Principles of Software Construction: Objects, Design, and Concurrency

Part 6: Concurrency and distributed systems

Abstractions of State

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Administrivia

- Homework 6…
- Final exam Tuesday, May 5th, 1 – 4 p.m. DH 2210
  - Final exam review session Sunday, May 3rd, 4 – 6:30 p.m., Hamburg 1000

Key concepts from Tuesday

Data consistency

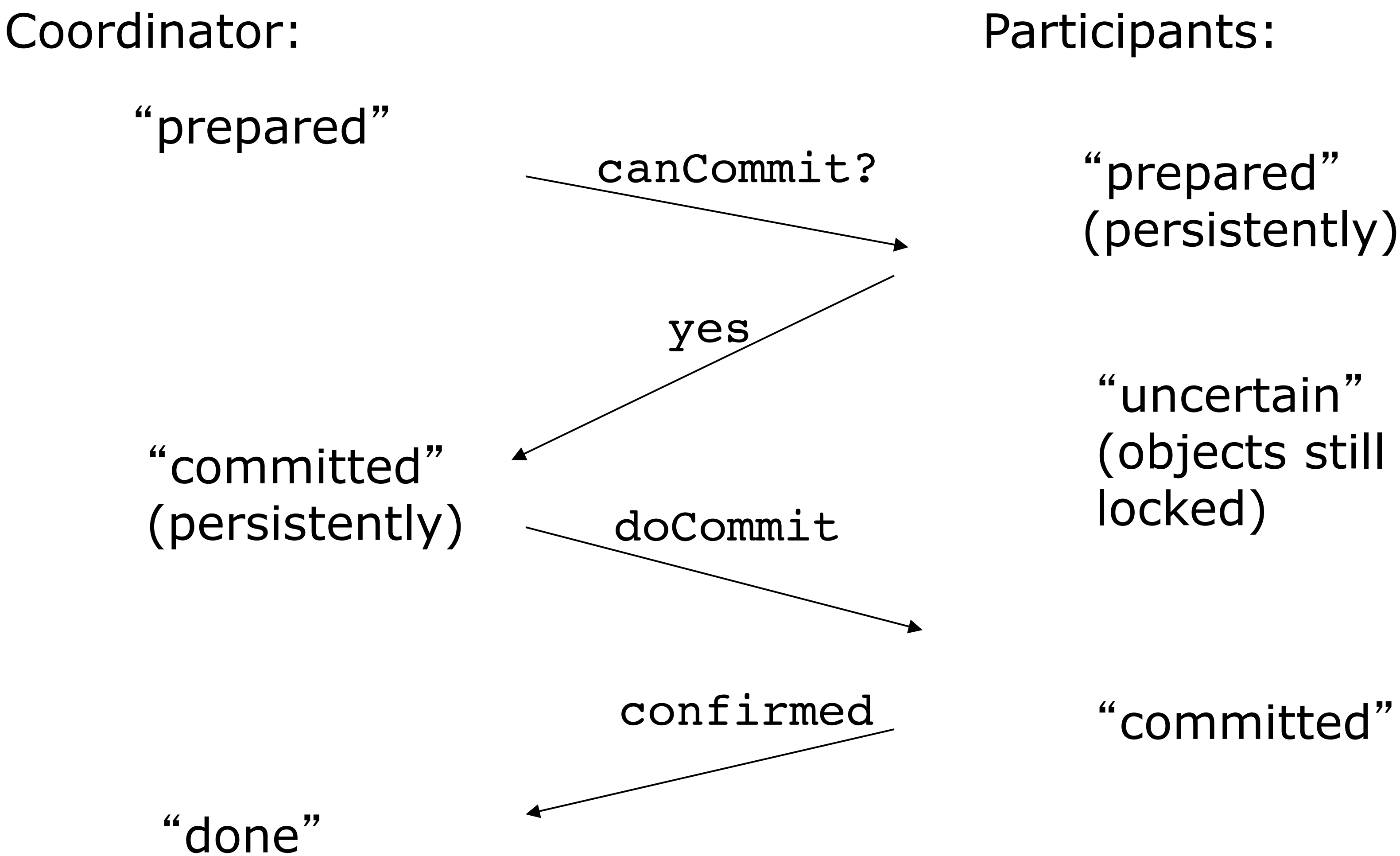
- Suppose $\mathcal{D}$ is the database for some application and φ is a function from database states to {true, false}
  - We call φ an *integrity constraint* for the application if $\varphi(\mathcal{D})$ is true if the state $\mathcal{D}$ is "good"
  - We say a database state $\mathcal{D}$ is *consistent* if $\varphi(\mathcal{D})$ is true for all integrity constraints φ
  - We say $\mathcal{D}$ is inconsistent if $\varphi(\mathcal{D})$ is false for any integrity constraint φ

- Transaction ACID properties:
  - Atomicity: All or nothing
  - Consistency: Application-dependent as before
  - Isolation: Each transaction runs as if alone
  - Durability: Database will not abort or undo work of a transaction after it confirms the commit

Concurrent transactions and serializability

- For good performance, database interleaves operations of concurrent transactions
- Problems to avoid:
  - Lost updates
    - Another transaction overwrites your update, based on old data
  - Inconsistent retrievals
    - Reading partial writes by another transaction
    - Reading writes by another transaction that subsequently aborts
- A schedule of transaction operations is *serializable* if it is equivalent to some serial ordering of the transactions

2PC sequence of events for a successful commit



Problems with two-phase commit?

Problems with two-phase commit?

- Failure assumptions are too strong
  - Real servers can fail permanently
  - Persistent storage can fail permanently
- Temporary failures can arbitrarily delay a commit
- Poor performance
  - Many round-trip messages

Aside: The CAP theorem for distributed systems

- For any distributed system you want…
  - Consistency
  - Availability
  - tolerance of network Partitions
- …but you can support at most two of the three

Today: Abstractions of state

- State-based models of computation
  - Finite state machines (FSMs)
- The State design pattern
- A distributed application: The actor model

An aside: I need two volunteers…

Memorize the following number:

4 2

What was the number?

Memorize the following number:

4 2 9 7

What was the number?

Memorize the following number:

4 2 9 7 2 8

What was the number?

Memorize the following number:

4	2	9	7	2	8	6	1	9	3
9	1	0	2	8	4	0	0	2	8
8	2	1	0	8	2	7	3	2	3
3	3	2	8	6	6	7	1	0	0
8	0	9	1	0	8	2	8	6	4
2	8	5	6	0	9	1	7	2	8
2	7	8	1	6	8	7	2	0	9

Memorize the following number:

4	2	4	2	4	2	4	2	4	2
4	2	4	2	4	2	4	2	4	2
4	2	4	2	4	2	4	2	4	2
4	2	4	2	4	2	4	2	4	2
4	2	4	2	4	2	4	2	4	2
4	2	4	2	4	2	4	2	4	2
4	2	4	2	4	2	4	2	4	2

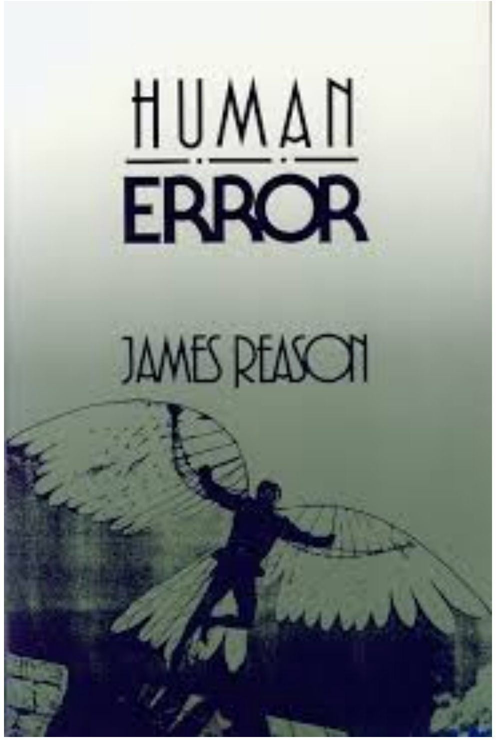
An aside's aside: Run-length encodings

4 2 (5*7 times)

What causes programming errors?

What causes programming errors?

- Knowledge problems: Inadequate, inert, heuristic, oversimplified, or interfering content or organization
- Attentional problems: Fixation, loss of situational awareness, or working memory strain
- Strategic problems: Unforeseen interactions from goal conflict resolution or bounded rationality



Recommended: A. Ko and B. Myers, "*Development and Evaluation of a Model of Programming Errors*". HCC 2003.

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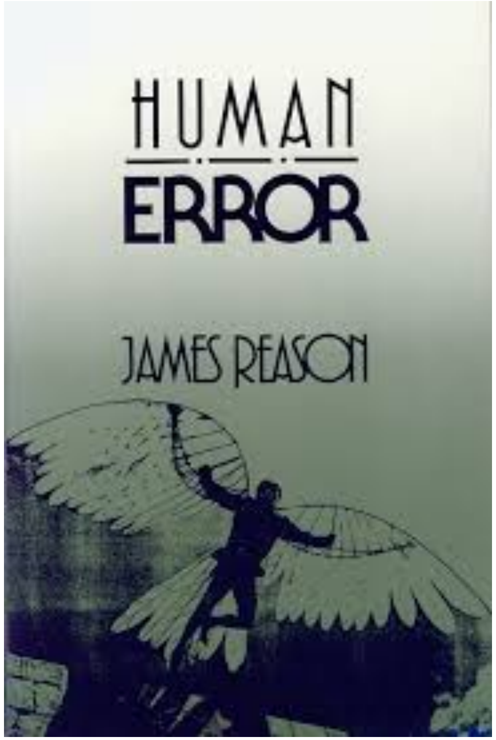

A goal: Eliminate complexity

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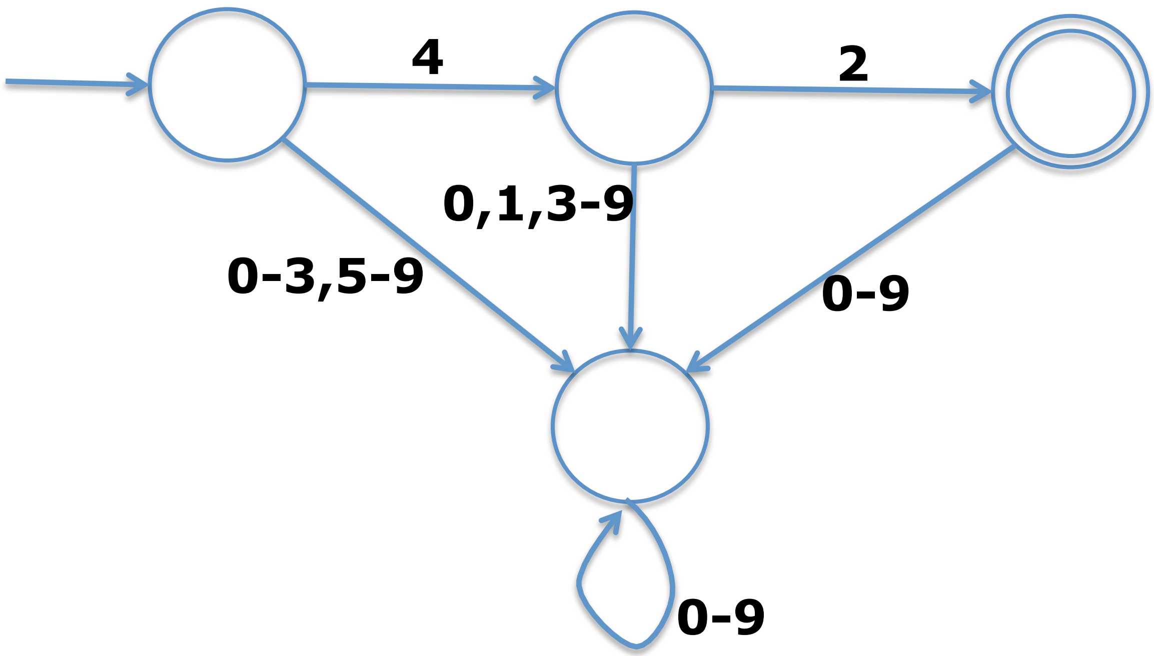
- State-based models of computation
  - Finite state machines (FSMs)
- The State design pattern
- A distributed application: The actor model

Related: Deterministic Finite Automata (DFAs)

- A simple model of computation in which input is accepted or rejected by a finite state machine
  - e.g. A DFA that accepts the input 42:



Related: Deterministic Finite Automata (DFAs)

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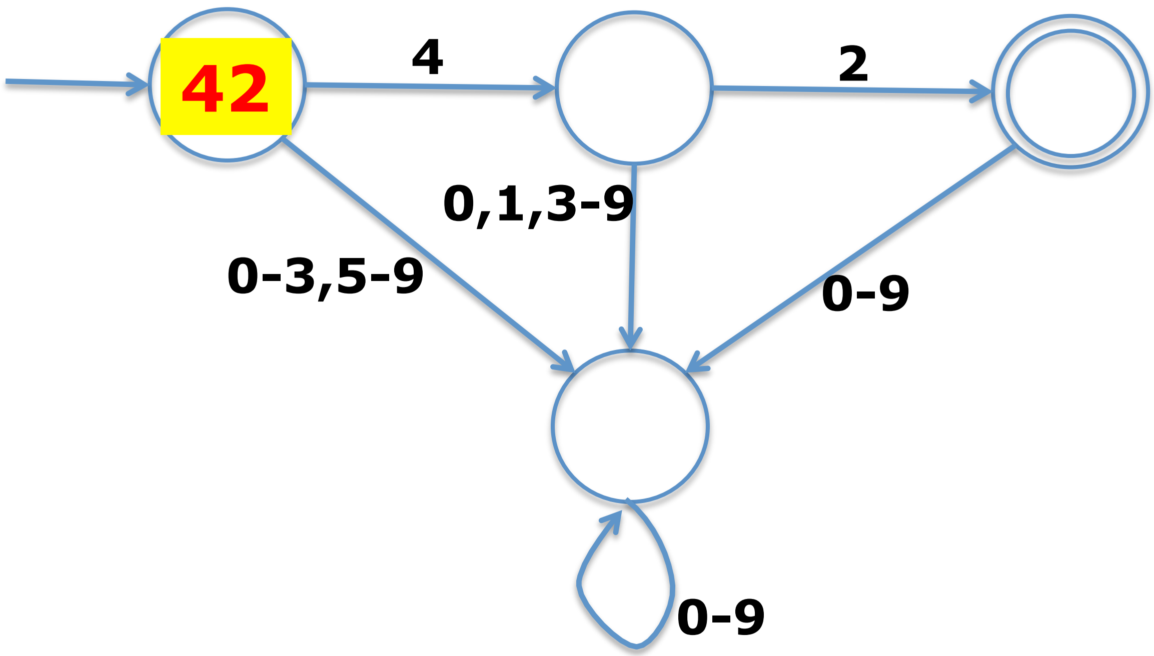

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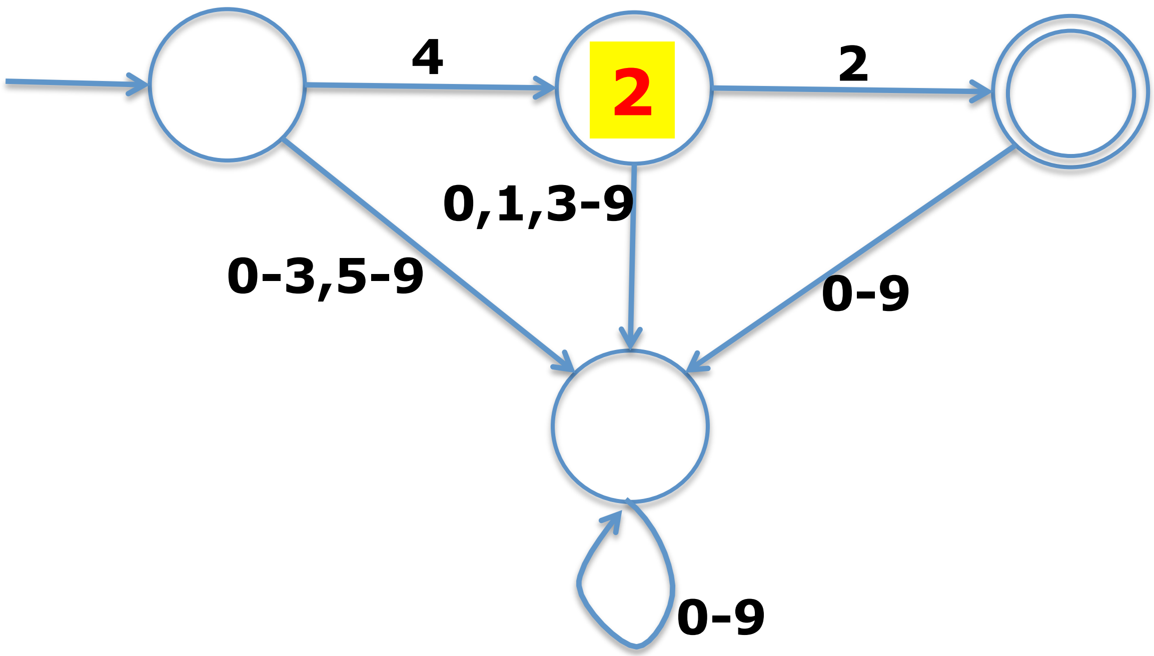

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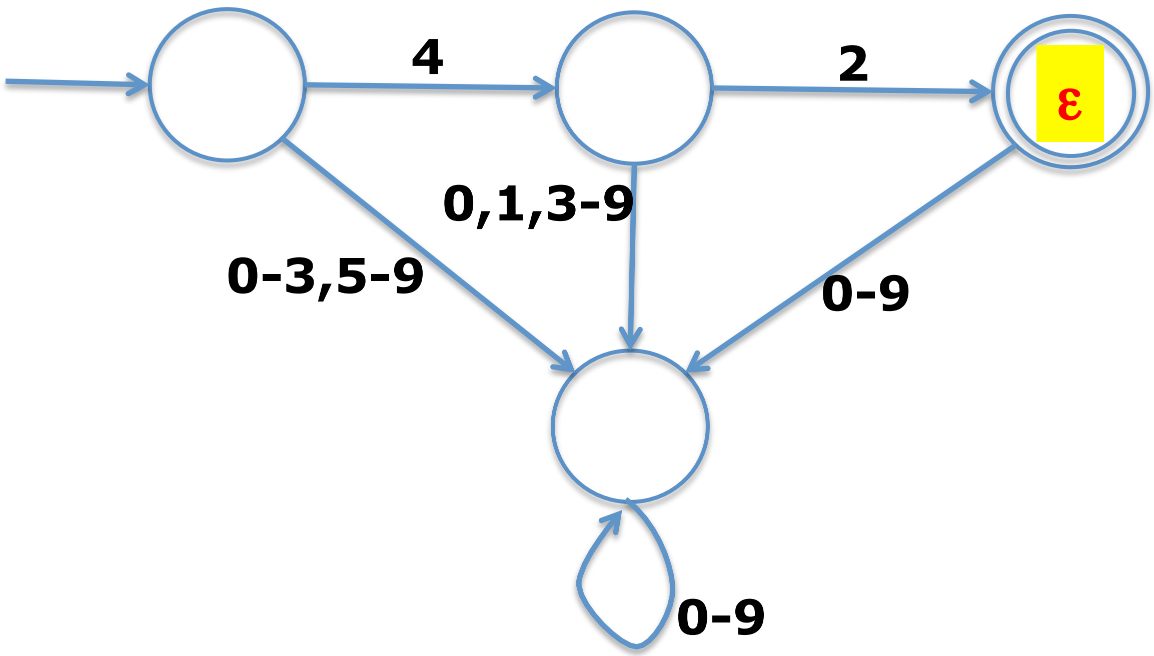
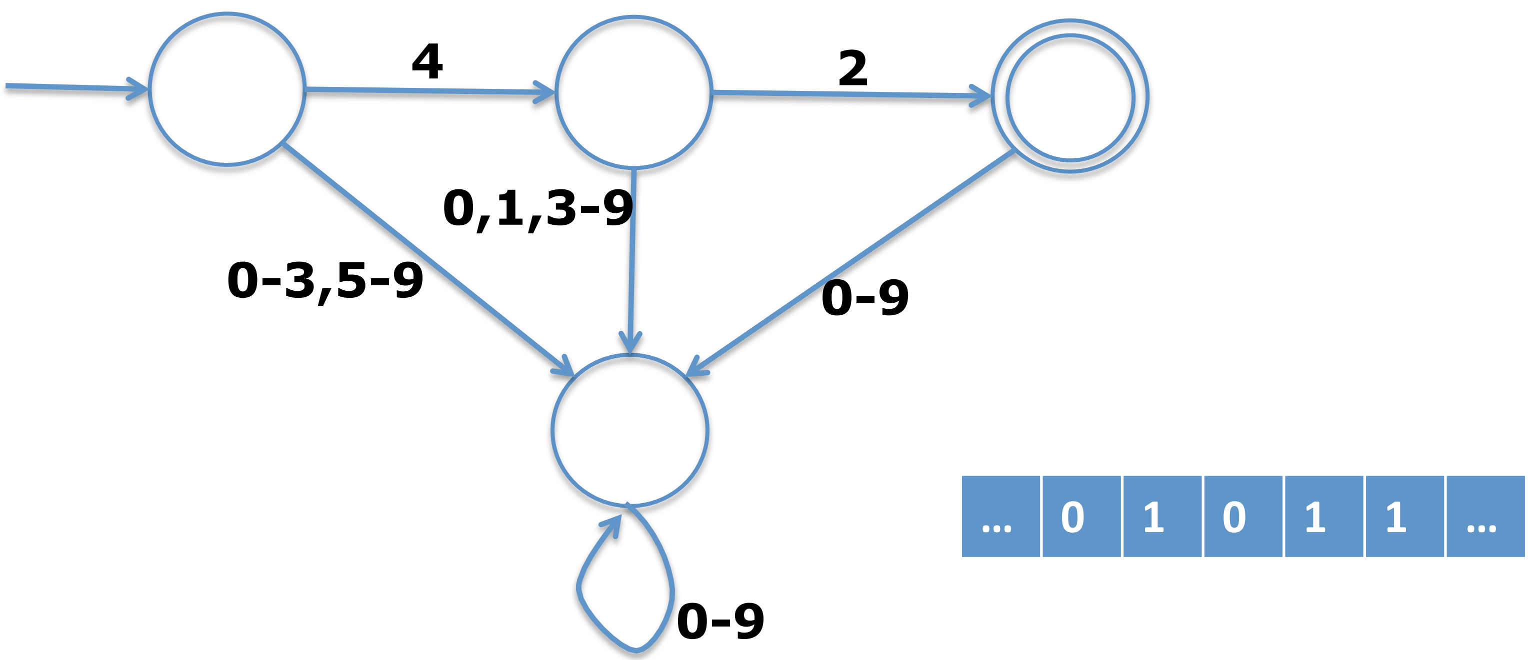


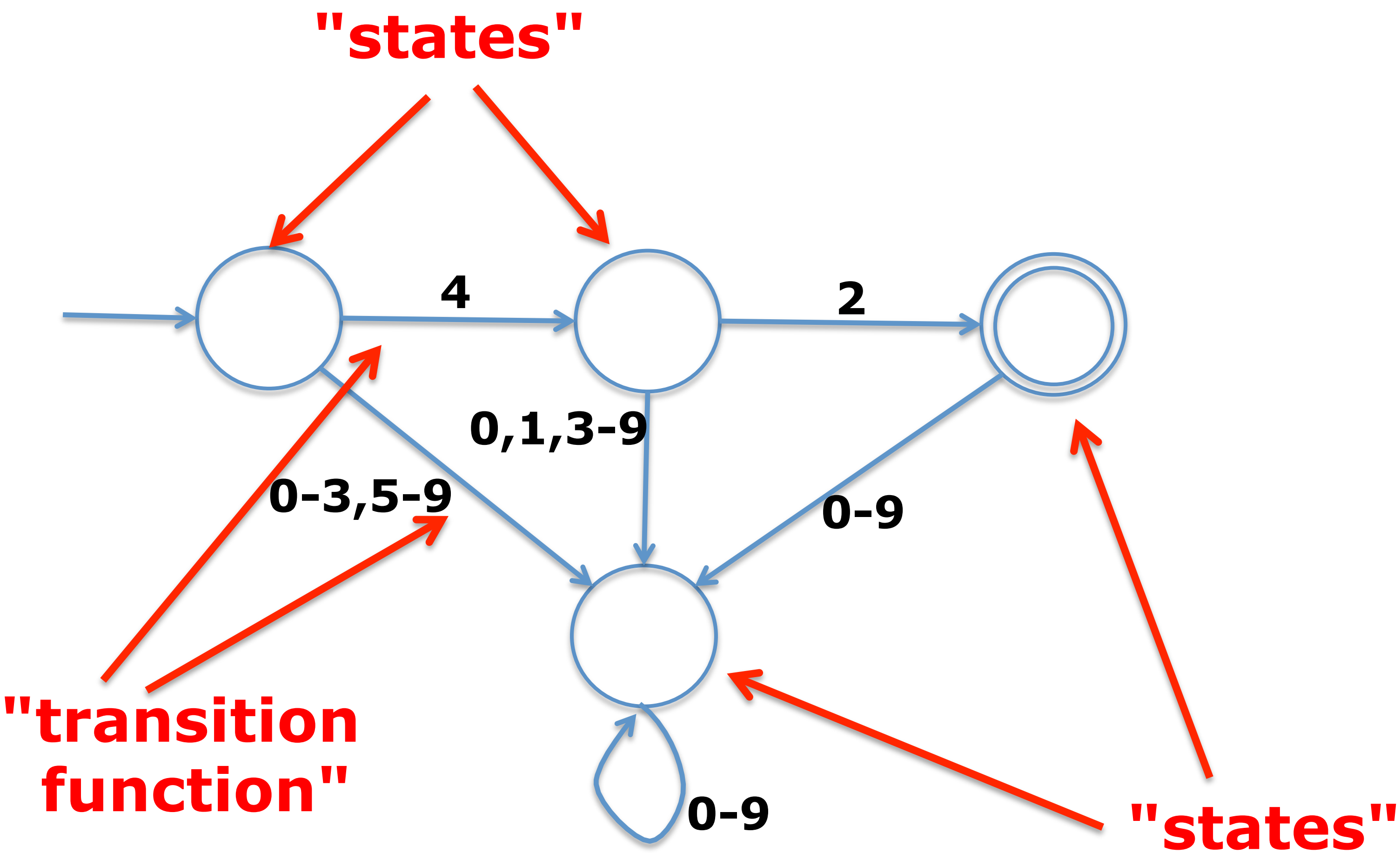
Related: Turing Machines

slightly more complex

- A ~~simple~~ model of computation in which input is accepted or rejected by a finite state machine
  - Essentially a DFA with an infinite memory tape



Finite state machines (FSMs)



FSMs simply represent system behavior

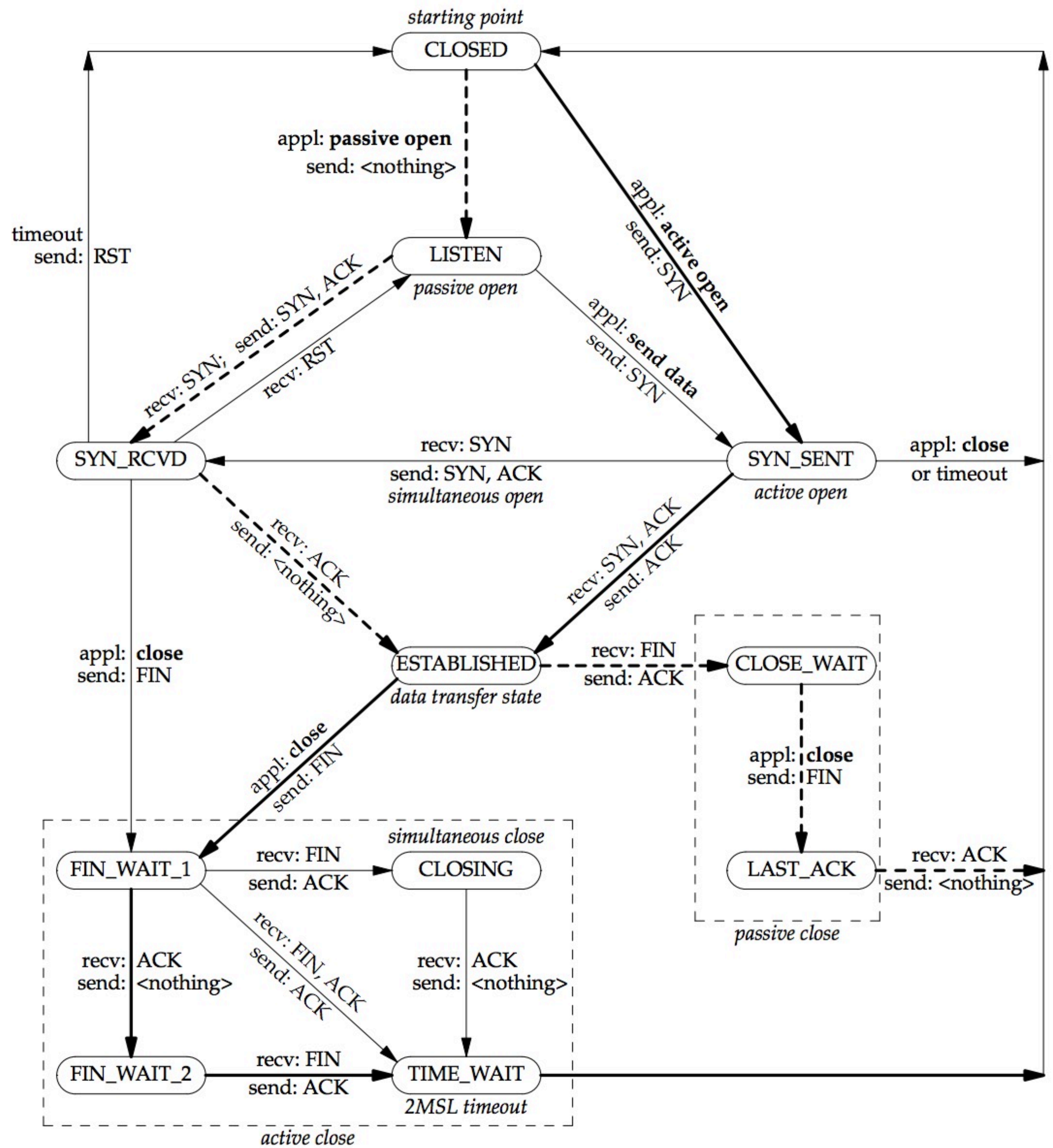
- E.g., a 4-function calculator

FSMs simply represent system behavior

- E.g., a 4-function calculator
- E.g., the traffic light at Forbes and Morewood

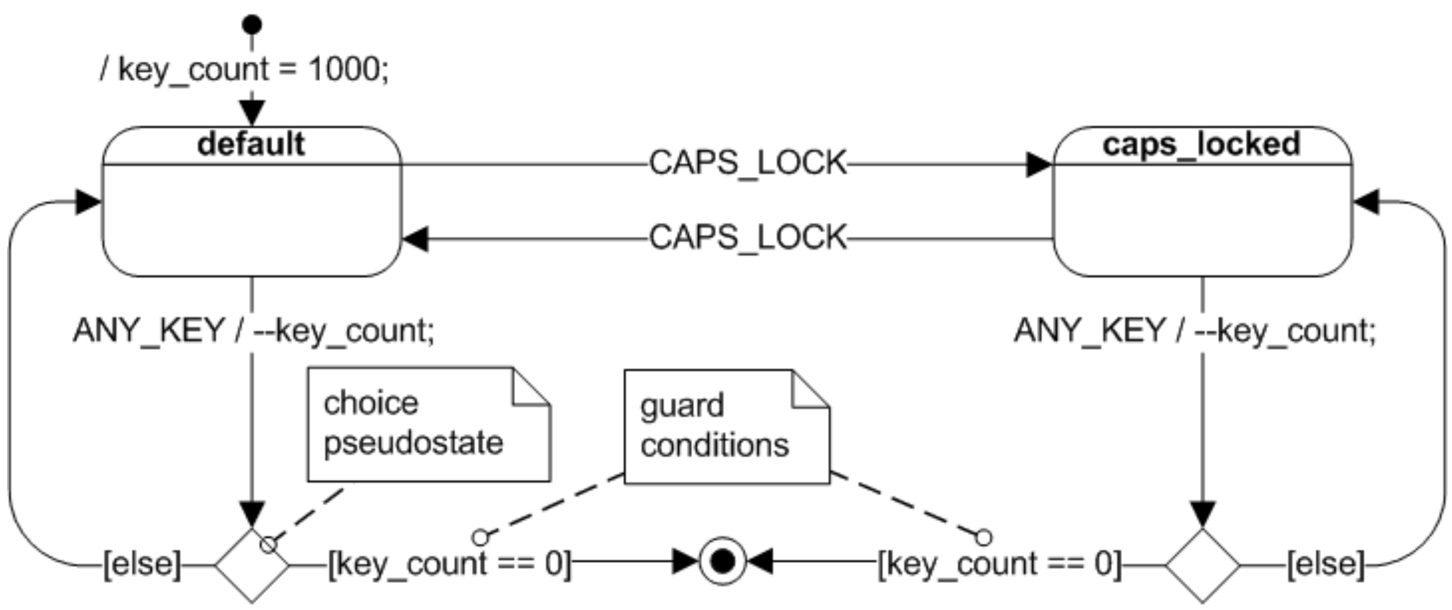
FSMs enable precise communication

- E.g., the Transmission Control Protocol (TCP)



UML state diagrams enable richer communication

- Conditional transitions
- Independent events/actions



(example from Wikipedia...)

FSMs can help organize the implementation

- See StateMachineCalculator.java

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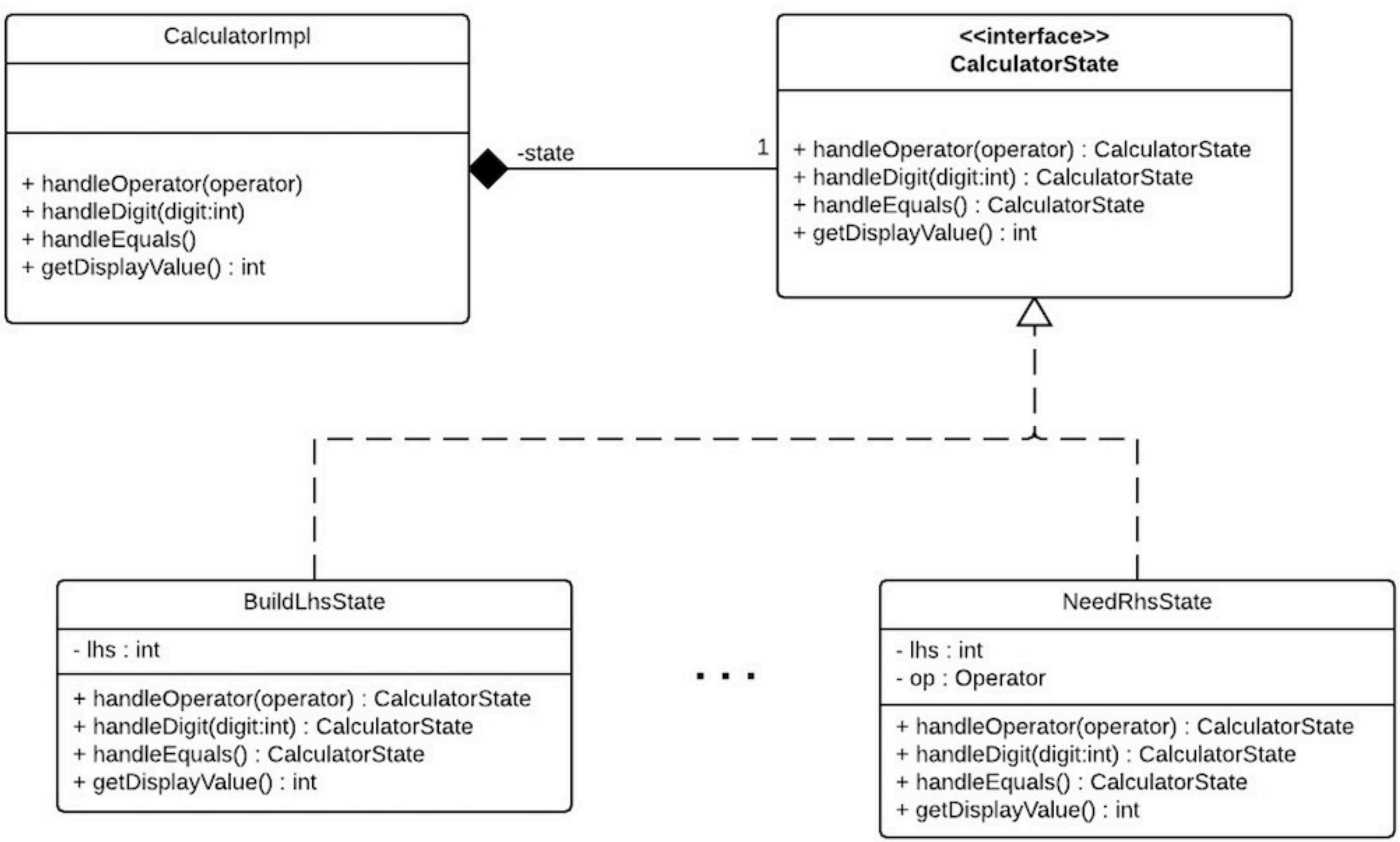
- See StateMachineCalculator.java
  - Warning: The StateMachineCalculator intentionally demonstrates poor design.

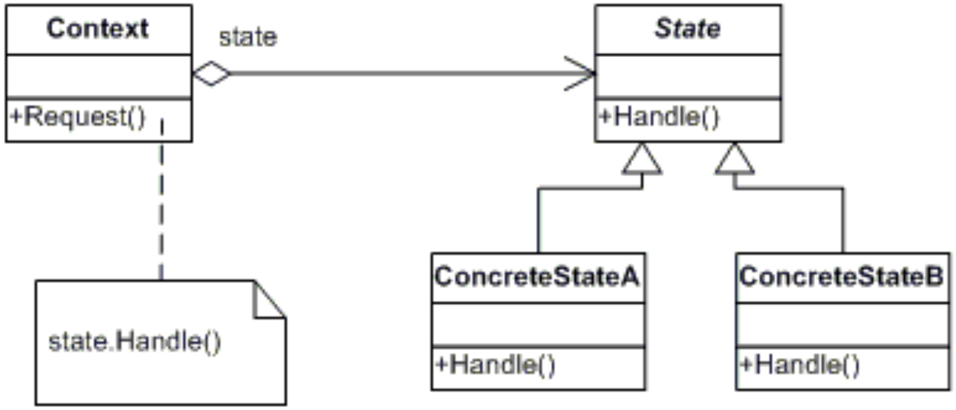
A calculator with the State design pattern



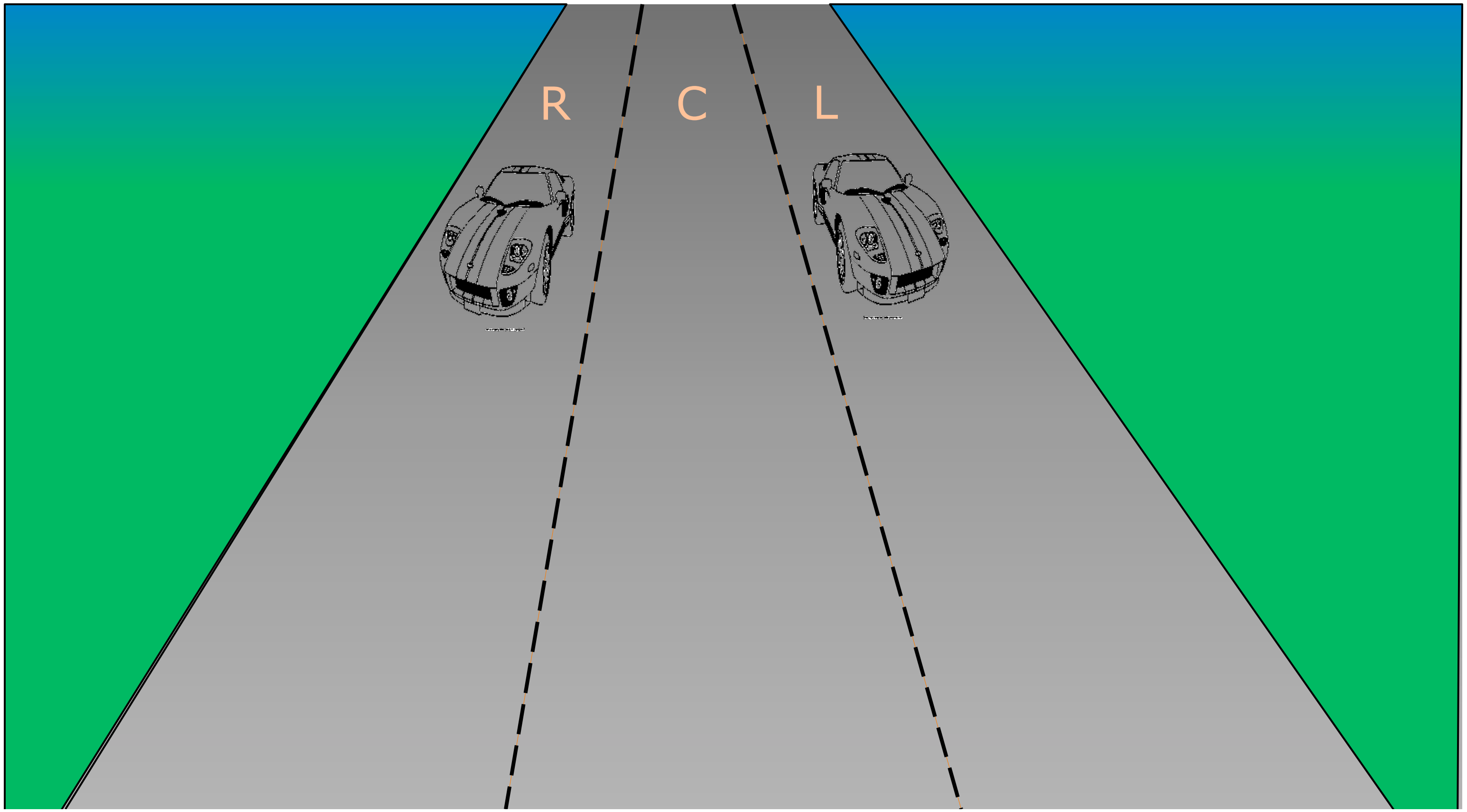
- See StatePatternCalculator.java

The State design pattern

- Applicability:
  - An object's behavior depends on its state, and it must change its behavior at run-time based on that state
  - Transition function between states is highly state-dependent and complex
- Consequences:
  - State-specific behavior is partitioned, localized, and cohesive
  - State transitions are explicit
  - State objects can be shared



Recall a problem of concurrency: Shared state



MapReduce's approach to shared state

- E.g., for each word on the Web, count the number of times that word occurs
  - For Map: `key1` is a document name, `value` is the contents of that document
  - For Reduce: `key2` is a word, `values` is a list of the number of counts of that word

```
f1(String key1, String value):
  for each word w in value:
    EmitIntermediate(w, 1);
```

```
f2(String key2, Iterator values):
  int result = 0;
  for each v in values:
    result += v;
  Emit(key2, result);
```

Map: (key1, v1) → (key2, v2)* Reduce: (key2, v2*) → (key3, v3)*

MapReduce: (key1, v1)* → (key3, v3)*

MapReduce: (docName, docText)* → (word, wordCount)*

Transactional approach to shared state

- For good performance, database interleaves operations of concurrent transactions
- Problems to avoid:
  - Lost updates
    - Another transaction overwrites your update, based on old data
  - Inconsistent retrievals
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Models of concurrency and parallelism

- Explicit concurrency: threads and locking
- Functional programming
- Transactions and serializability
- MapReduce and other data-centric architectures
- SIMD and data parallelism
- Communicating sequential processes
  - Message passing
  - Channels
  - The actor model

The actor model

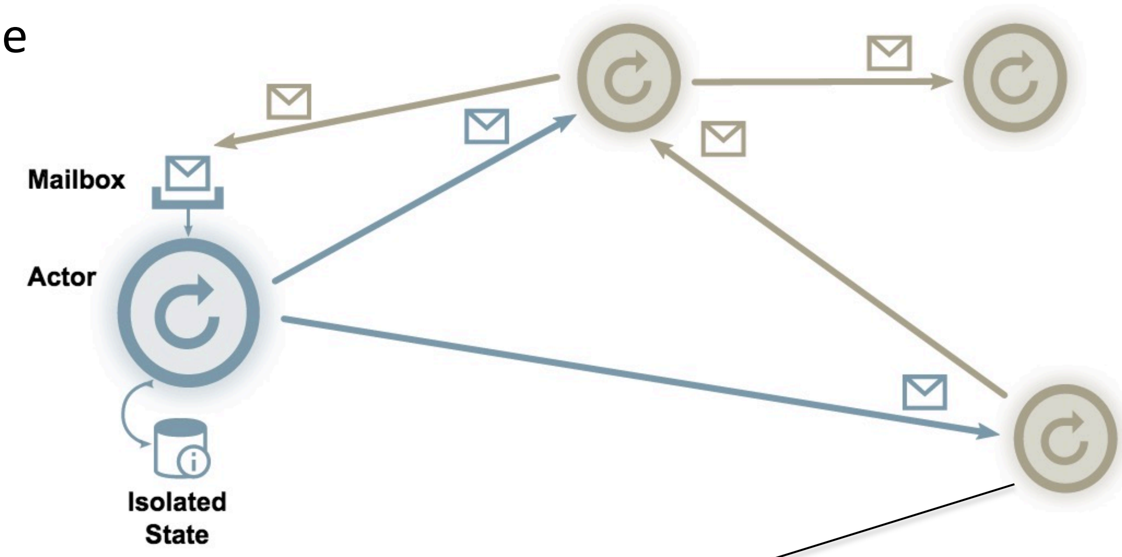
- System is composed of independent *actors* that communicate via asynchronous messages

i.e. concurrent function calls without return values

sequential, no shared state

The actor model

- System is composed of independent *actors* that communicate via asynchronous messages
- Properties of actors:
  - Sequential and non-blocking
  - Non-shared, mutable state
  - Queue for incoming messages
  - Inherently concurrent
  - Extremely lightweight
  - Distributed by default




```
while true:
      process next message
```

Implementations of the actor model

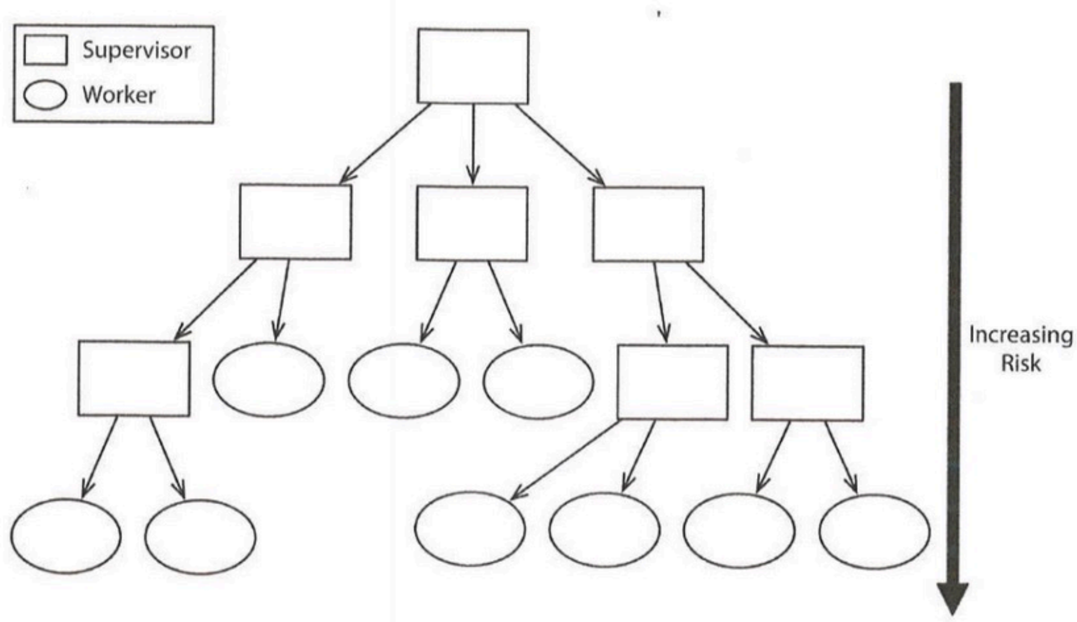
- Frameworks:
  - Java: Akka
  - Python: Pykka
  - C++: CAF (C++ Actor Framework)
- Languages:
  - Scala
  - Scratch
  - Erlang
  - Elixer
- Typically provide:
  - Communication between actors
  - Distribution among servers
  - Supervisory relationships between actors
  - Lightweight management and scheduling

Processing messages

- An actor may:
  - Change its internal state
  - Send one or more messages to other actors
  - Create one or more new actors

Processing messages

- An actor may:
  - Change its internal state
  - Send one or more messages to other actors
  - Create one or more new actors
    - Defines a hierarchy of actors



(source: *Seven Concurrency Models in Seven Weeks* by Paul Butcher.

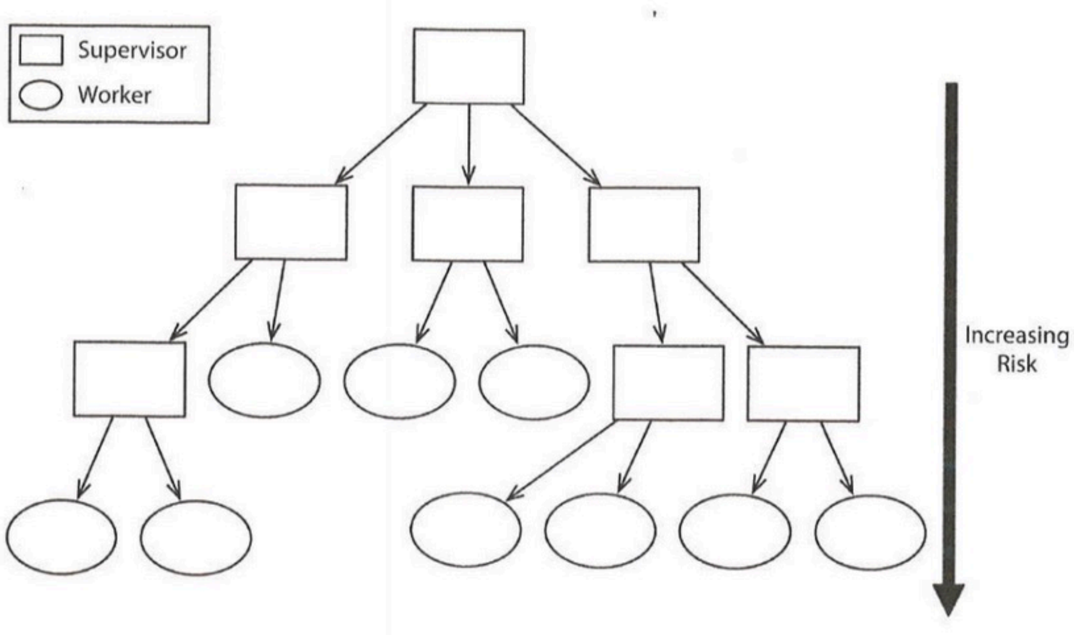
Recall an advantage of Exceptions

- Separates normal and exceptional control flow

```
try {
    FileInputStream fileInput = new FileInputStream(filename);
    DataInput dataInput = new DataInputStream(fileInput);
    int i = dataInput.readInt();
    fileInput.close();
    return i;
} catch (FileNotFoundException e) {
    System.out.println("Could not open file " + filename);
    return -1;
} catch (IOException e) {
    System.out.println("Error reading binary data from file "
                        + filename);
    return -1;
}
```

Error handling in the actor model

- "Let it crash"
  - Resume or restart failed actors
  - Escalate errors to higher level



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Trade-offs of the actor model

- Strengths:
  - Strong encapsulation via isolation and messaging
  - Fault tolerance
  - Inherently distributed and concurrent
- Weaknesses:
  - Messages expensive compared to shared, local memory
  - Subtle systemic problems, e.g. overflowing mailboxes

Next time…

- Version control systems