CS244b – Distributed Systems

Instructors: Jack Humphries & David Mazières

CAs: Samidh Mehta, Yiting Wu, Julius Zhang, more to come

Stanford University

Outline

1. Administrivia
2. Remote procedure call
3. Consensus in asynchronous systems

Administrivia

- **Class web page:** `http://cs244b.scs.stanford.edu/`
  - All handouts, lecture notes are on line
- **Please join edstem**
  - Can ask questions by noon on lecture day to influence lecture
  - Also find teammates, delve into topics with more detail, etc.
- **Each class will involve discussing papers**
  - Print, read the papers before class
  - Class participation is required (or edstem if you have special dispensation not to attend)[1]
  - We will post discussion notes after lecture
- **Zoom should work for SCPD (please mute your mic)**
- **Staff mailing list:** `cs244b-staff@scs.stanford.edu`
  - Please email all staff rather than individual members

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[1] subject to change depending on enrollment

Assignments

- **Read papers before class (count several hours)**
- **Final project**
  - Perform a small research project in teams of 2–4 students
  - Use ideas from papers we've discussed in class
- **Schedule:**
  - April 15: Form team (can use mailing list to find teammates)
  - April 22: Schedule meeting with Instructor or CA to discuss project
  - Shortly after meeting: project title and one paragraph
  - May 31: Submit git repository, and revised title/paragraph
  - June 7: Submit paper on project (up to 6 pages)
  - June 8: Project presentations/demos (8:30am–5pm)
    - ▷ Refreshments and lunch will be served
- **Final project most important part of grade**
  - Also based on class participation, possible homeworks/midterm(s)

Why study distributed systems?

- Most real systems are actually distributed systems
- **If you want fault-tolerance or scalability**
  - Must replicate or shard across multiple machines
- **If you want systems that span administrative realms**
  - Web sites, peer-to-peer systems, communication systems

Class topics

- **Distributed programming models**
- **Dealing with failure, including Byzantine failure**
- **Scalability**
- **Techniques: Consensus, Replication, Consistency…**
- **Case studies: production systems at Google, Amazon, …**

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Remote procedure call (RPC)

- **Procedure calls are a well-understood mechanism**
  - Transfer control and data on single computer
- **RPC's goal is to make distributed programming look like as much as possible like normal programming**
  - Code libraries provide APIs to access functionality
  - RPC servers export interfaces accessible through local APIs
  - See [Birrell] for good description of one implementation
- **Implement RPC through request-response protocol**
  - Procedure call generates network request to server
  - Server return generates response
- **Good example of how distributed systems differ...**

Procedure vs. RPC

- **Consider the following ordinary procedure:**

  ```
  bool add_user(string user, string password);
  ```

- **Possible return values:**
  1. `true`: user added
  2. `false`: user not added (e.g., user invalid or already exists)
- **Now say you have an RPC version**
  - Must somehow set up connections, bind to server, think about authentication, etc., but ignore all that for now
- **What are the possible return values of `add_user` RPC?**

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  1. `true`
  2. `false`
  3. "I don't know"

RPC Failure

- **Normal procedure call has caller/callee fate sharing**
  - Single process: if callee fails, caller fails, too
- **RPC introduces more failure modes**
  - Machine failures at only one end (caller or callee)
  - Communication failures
- **Result: RPCs can return “failure” instead of results**
- **What are the possible outcomes after failure?**
  - Procedure did not execute
  - Procedure executed once
  - Procedure executed multiple times
  - Procedure partially executed
- **Many systems aspire to “at most once semantics”**

Implementing at most once semantics

- **Danger: Request message lost**
  - Client must retransmit requests when it gets no reply
- **Danger: Reply message may be lost**
  - Client may retransmit previously executed request
  - Okay if operations are idempotent, but many are not (e.g., process order, charge customer, . . .)
  - Server must keep “replay cache” to reply to already executed requests
- **Danger: Server takes too long to execute procedure**
  - Client will retransmit request already in progress
  - Server must recognize duplicate—can reply “in progress”

Server crashes

- **Danger: Server crashes and reply lost**
  - Can make replay cache persistent—slow
  - Can hope reboot takes long enough for all clients to fail
- **Danger: Server crashes during execution**
  - Can log enough to restart partial execution—slow and hard
  - Can hope reboot takes long enough for all clients to fail
- **Can use “cookies” to inform clients of crashes**
  - Server gives client cookie which is time of boot
  - Client includes cookie with RPC
  - After server crash, server will reject invalid cookie

Parameter passing

- **Trivial for normal procedure calls**
- **RPC must worry about different data representations**
  - Big/little endian
  - Size of data types
- **RPC has no shared memory**
  - No global variables
  - How to pass pointers
  - How to garbage-collect distributed objects
- **How to pass unions (“sum types”) over RPC?**

Interface Definition Languages

- **Idea: Specify RPC call and return types in IDL**
- **Compile interface description with IDL compiler. Output:**
  - Native language types (e.g., C/C++/Java/go/etc. structs)
  - Code to *marshal* (serialize) native types into byte streams
  - *Stub* routines on client to forward requests to server
- **Stub routines handle communication details**
  - Helps maintain RPC transparency, but…
  - Still have to bind client to a particular server
  - Still need to worry about failures

C++ RPC-related systems in use today

- **XML, JSON over HTTP – no IDL, hard to parse**
- **CBOR – like JSON but more tasteful, compact binary format**
- **Cereal – C++11 structure serializer**
- **Google protobufs + gRPC, Apache Thrift**
  - + Compact encoding, defensively coded (protobufs)
  - + Good support for incrementally evolving messages
  - – Complex encoding, no canonical representation
- **Apache Avro – self-describing messages contain schema**
- **Cap'n Proto, Google FlatBuffers**
  - + Same representation in memory and on wire, very fast
  - – Less mature, non-deterministic wire format, bigger attack surface
- **XDR (+ RPC) – used by Internet standards such as NFS**
  - + Simple, good features (unions, fixed- and variable-size arrays, . . .)
  - – Big endian, binary but rounds everything to multiple of 4 bytes

“Homework”

- **Write and run a simple distributed application using RPC**
  - Use any of the technologies from previous slide
  - Or any other RPC system you like
  - Try a different technology if you already use one regularly
- **We won’t grade it, but it will help with your project**

Case study: XDR

```
enum MyEnum { NO, YES, MAYBE };

struct MyMessage {
  string name<16>;   /* up to 16 characters */
  string desc<>;     /* up to 2^32-1 characters */
  opaque cookie[8];  /* 8 bytes (fixed) */
  opaque sig<16>;    /* 0-16 bytes (variable-length) */
  unsigned int u;    /* Unsigned 32-bit integer */
  hyper ii;          /* Signed 64-bit integer */
  MyEnum me;         /* Another user-defined type */
  int ia[5];         /* Fixed-length array */
  int iv<>;          /* Variable length array */
  int iv1<5>;        /* Up to 5 ints */
  MyMessage *mep;    /* optional MyMessage (or NULL) */
};

typedef MyMessage *OptionalMyStruct;
```

XDR base types

- **All numeric values encoded in big-endian order**
- `int`, `unsigned [int]`, **all** `enum`**s: 4 bytess**
- `bool`: **equivalent to "**`enum bool { FALSE, TRUE }`**"**
- `hyper`, `unsigned hyper`: **8 bytes**
- `float`, `double`, `quadruple`: **4-, 8-, or 16-byte floating point**
- `opaque bytes[Len]` **(fixed-size)**
  - Encoded as content + 0–3 bytes padding to make size multiple of 4
- `string s<MaxLen>`, `opaque a<MaxLen>` **(variable-size)**
  - 4-byte length + content + (0–3 bytes) padding

XDR containers and structs

- **(Fixed) arrays –** `MyType var[`*n*`]`
  - Encoded as *n* copies of `MyType`
- **Vectors –** `MyType var<>` **or** `MyType var<`*n*`>`
  - Can hold variable number (0–*n*) `MyType`s
  - Encoded as 4-byte length followed by that many
  - Empty maximum length means maximum length $2^{32} - 1$ `MyType`s
- **Optional data –** `MyType *var`
  - Encoded exactly as `MyType var<1>`
  - Note this means single “present” bit consumes 4 bytes
- `struct` **– each field encoded in turn**

XDR `union` types

```
union type switch (simple_type which) {
  case value_A:
    type_A varA;
  case value_B:
    type_B varB;
  /* ... */
  default:
    void;
};
```

- **Must be discriminated, unlike C/C++**
- `simple_type` **must be** `[unsigned] int`**,** `bool`**, or** `enum`
- **Wire representation:**
  - 4-bytes for `which` + encoding of selected case
  - Special `void` type encoded as 0 bytes

Demo

```
git clone http://cs244b.scs.stanford.edu/xdrdemo.git
```

- **References for demo**
  - C++ RPC library: `https://github.com/xdrpp/xdrpp`
  - Go RPC library: `https://github.com/xdrpp/goxdr`
  - XDR specification: RFC4506
  - RPC specification: RFC5531

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Asynchronous systems[2]

- **A theoretical model for distributed systems**
  - Consists of a set of agents exchanging messages
  - No bound on message delays
  - No bound on the relative execution speed of agents
  - For convenience, model internal events such as timeouts as special messages, so the "network" controls all timing
- **Can't distinguish failed agent from slow network**
- **Idea of model is to be conservative**
  - Want robustness under any possible timing conditions
  - E.g., say backhoe tears fiber, takes a day to repair
  - Could see messages delays a *billion* times more than usual

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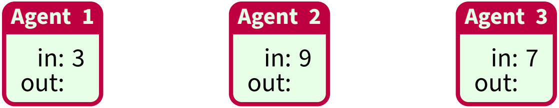
[2] Unrelated to "asynchronous IO" as used in event-driven systems.

The consensus problem



Agent 1
in: 3
out:

Agent 2
in: 9
out:

Agent 3
in: 7
out:

- **Goal: For multiple agents to agree on an output value**
- **Each agent starts with an input value**
  - Agents’ inputs may differ; any agent’s input is okay to output
- **Agents communicate following some *consensus protocol***
  - Use protocol to agree on one of the agent’s input values
- **Once decided, agents output the chosen value**
  - Output is write-once (an agent cannot change its value)

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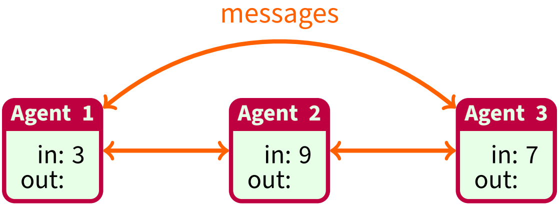

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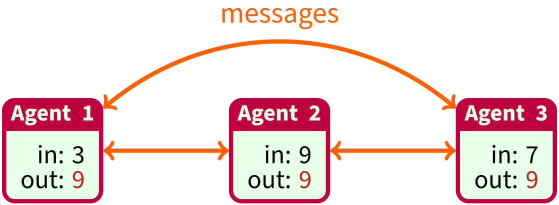

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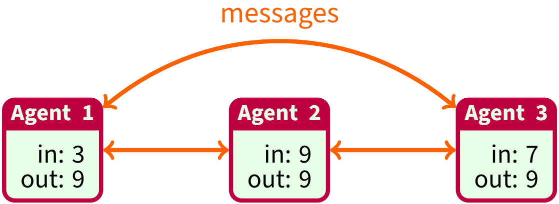
Properties of a consensus protocol

- **A consensus protocol provides *safety* if…**
  - Agreement – All outputs produced have the same value, and
  - Validity – The output value equals one of the agents' inputs
- **A consensus protocol provides *liveness* if…**
  - Termination – Eventually non-failed agents output a value
- **A consensus protocol provides *fault tolerance* if…**
  - It can survive the failure of an agent at any point
  - *Fail-stop* protocols handle agent crashes
  - *Byzantine-fault-tolerant* protocols handle arbitrary agent behavior

Theorem (FLP impossibility result)

No deterministic consensus protocol guarantees all three of safety, liveness, and fault tolerance in an asynchronous system.

Bivalent states



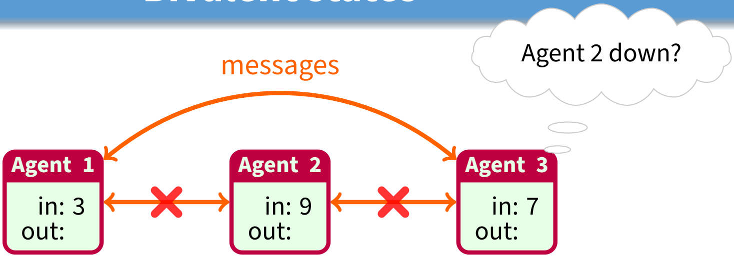
⟶ **Recall agents chose value 9 in last example**

- **But a network outage could look like agent 2 failing**
- **If fault-tolerant, Agents 1 & 3 might decide to output 7**
- **Once network back, Agent 2 must also output 7**

Definition (Bivalent)

An execution of a consensus protocol is in a bivalent state when the network can affect which value agents choose.

Bivalent states



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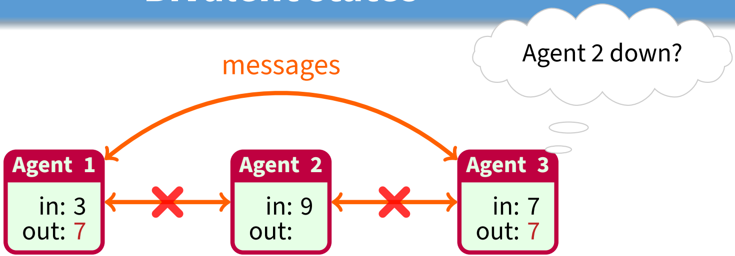

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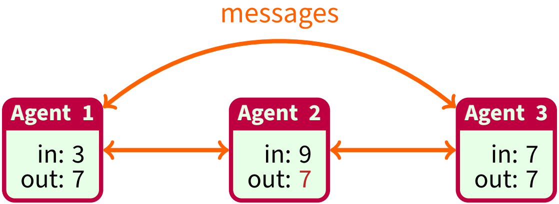

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Definition (Bivalent)

An execution of a consensus protocol is in a bivalent state when the network can affect which value agents choose.

Univalent and stuck states

Definition (Univalent, Valent)

An execution of a consensus protocol is in a univalent state when only one output value is possible. If that value is i, call the state i-valent.

Definition (Stuck)

An execution of a [broken] consensus protocol is in a stuck state when one or more non-faulty nodes can never output a value.

- **Recall output is write once and all outputs must agree**
  - Hence, no output is possible in bivalent state
- **If an execution starts in a bivalent state and terminates, it must at some point reach a univalent state**

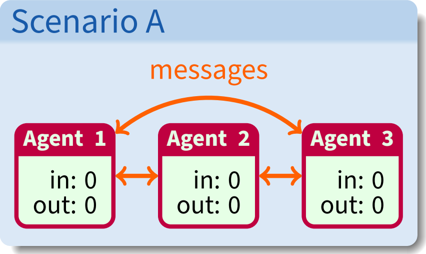
FLP intuition

- **Consider a terminating execution of a bivalent system**
- **Let *m* be last message received in a bivalent state**
  - Call *m* the execution's deciding message
  - Any terminating execution requires a deciding message
- **Suppose the network had delayed *m***
  - Other messages could cause transitions to other bivalent states
  - Then, receiving *m* might no longer lead to a univalent state
  - In this case, we say *m* has been neutralized

Overview of FLP proof.

1. **There are bivalent starting configurations**
2. **The network can neutralize any deciding message**
3. **Hence, the system can remain bivalent in perpetuity** ☐

There exists a bivalent state



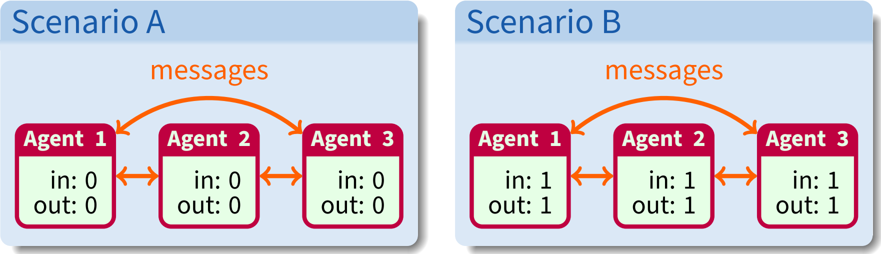
- **Assume you could have liveness with an agent failure**

⟶ **If all inputs 0, correct agents must eventually output 0**

  - Similarly, if all inputs 1, correct agents must eventually output 1

- **Now say we start flipping one input bit at a time**
- **Find 0- and 1-valent states differing at only one input**
  - Suppose node with this differing input fails
  - By assumption, the system nonetheless reaches consensus
  - Hence output depends on network; at least one state was bivalent

There exists a bivalent state



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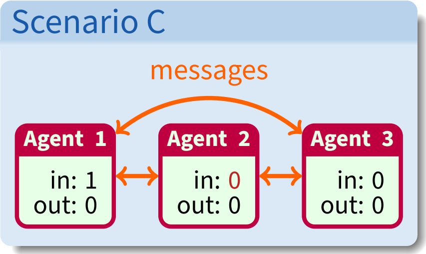


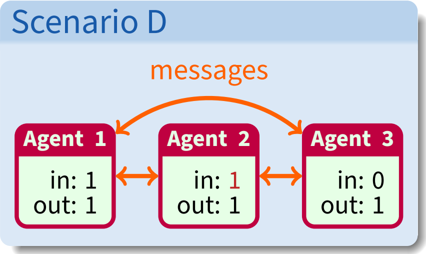
Scenario C

messages

Agent 1
in: 1
out: 0

Agent 2
in: 0
out: 0

Agent 3
in: 0
out: 0



Scenario D

messages

Agent 1
in: 1
out: 1

Agent 2
in: 1
out: 1

Agent 3
in: 0
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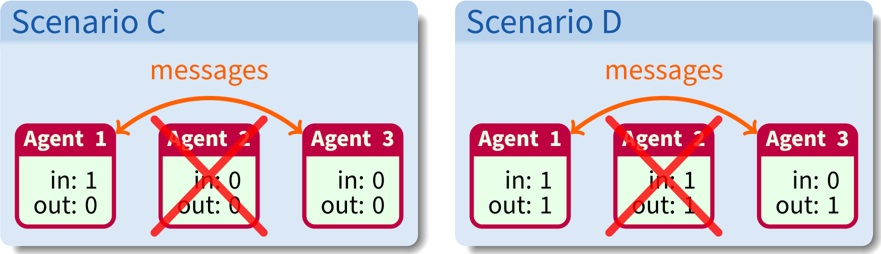

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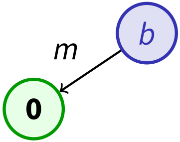
Any message can be neutralized



⟶ **Let *m* be a deciding message for value 0 from state *b***
  - Let's assume *m* cannot be neutralized and derive a contradiction
- **Consider a message schedule from *b* to a 1-valent state**
  - If *m* is on the path, it leads to a bi-valent state (so neutralized)
  - If *m* is not on the path, append it to the (1-valent) path
- **Apply *m* to each node on the path**
  - Either *m* will lead to a bi-valent state (neutralized), or it will produce differing univalent states on adjacent nodes c_0 and c_1

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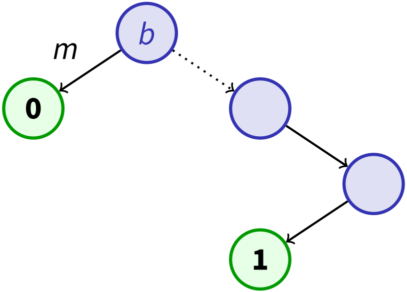

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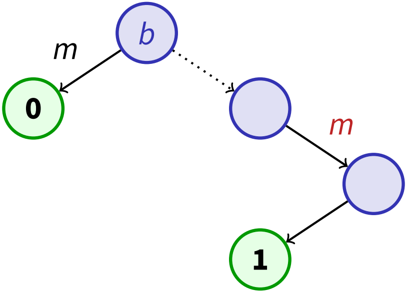

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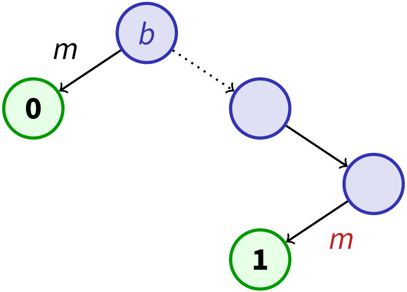

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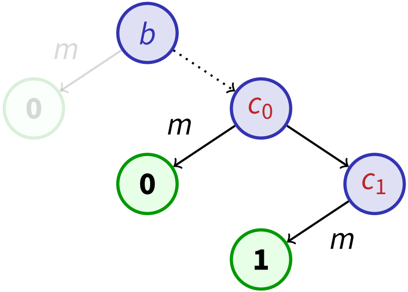

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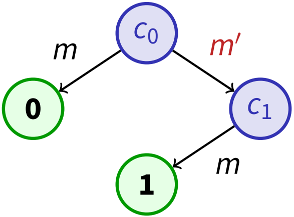
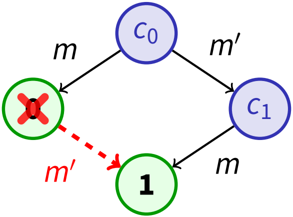


⟶ **Let m' be the message that transitions between c_0 and c_1**

- **If m, m' received by different agents, order won't matter**
  - But if delivering *both* messages yields a 1-valent state, delivering just m can't yield a 0-valent state
- **Hence, m and m' were addressed to the same agent A, making order significant**
- **Yet if A slow after c_0, system must terminate without it**

Any message can be neutralized



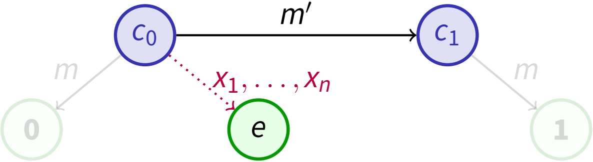
- **Let m' be the message that transitions between c_0 and c_1**

⟶ **If m, m' received by different agents, order won't matter**

  - But if delivering *both* messages yields a 1-valent state, delivering just m can't yield a 0-valent state

- **Hence, m and m' were addressed to the same agent A, making order significant**
- **Yet if A slow after c_0, system must terminate without it**

Any message can be neutralized

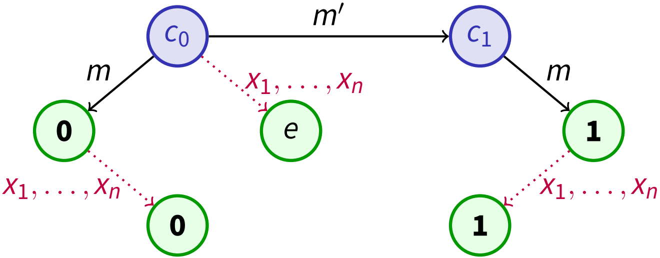


⟶ **Consider a run that terminates without A**

  - Let $x_1, \dots, x_n$ be the messages received (by nodes other than A)
  - Let e be a univalent state reached during the run

- **Deliver $x_1, \dots, x_n$ to terminating states after m**
  - Since ms and xs received by different nodes, can re-order
  - Means e not univalent (leads to both 0- and 1-valent states)!
- **Contradiction means m must be neutralized somewhere**

Any message can be neutralized



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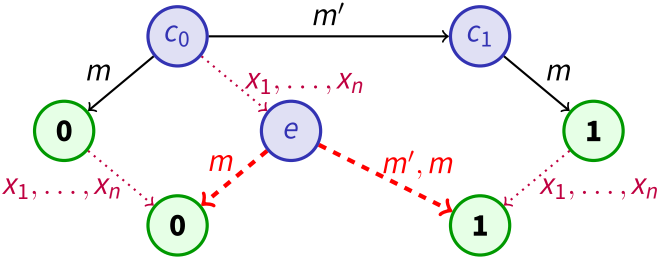

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Coping with FLP

- **This class will cover**
  - Many systems that require consensus
  - Many techniques for consensus
- **Safety is generally pretty important**
- **But can reasonably weaken liveness requirement**
  - Termination not guaranteed doesn't mean it won't happen
  - If your algorithm prevents completely stuck states
    …can often make it terminate "in practice"
- **Can weaken asynchronous system assumption**
- **Can make agents non-deterministic**
  - Have all nodes flip a coin to pick value—might all pick same value
  - Make it intractable for network to "guess" pathological delivery 100% accurately in perpetuity