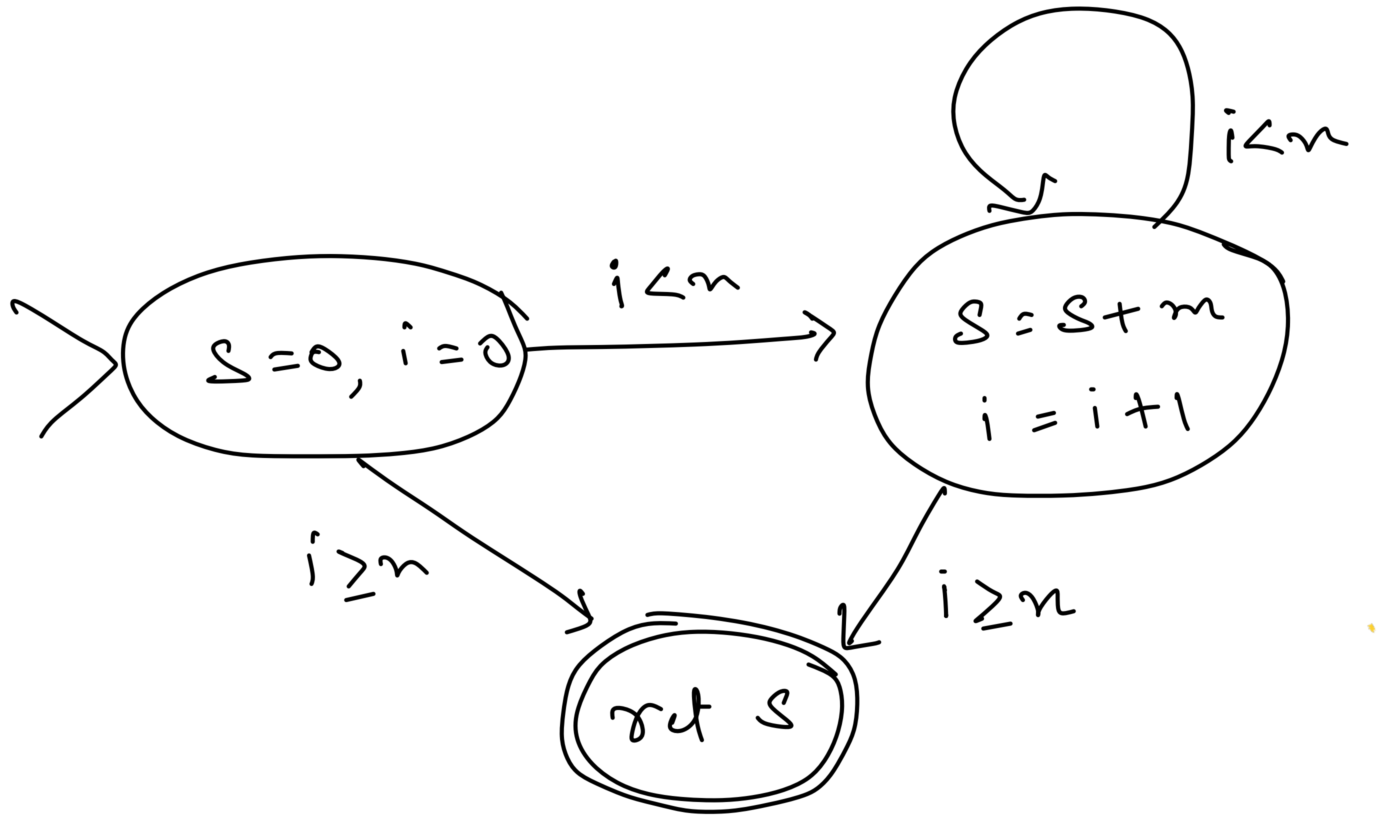
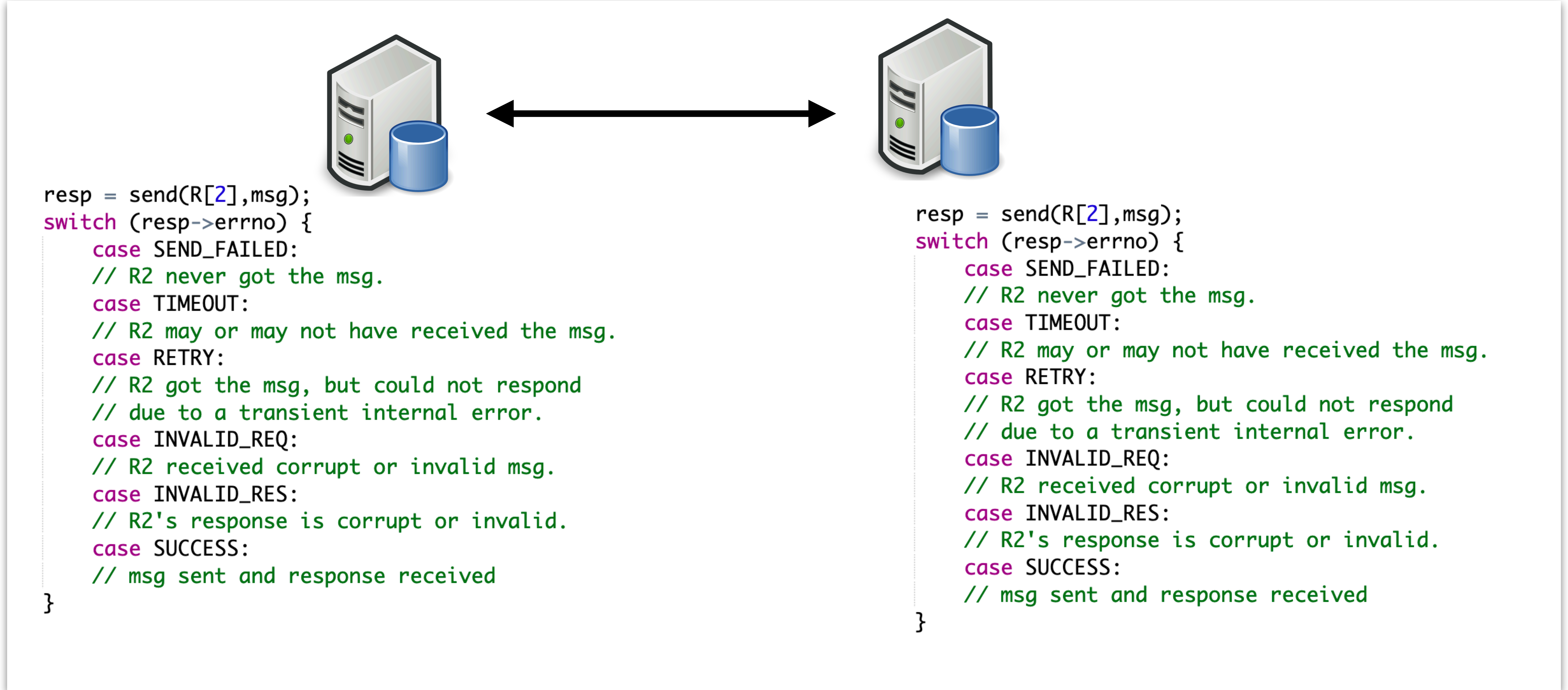
$\cong$





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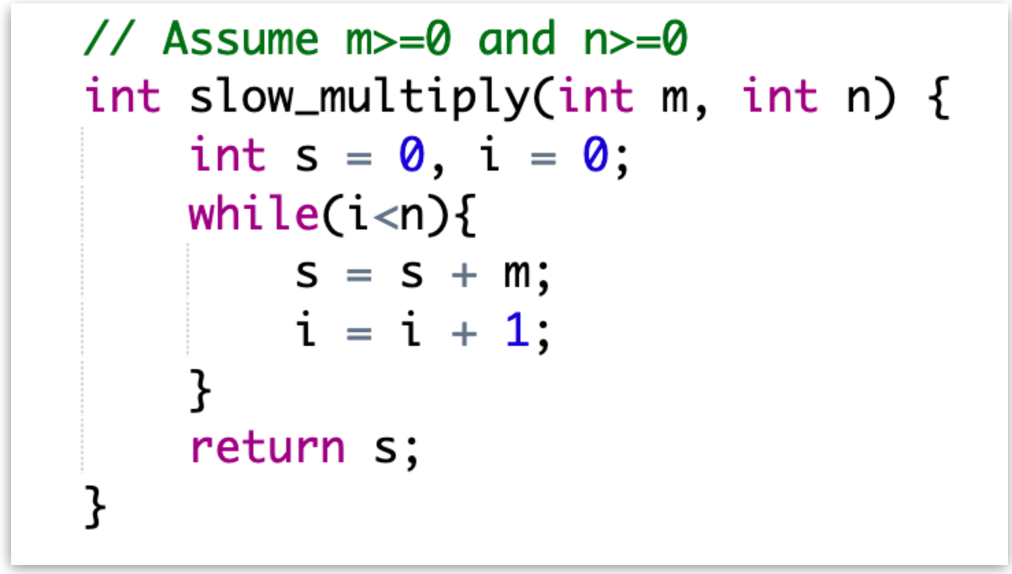
Formal Verification for Distributed Systems

- How do we formalize a distributed system/program?
- What are the properties of interest? How are they specified?

LTL, variants of FOL,



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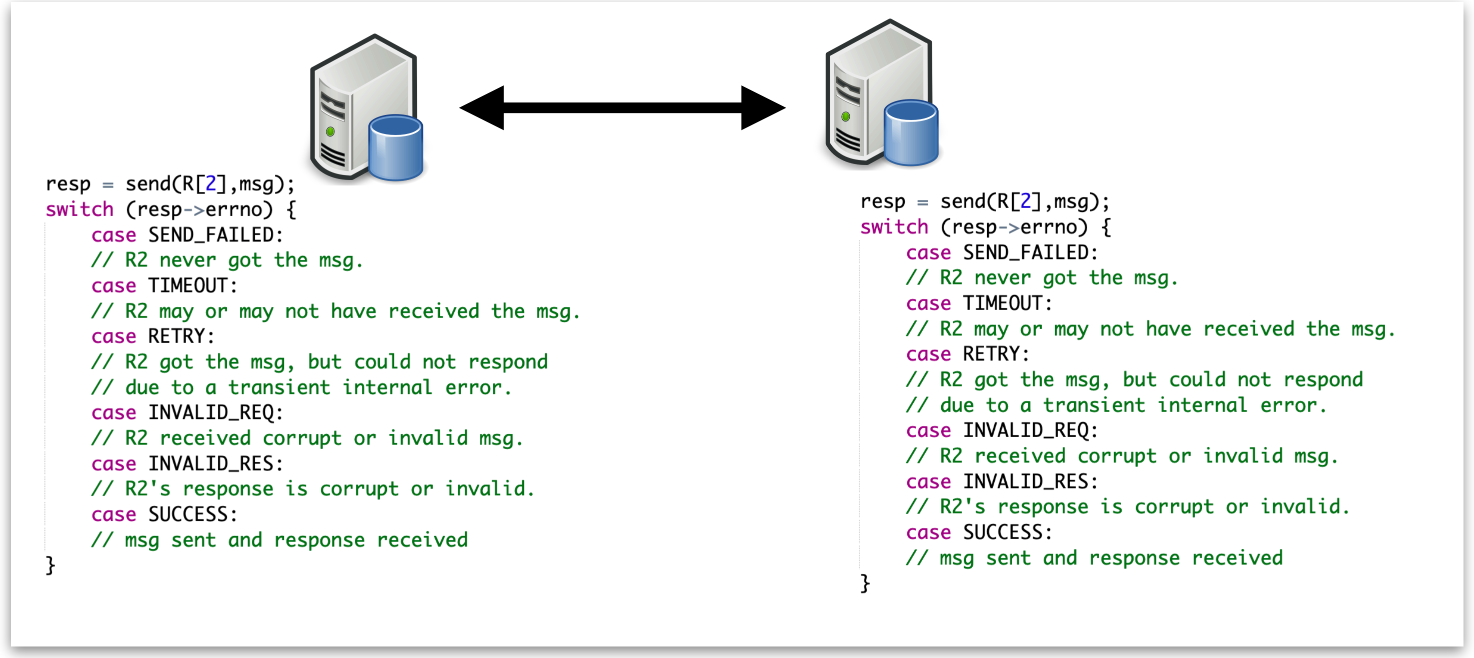

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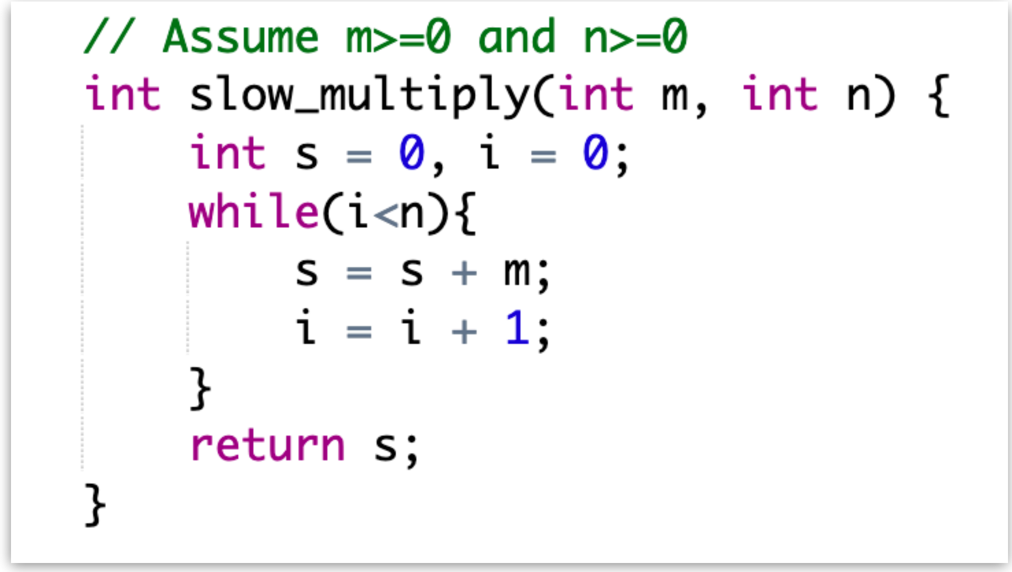
- How do we prove those properties (automatically)?



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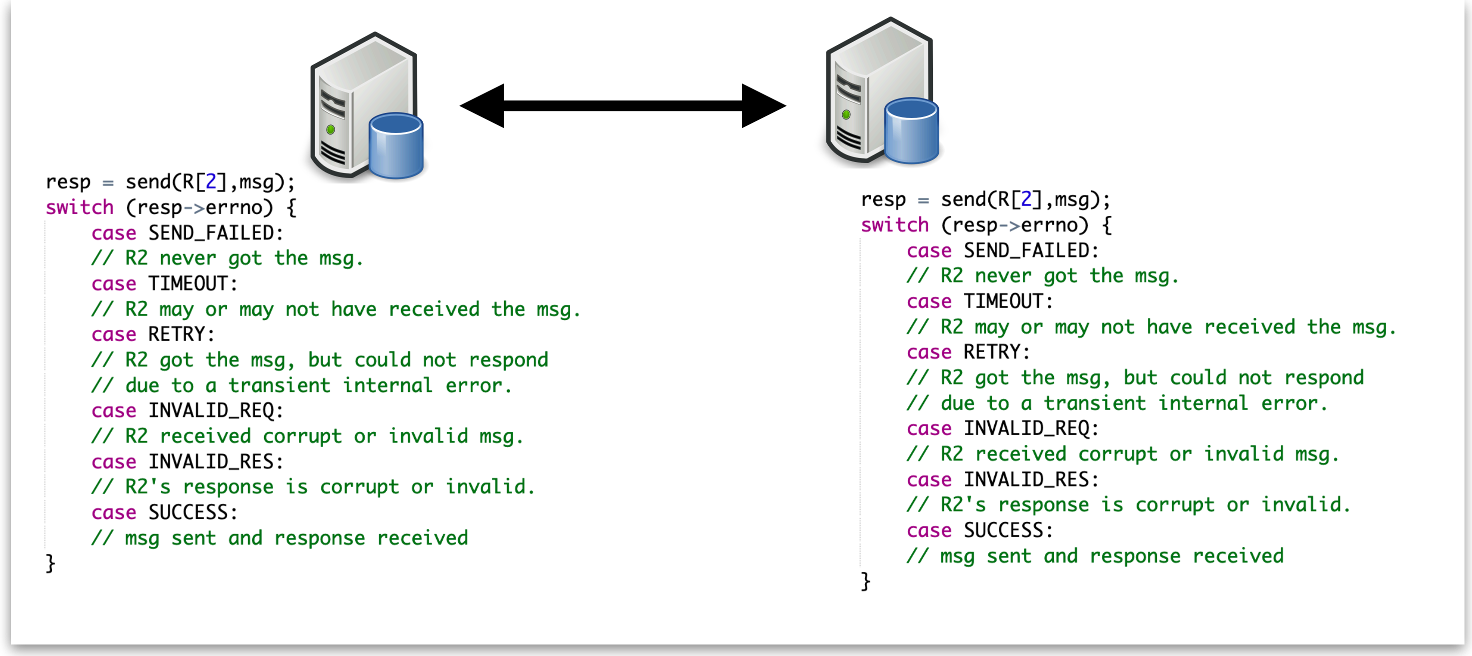
Induction



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???

We hand-wrote informal manual proof of correctness for slow_mult. We don't want to do this for complex distributed programs. How do we automate the reasoning?

Formal Verification for Distributed Systems

- How do we formalize a distributed system/program?
- What are the properties of interest? How are they specified?
- How do we prove those properties (automatically)?

+

- Effective testing strategies
- Design principles
- Domain-specific reasoning techniques

This course!