EECS 570 **Programming Assignment 2**

Discussion

February 17 2020

Announcements

Midterm Exam Wed 2/26

Project Milestone 1

- Report: due Sun 3/8
- Meeting: Mon 3/9

PA2

- Waypoint Report: due Mon 3/16
- Final Submission: due Mon 3/30

1. **Cache Coherence**
2. **PA 2 Overview**
3. **Murphi** (Tutorial)

EECS 570

Designing Cache Coherence Protocol using Murphi

Winter 2020

Slides developed in part by Profs. Adve, Falsafi, Hill, Lebeck, Martin, Narayanasamy, Nowatzyk, Reinhardt, Roth, Smith, Singh, and Wenisch.

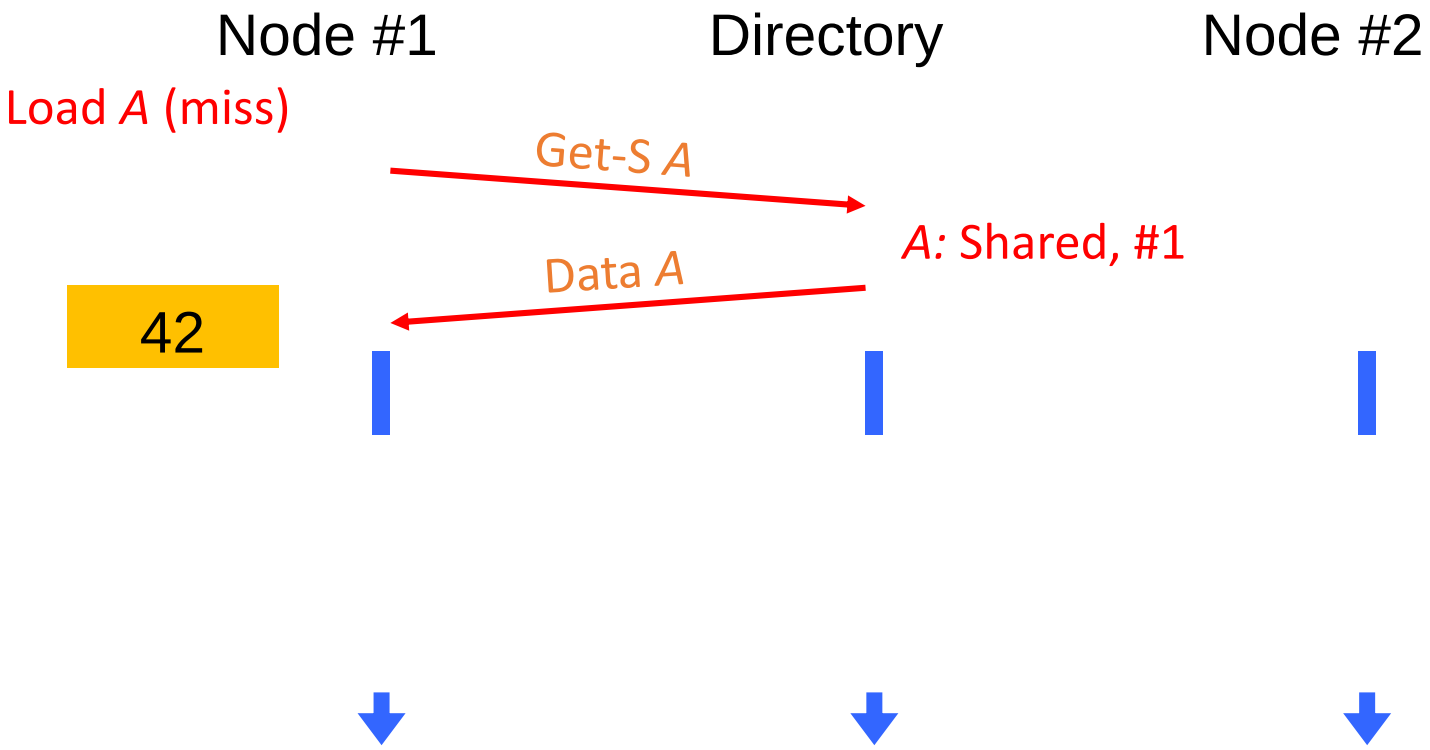
Cache Coherence

- Why?
  - In the presence of caches, orchestrate access to shared memory in a multi-core system
- What?
  - A load returns the most recent value written
  - For a single memory location only
- How?
  - Well, many many flavors!

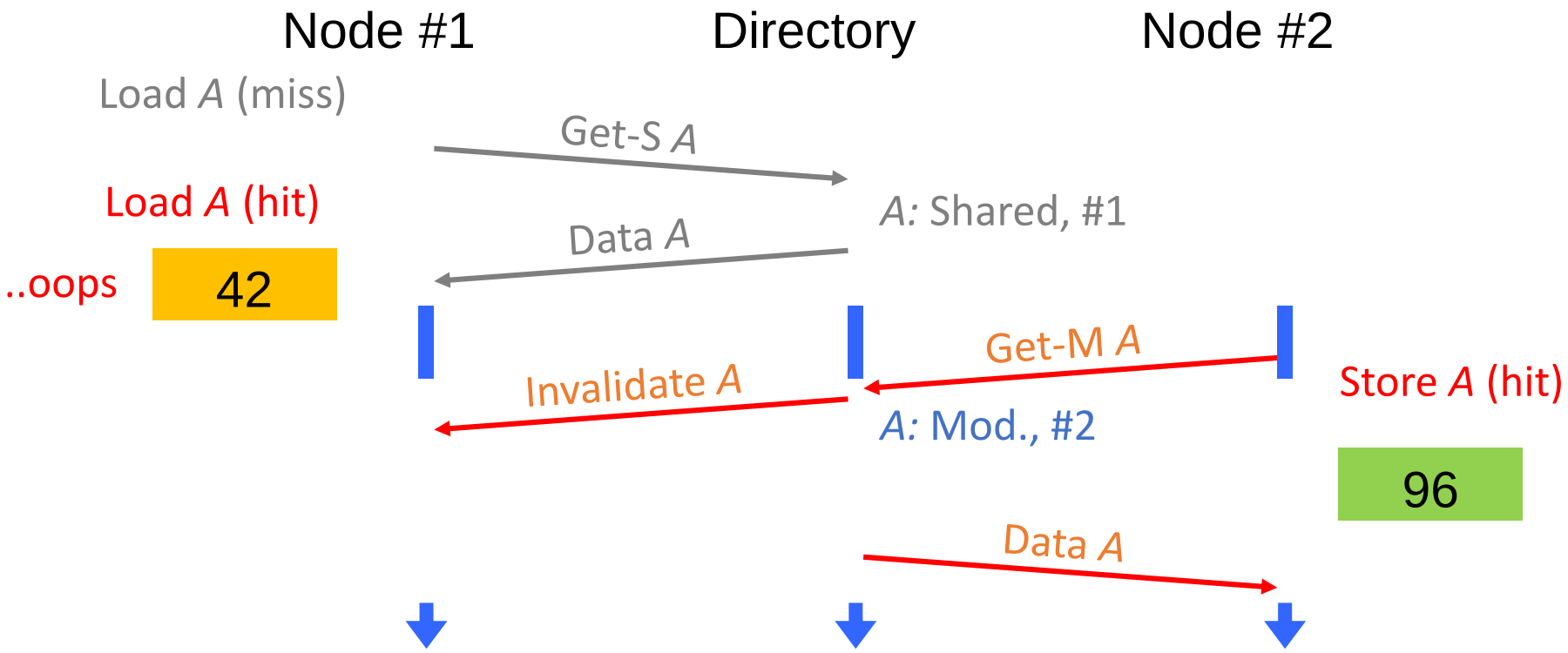
Cache Coherence – How?

- Interconnection network
  - Bus: Snoop-based protocols
  - Point-to-point: Directory-based protocols
- Stable states?
  - VI, MSI, MESI, MOSI, MOESI
- Optimizations employed – countless papers!!
  - 3-hop vs 4-hop
  - Self-downgrade (M->S)
  - Cruise missile invalidations, etc.

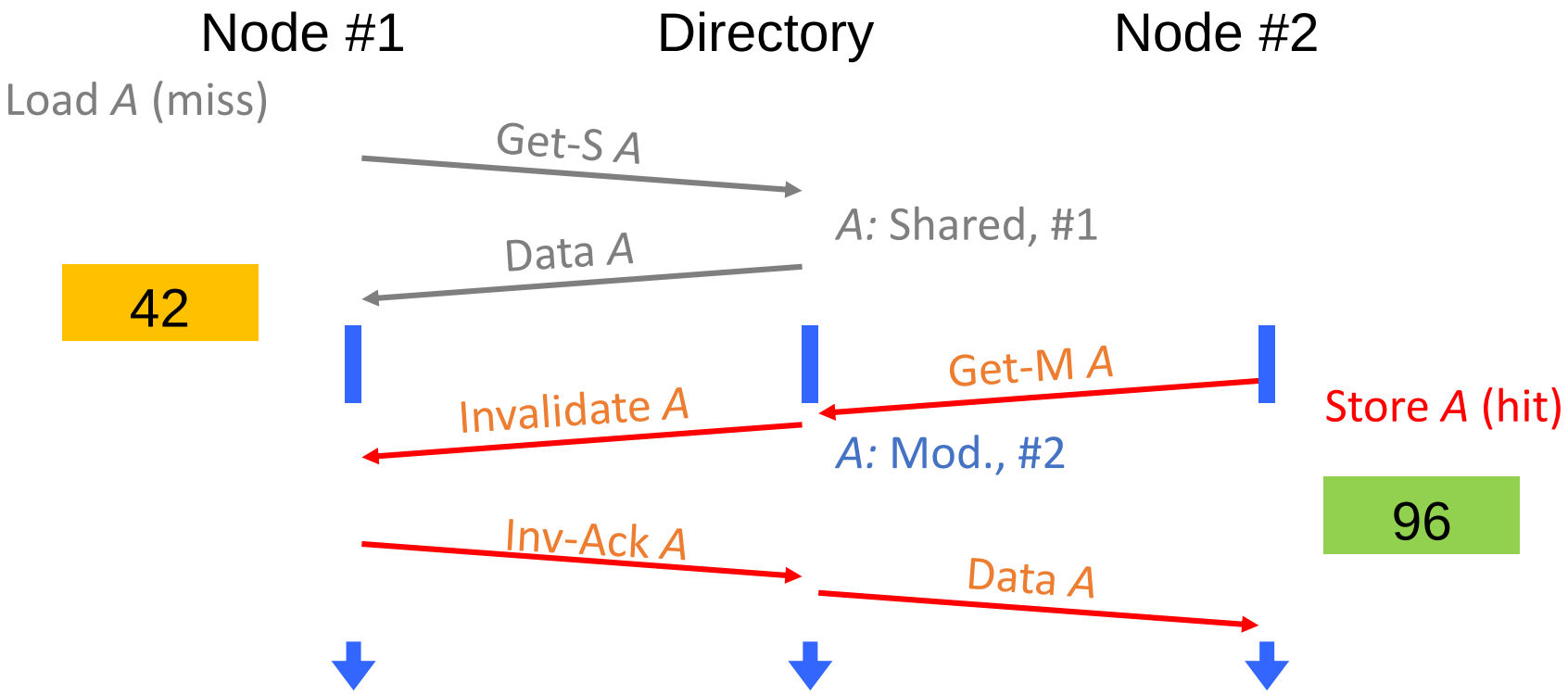
Basic Directory Operation: Read



Basic Directory Operation: Write



Basic Directory Operation: Write



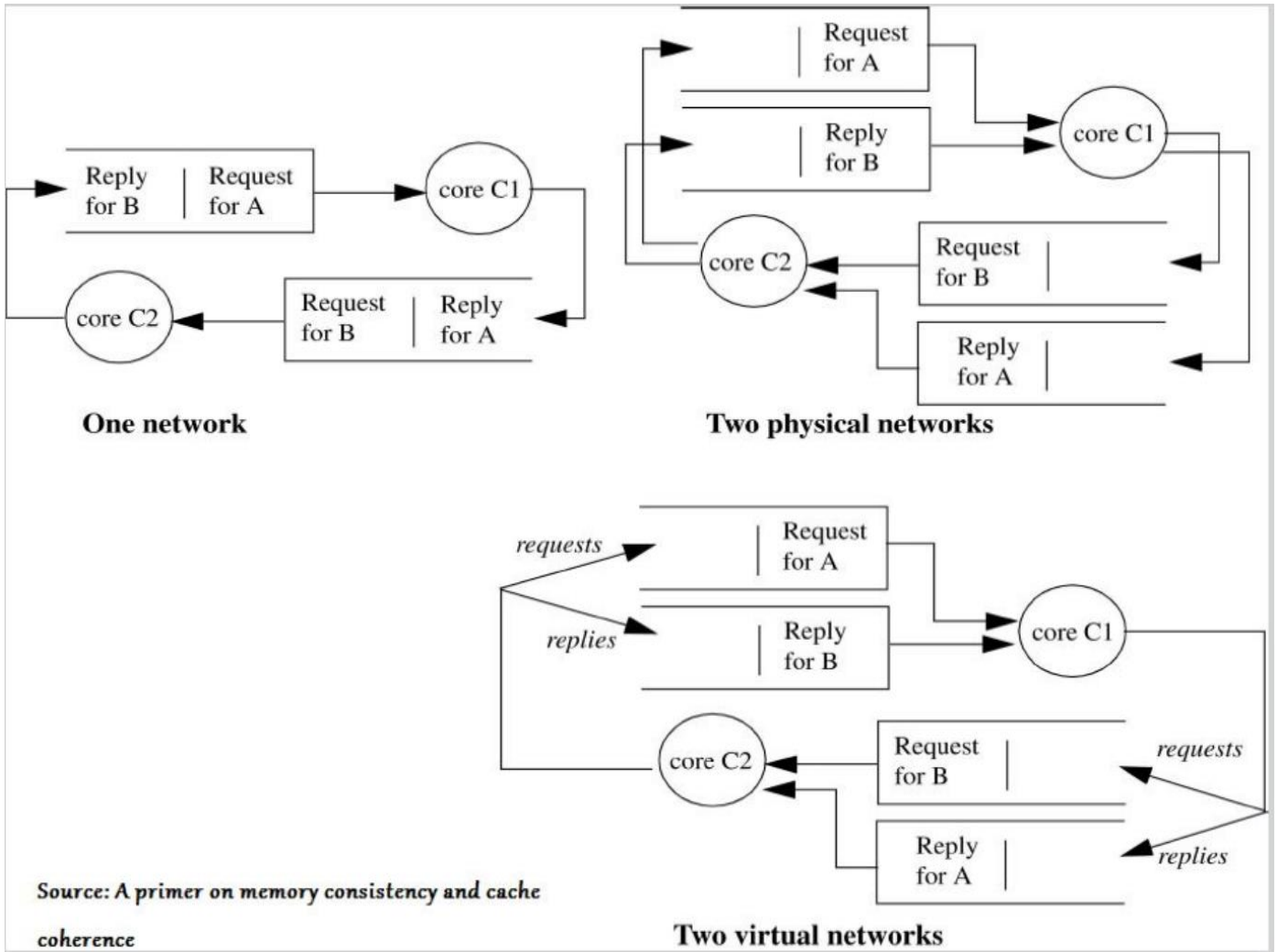
Deadlock!

- Protocol deadlock
  - Wait for a message that is never sent
  - **Solution:** Design your state machine correctly

- Network deadlock
  - Coherence messages hold resources in circular manner
  - **Solution:** Dedicated virtual networks for different messages

Virtual Networks

- Solve network-dependent deadlocks
  - Have separate VN for every message class



Source: A primer on memory consistency and cache coherence

Assignment 2 [link] **Read !!**

- Design a CC protocol → state transition diagram
- Learn a formal verification language
- Specify your CC protocol formally and verify it

Requirements

- Verify with at least **3 processors**, **1 memory location**
- Connected via an arbitrary interconnect
  - Network can **reorder messages**
  - **Infinite buffers**
  - **Multiple virtual channels** as many as you need but h/w cost, so minimize
- Directory-based memory unit (directory co-located w/ memory)

Designing a CC Protocol

- MSI Base Protocol
- Figure out different message types needed
- Nack-free → more difficult
- Allow silent drop of clean data or maintain precise sharing? What are the implications?
- How many protocol lanes needed?
- Figure out all the transient states required for processors and directory

- At least one optimization over your base protocol

Murphi

"Protocol Verification as a Hardware Design Aid," David L. Dill, Andreas J. Drexler, Alan J. Hu and C. Han Yang, 1992

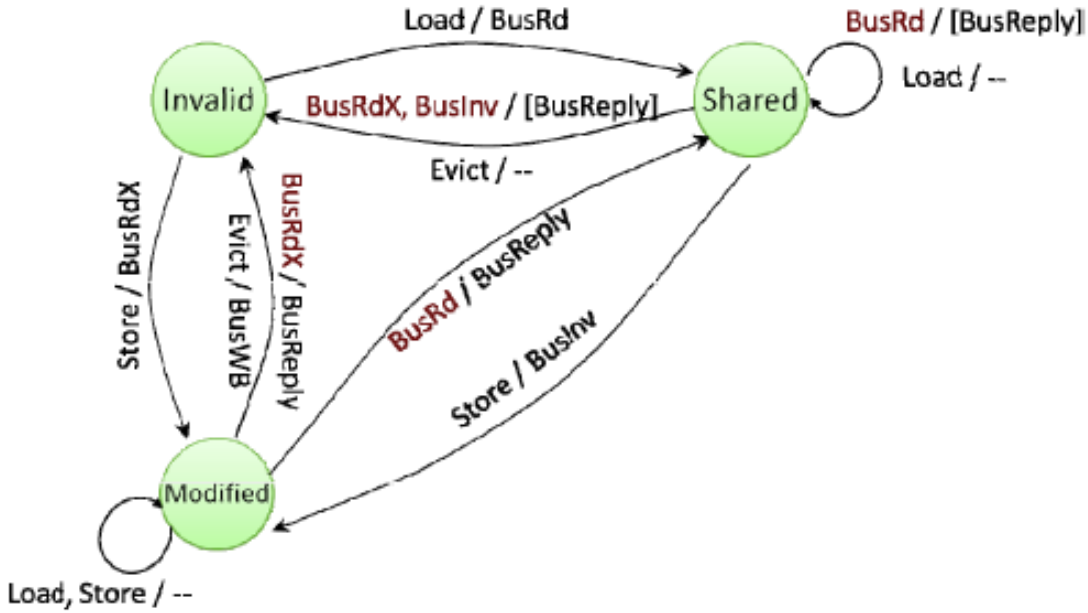
- Formal verification of finite state machines

  State space exploration

  - *explicit enumeration*- explores all reachable states
  - tracks queue of “to-be-explored” states
  - keeps giant table of all previously visited states
  - *canonical representations* & hashing for efficiency
  - exploits *symmetry* to canonicalize redundant states

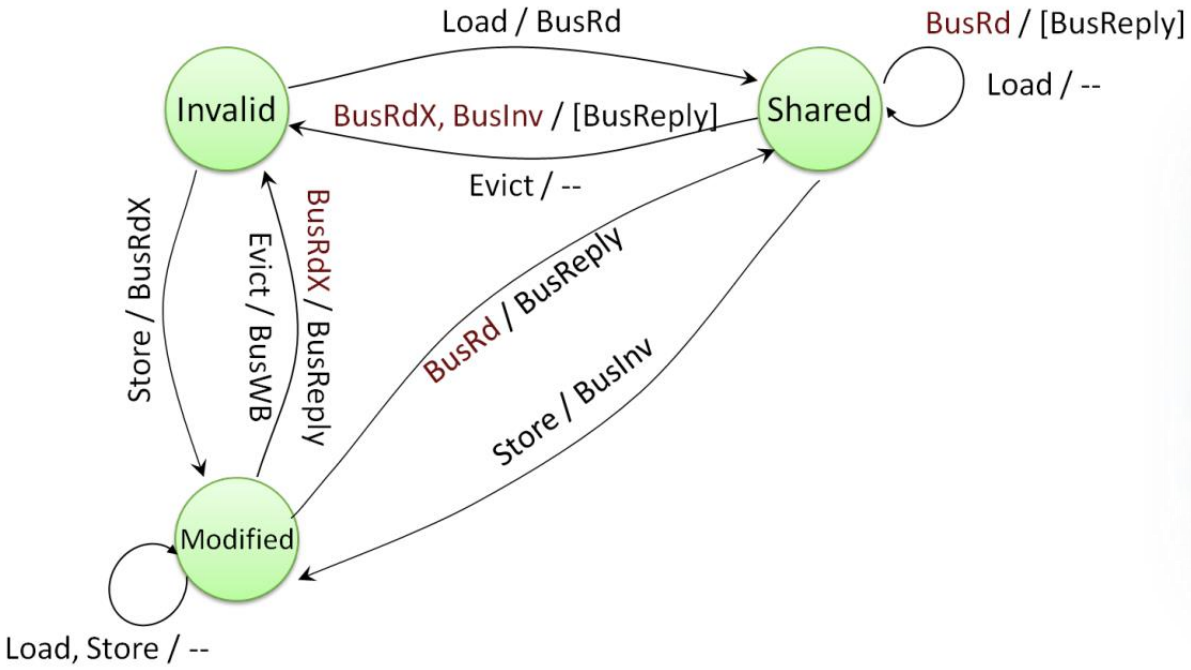
State Space Exploration

- States
  - stable and transient
- Actions
  - Prerequisite for an action to happen?
  - What is the outcome?
- Invariants
  - To ensure correctness
  - Example?



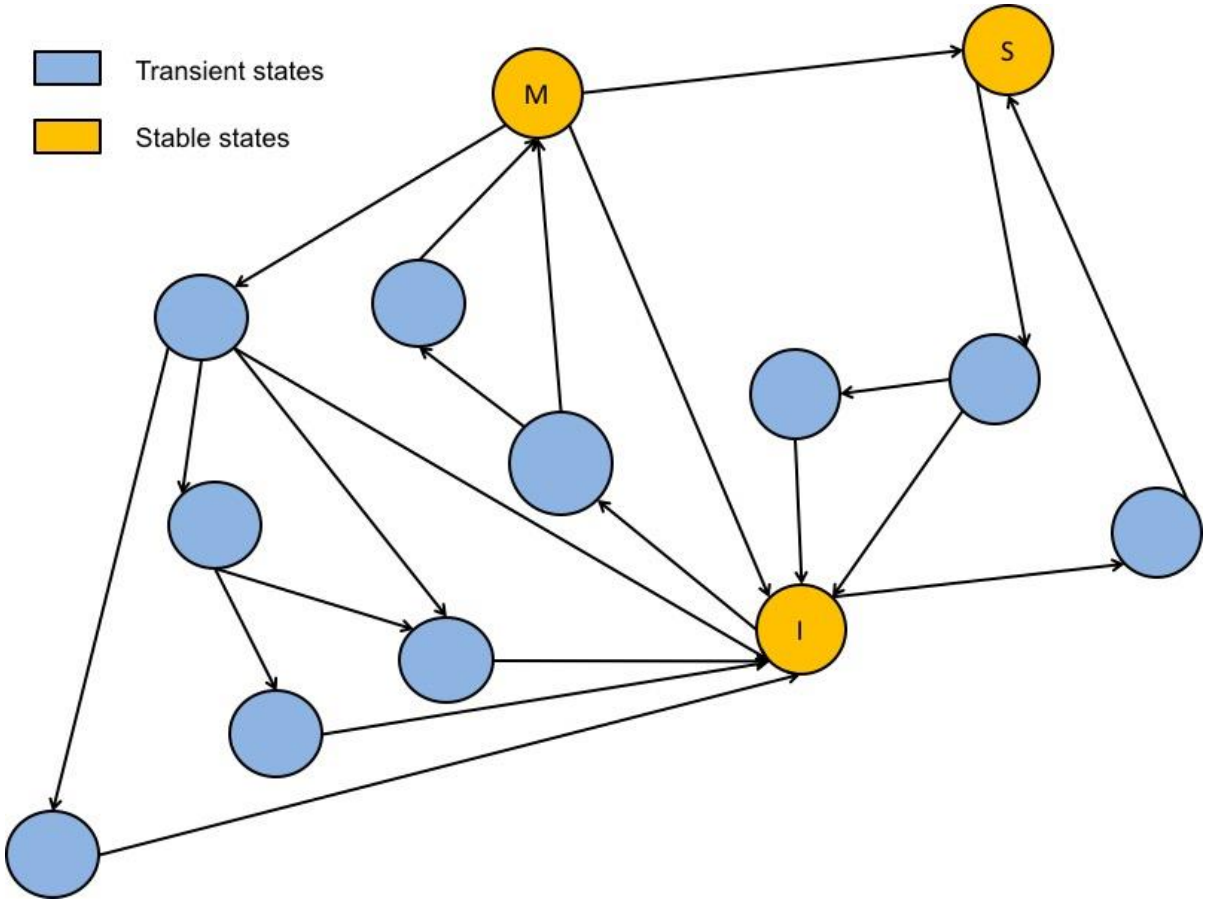
3-Hop MSI Protocol

How you think it should look like



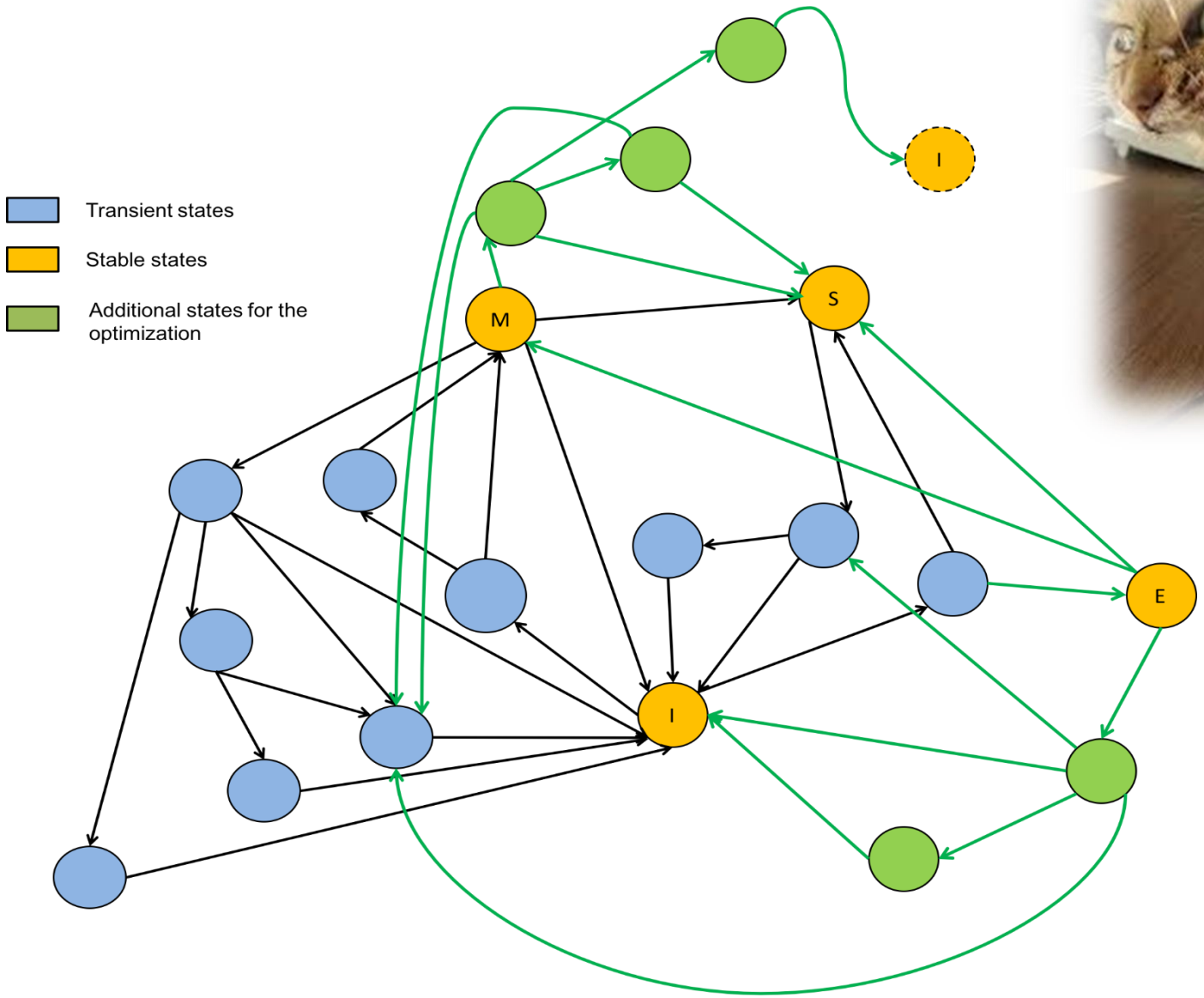
3-Hop MSI Protocol

How it really looks like



MESI w/ Self Downgrade on 4 Procs

What you end up implementing



Solutions

3-hop MSI (NACK-free), 3 procs

```
47744 states, 207008 rules fired in 4.42s.
```

+ Self-Downgrade + Cruise Missile Invalidation, 4 procs

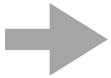
```
4690993 states, 27254378 rules fired in 1594.70s.
```

Numbers will be different for your implementations

Murphi Model Checker

(Tutorial)

Tips!



Sorin et al - A Primer on Memory Consistency and Cache Coherence, Ch. 8

Start early

- One change at a time
  - Start simple, add incrementally
  - Compile at each step
  - Use version control
- Murphi Options: **`$./twostate -h`**
- Memory
  - You will soon run out of default memory allocated
  - Use: **`-m<n>`**, n megabytes while running executable
- Debugging tips in Murphi Manual