Network Applications: High-performance Server Design: Async Servers/Operational Analysis

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http://zoo.cs.yale.edu/classes/cs433/

2/24/2016

Admin

- Assignment three posted.

- Decisions
  - Projects or exam 2

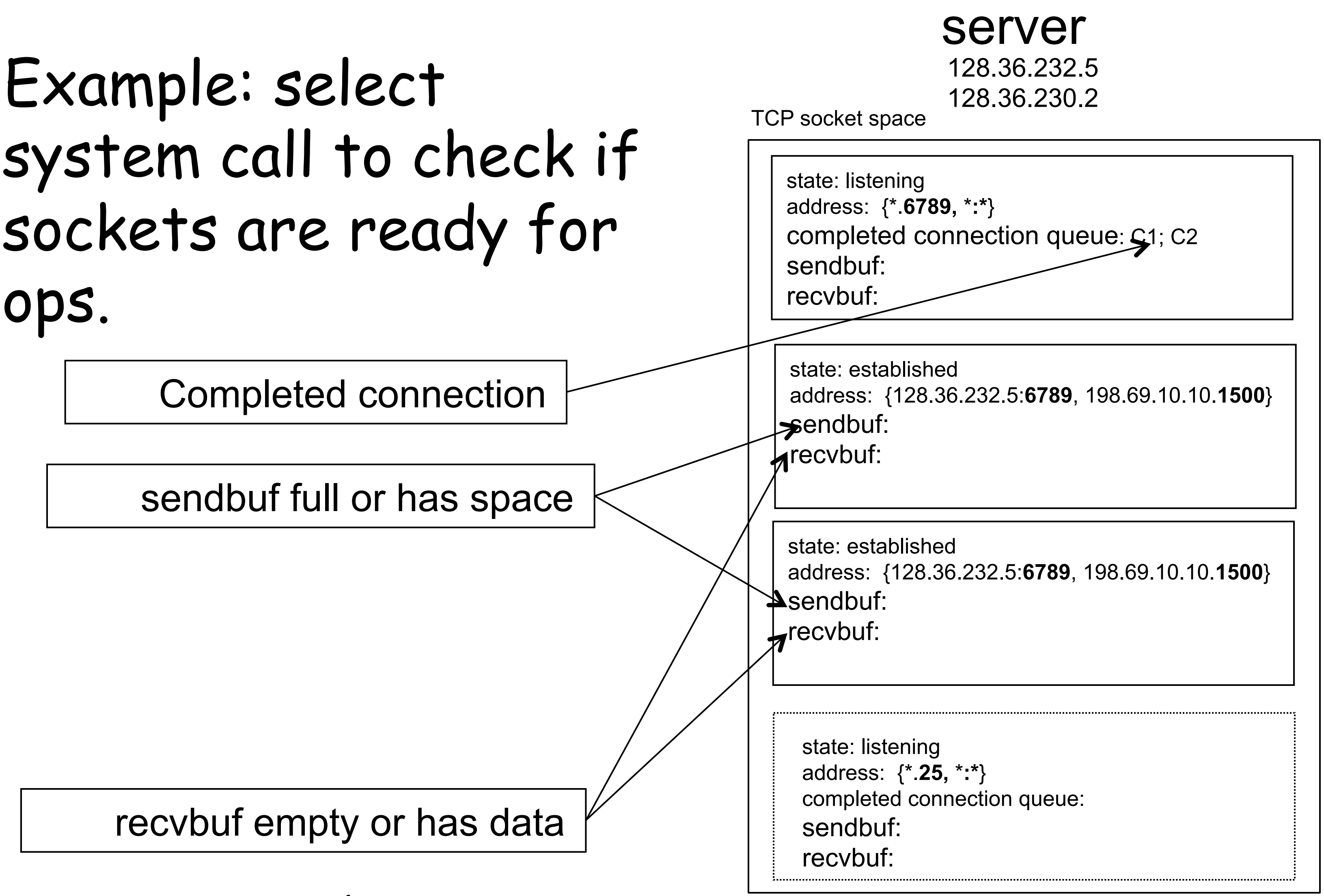
  - Date for exam 1

Recap: Async Network Server

- Basic ideas: non-blocking operations
  1. peek system state (using a select mechanism) to issue only ready operations
  2. asynchronous initiation (e.g., aio_read) and completion notification (callback)

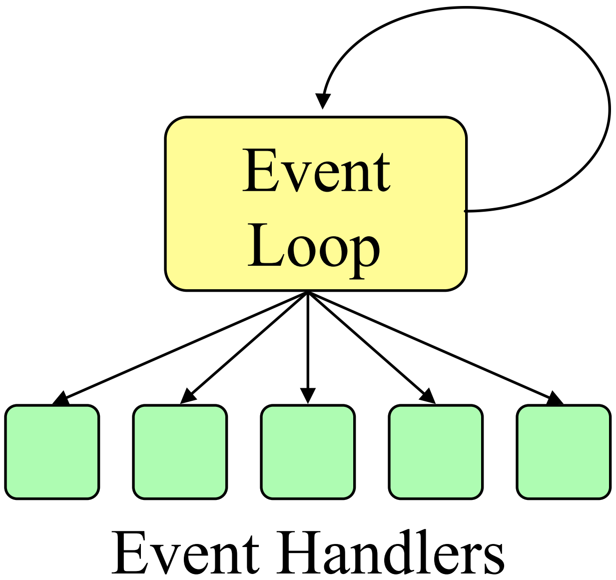
Recap: Async Network Server using Select

- Example: select system call to check if sockets are ready for ops.



Recap: Async Network Server using Select

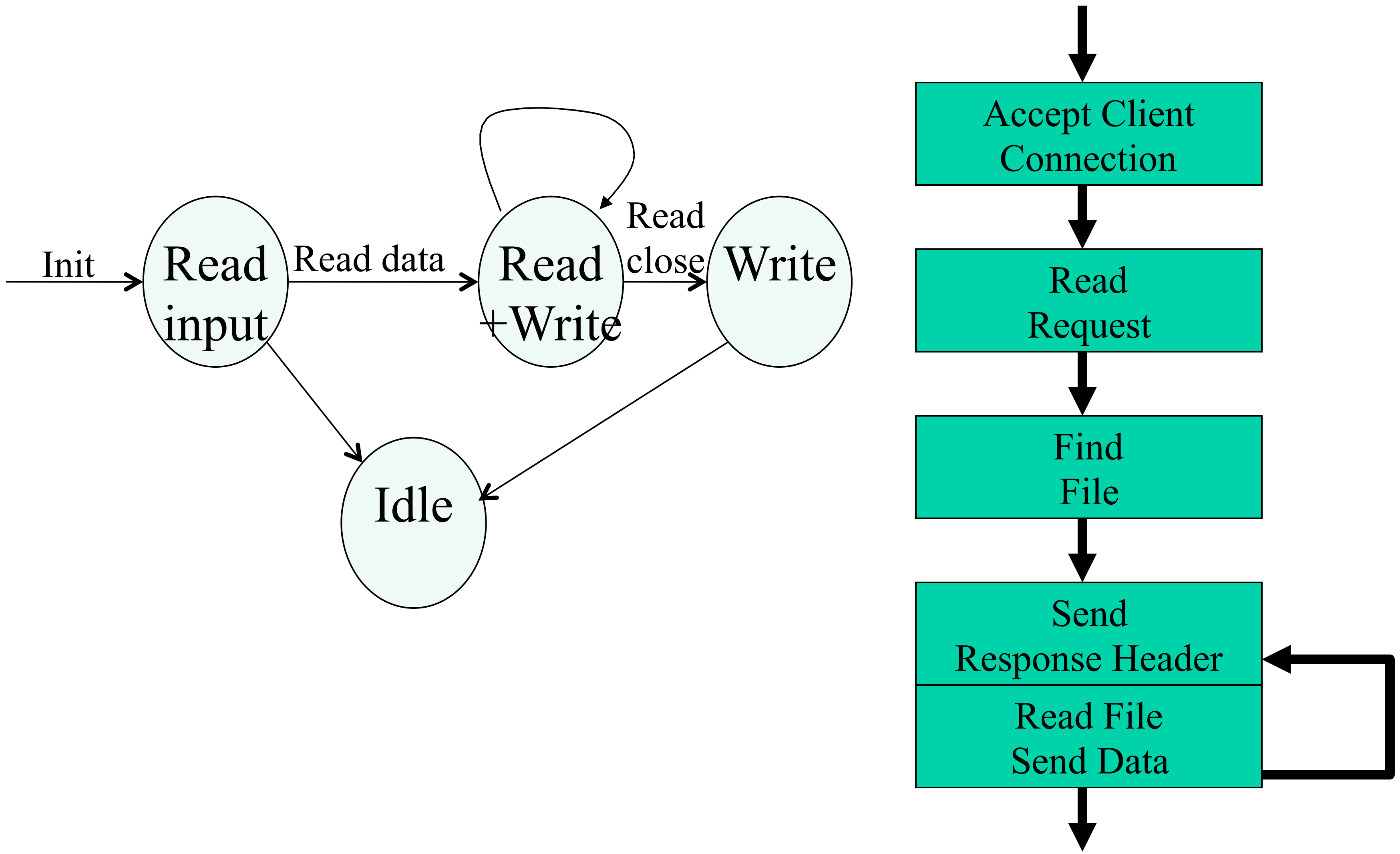
- A event loop issues commands, waits for events, invokes handlers (callbacks)



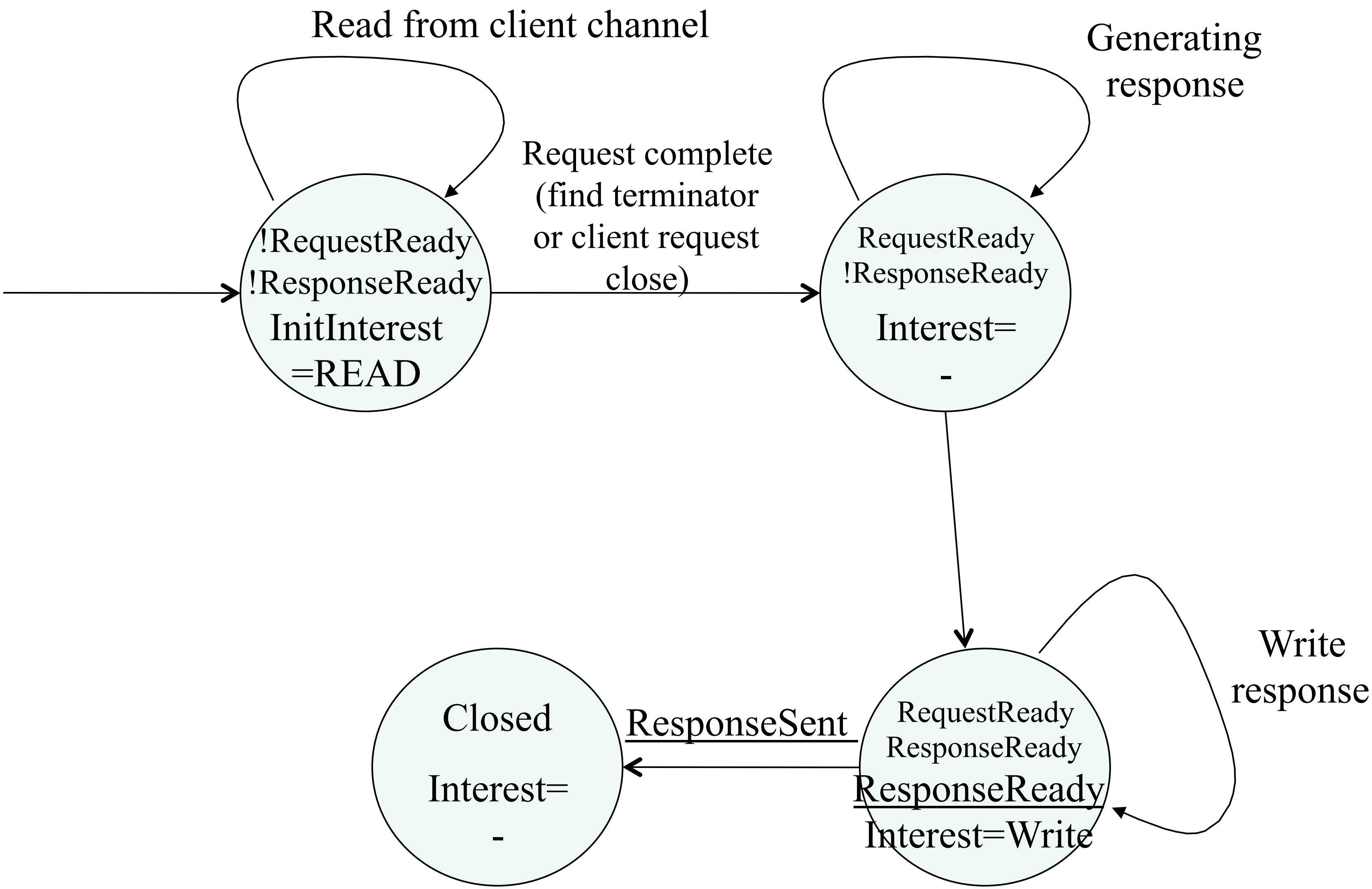

```
// clients register interests/
   handlers on events/sources
while (true)  {
   - ready events = select()
        /* or selectNow(),
           or  select(int timeout) */

   - foreach ready event {
        switch event type:
        accept: call accept handler
        readable: call read handler
        writable: call write handler
     }
}
```

Recap: Need to Manage Finite State Machine



Another Finite State Machine



Finite State Machine Design

- EchoServerV2:
  - Mixed read and write
- Example last slide: staged
  - First read request and then write response
- Choice depends on protocol and tolerance of complexity, e.g.,
  - HTTP/1.0 channel may use staged
  - HTTP/1.1/2/Chat channel may use mixed

Toward More General Server Framework

- Our example EchoServer is for a specific protocol
- A general async/io programming framework tries to introduce structure to allow substantial reuse
  - Async io programming framework is among the more complex software systems
  - We will see one simple example, using EchoServer as a basis

A More Extensible Dispatcher Design

- Fixed accept/read/write functions are not general design
- Requirement: map from key to handler
- A solution: Using attachment of each channel
  - Attaching a `ByteBuffer` to each channel is a narrow design for simple echo servers
  - A more general design can use the attachment to store a callback that indicates not only data (state) but also the handler (function)

A More Extensible Dispatcher Design

- Attachment stores generic event handler
  - Define interfaces
    - IAcceptHandler and
    - IReadWriteHandler
  - Retrieve handlers at run time

```
if (key.isAcceptable()) { // a new connection is ready
    IAcceptHandler aH = (IAcceptHandler) key.attachment();
    aH.handleAccept(key);
}

if (key.isReadable() || key.isWritable())  {
    IReadWriteHandler rwH = IReadWriteHandler)key.attachment();
    if (key.isReadable())  rwH.handleRead(key);
    if (key.isWritable())  rwH.handleWrite(key);
}
```

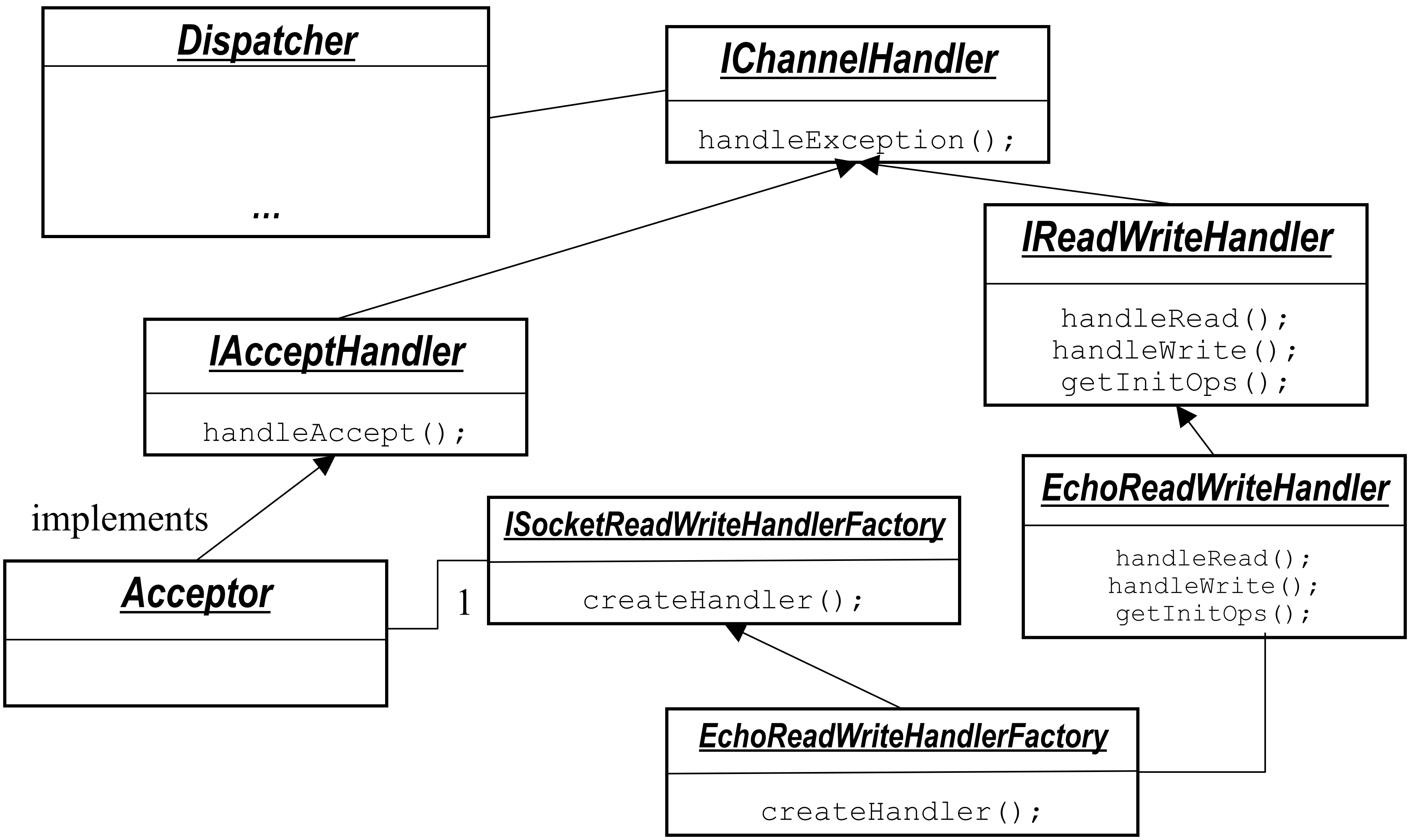
Handler Design: Acceptor

- What should an accept handler object know?
  - ServerSocketChannel (so that it can call accept)
    - Can be derived from SelectionKey in the call back
  - Selector (so that it can register new connections)
    - Can be derived from SelectionKey in the call back
  - What ReadWrite object to create (different protocols may use different ones)?
    - Pass a Factory object: SocketReadWriteHandlerFactory

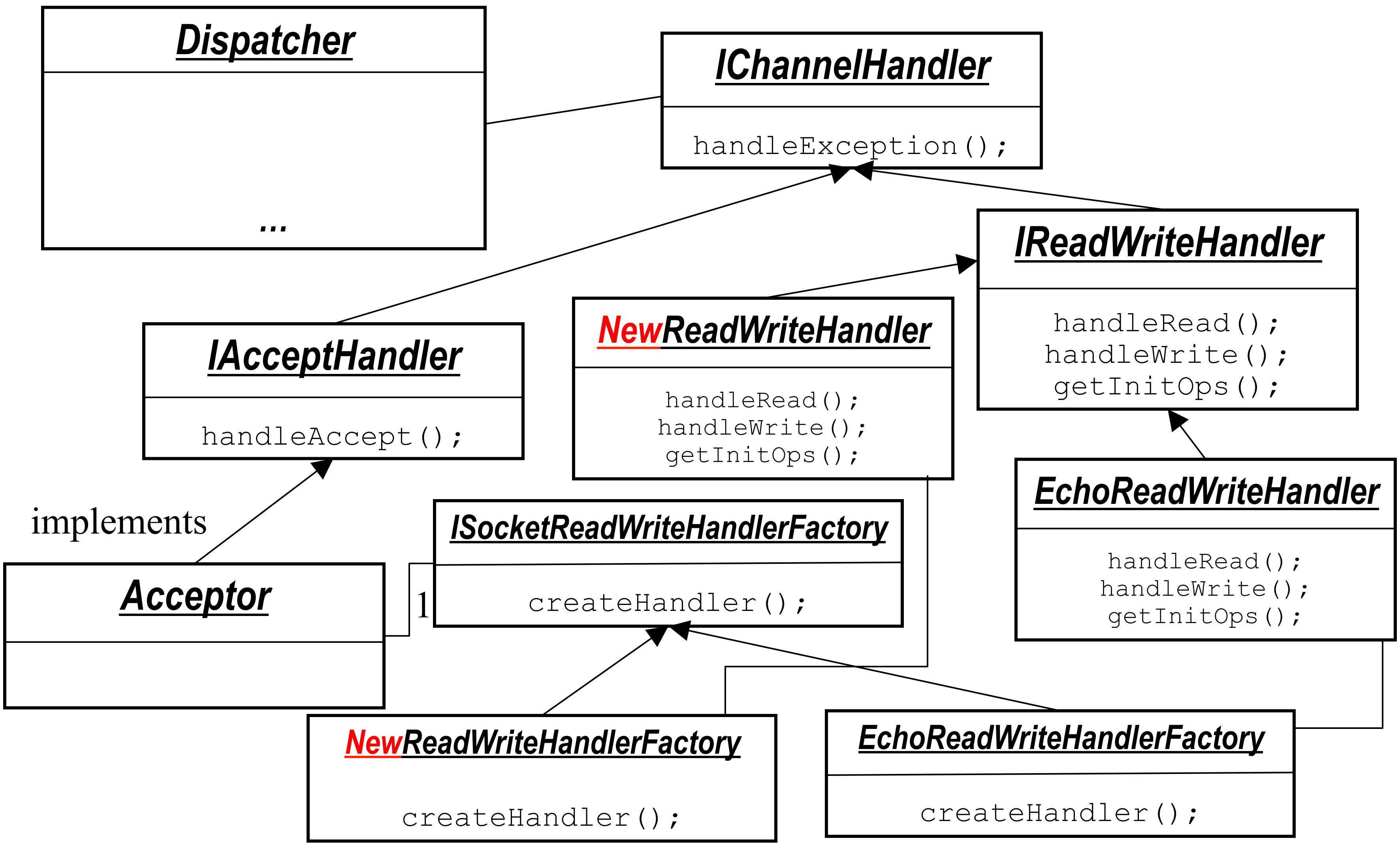
Handler Design: ReadWriteHandler

- What should a ReadWrite handler object know?
  - SocketChannel (so that it can read/write data)
    - Can be derived from SelectionKey in the call back
  - Selector (so that it can change state)
    - Can be derived from SelectionKey in the call back

Class Diagram of SimpleNAIO



Class Diagram of SimpleNAIO



SimpleNAIO

- See AsyncEchoServer/v3/*.java

Discussion on SimpleNAIO

- In our current implementation (Server.java)

```
1. Create dispatcher
2. Create server socket channel and
   listener
3. Register server socket channel to
   dispatcher
4. Start dispatcher thread
```

Can we switch 3 and 4?

Extending SimpleNAIO

- A production network server often closes a connection if it does not receive a complete request in TIMEOUT
- One way to implement time out is that
  - the read handler registers a timeout event with a timeout watcher thread with a call back
  - the watcher thread invokes the call back upon TIMEOUT
  - the callback closes the connection

  Any problem?

Extending Dispatcher Interface

- Interacting from another thread to the dispatcher thread can be tricky
- Typical solution: async command queue

```
while (true)  {
   - process async. command queue
   - ready events = select (or selectNow(), or
   select(int timeout)) to check for ready events
   from the registered interest events of
   SelectableChannels


   - foreach ready event
       call handler
}
```

Question

- How may you implement the async command queue to the selector thread?

```
public void invokeLater(Runnable run) {
   synchronized (pendingInvocations) {
     pendingInvocations.add(run);
   }
   selector.wakeup();
 }
```

Question

- What if another thread wants to wait until a command is finished by the dispatcher thread?

```
public void invokeAndWait(final Runnable task)
  throws InterruptedException
 {
  if (Thread.currentThread() == selectorThread) {
    // We are in the selector's thread. No need to schedule
    // execution
    task.run();
  } else {
    // Used to deliver the notification that the task is executed
    final Object latch = new Object();
    synchronized (latch) {
      // Uses the invokeLater method with a newly created task
      this.invokeLater(new Runnable() {
        public void run() {
          task.run();
          // Notifies
          synchronized(latch) { latch.notify(); }
        }
      });
      // Wait for the task to complete.
      latch.wait();
    }
    // Ok, we are done, the task was executed. Proceed.
  }
 }
```

Recap: Async Network Server

- Basic idea: non-blocking operations
  1. peek system state (select) to issue only ready operations
  2. asynchronous initiation (e.g., aio_read) and completion notification (callback)

Alternative Design: Asynchronous Channel using Future/Listener

- Java 7 introduces ASynchronousServerSocketChannel and ASynchornousSocketChannel beyond ServerSocketChannel and SocketChannel
  - accept, connect, read, write return Futures or have a callback. Selectors are not used

https://docs.oracle.com/javase/7/docs/api/java/nio/channels/AsynchronousServerSocketChannel.html

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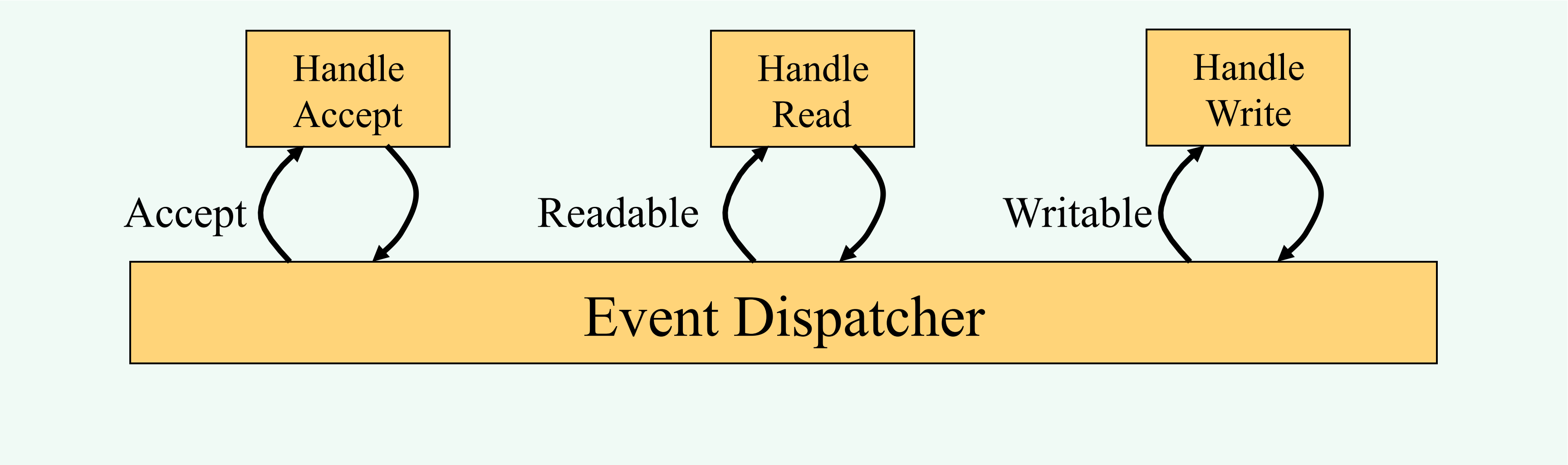
```java
SocketAddress address
   = new InetSocketAddress(args[0], port);
AsynchronousSocketChannel client
  =  AsynchronousSocketChannel.open();
Future<Void> connected
  = client.connect(address);

ByteBuffer buffer = ByteBuffer.allocate(100);

// wait for the connection to finish
connected.get();

// read from the connection
Future<Integer> future = client.read(buffer);

// do other things...

// wait for the read to finish...
future.get();

// flip and drain the buffer
buffer.flip();
WritableByteChannel out
   = Channels.newChannel(System.out);
out.write(buffer);
```

```java
class LineHandler implements
CompletionHandler<Integer, ByteBuffer> {

  @Override
  public void completed(Integer result, ByteBuffer buffer)
{
    buffer.flip();
    WritableByteChannel out
        = Channels.newChannel(System.out);
    try {
      out.write(buffer);
    } catch (IOException ex) {
      System.err.println(ex);
    }
  }

  @Override
  public void failed(Throwable ex,
                           ByteBuffer attachment) {
    System.err.println(ex.getMessage());
  }
}
```

```java
ByteBuffer buffer = ByteBuffer.allocate(100);
CompletionHandler<Integer, ByteBuffer>
      handler = new LineHandler();
channel.read(buffer, buffer, handler);
```

Extending FSM

- In addition to management threads, a system may still need multiple threads for performance (why?)
  - FSM code can never block, but page faults, file io, garbage collection may still force blocking
  - CPU may become the bottleneck and there maybe multiple cores supporting multiple threads (typically 2 n threads)



Summary: Architecture

- Architectures
  - Multi threads
  - Asynchronous
  - Hybrid

- Assigned reading: SEDA

Problems of Event-Driven Server

- Obscure control flow for programmers and tools
- Difficult to engineer, modularize, and tune
- Difficult for performance/failure isolation between FSMs

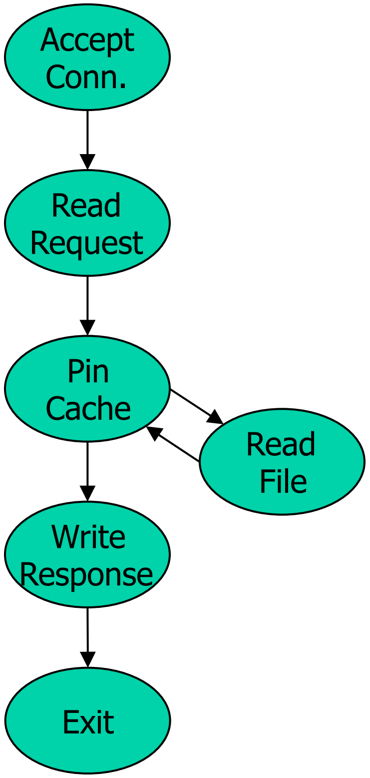
Another view

- Events obscure control flow
  - For programmers *and* tools

Threads	*Events*

thread_main(int sock) {
    struct session s;
    accept_conn(sock, &s);
    read_request(&s);
    pin_cache(&s);
    write_response(&s);
    unpin(&s);
}
 	
pin_cache(struct session *s) {
    pin(&s);
    if(!in_cache(&s))
        read_file(&s);
}
	AcceptHandler(event e) {
	    struct session *s = new_session(e);
	    RequestHandler.enqueue(s);
	}
	RequestHandler(struct session *s) {
	    …; CacheHandler.enqueue(s);
	}
	CacheHandler(struct session *s) {
	    pin(s);
	    if(!in_cache(s)) ReadFileHandler.enqueue(s);
	    else ResponseHandler.enqueue(s);
	}
	. . .
	ExitHandlerr(struct session *s) {
	    …; unpin(&s); free_session(s); }

Web Server



[von Behren]

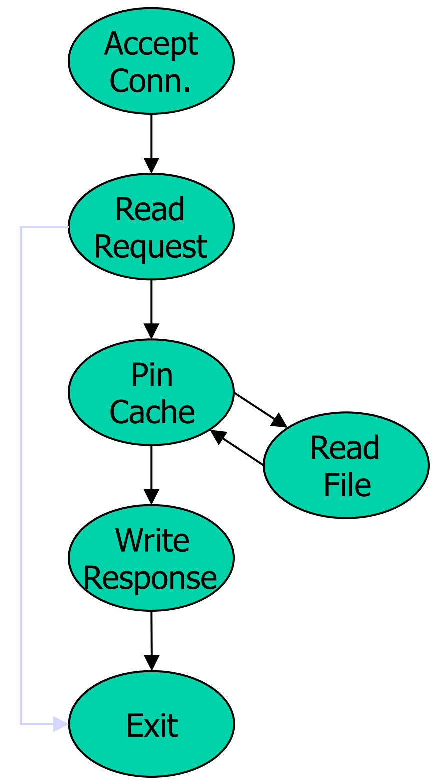
State Management

- Events require manual state management
- Hard to know when to free
  - Use GC or risk bugs

Threads	*Events*

<pre>thread_main(int sock) {
    struct session s;
    accept_conn(sock, &s);
    if(!read_request(&s))
        return;
    pin_cache(&s);
    write_response(&s);
    unpin(&s);
}
 	
pin_cache(struct session *s) {
    pin(&s);
    if(!in_cache(&s))
        read_file(&s);
}</pre>
	<pre>CacheHandler(struct session *s) {
	    pin(s);
	    if(!in_cache(s)) ReadFileHandler.enqueue(s);
	    else ResponseHandler.enqueue(s);
	}
	RequestHandler(struct session *s) {
	    …; if(error) return; CacheHandler.enqueue(s);
	}
	. . .
	ExitHandlerr(struct session *s) {
	    …; unpin(&s); free_session(s);
	}
	AcceptHandler(event e) {
	    struct session *s = new_session(e);
	    RequestHandler.enqueue(s); }</pre>

Web Server



[von Behren]

Summary: The High-Performance Network Servers Journey

- Avoid blocking (so that we can reach bottleneck throughput)
  - Introduce threads
- Limit unlimited thread overhead
  - Thread pool, async io
- Coordinating data access
  - synchronization (lock, synchronized)
- Coordinating behavior: avoid busy-wait
  - Wait/notify; select FSM, Future/Listener
- Extensibility/robustness
  - Language support/Design for interfaces

Beyond Class: Design Patterns

- We have seen Java as an example

- C++ and C# can be quite similar. For C++ and general design patterns:
  - http://www.cs.wustl.edu/~schmidt/PDF/OOCP-tutorial4.pdf
  - http://www.stal.de/Downloads/ADC2004/pra03.pdf

Some Questions

- When is CPU the bottleneck for scalability?
  - So that we need to add helpers

- How do we know that we are reaching the limit of scalability of a single machine?

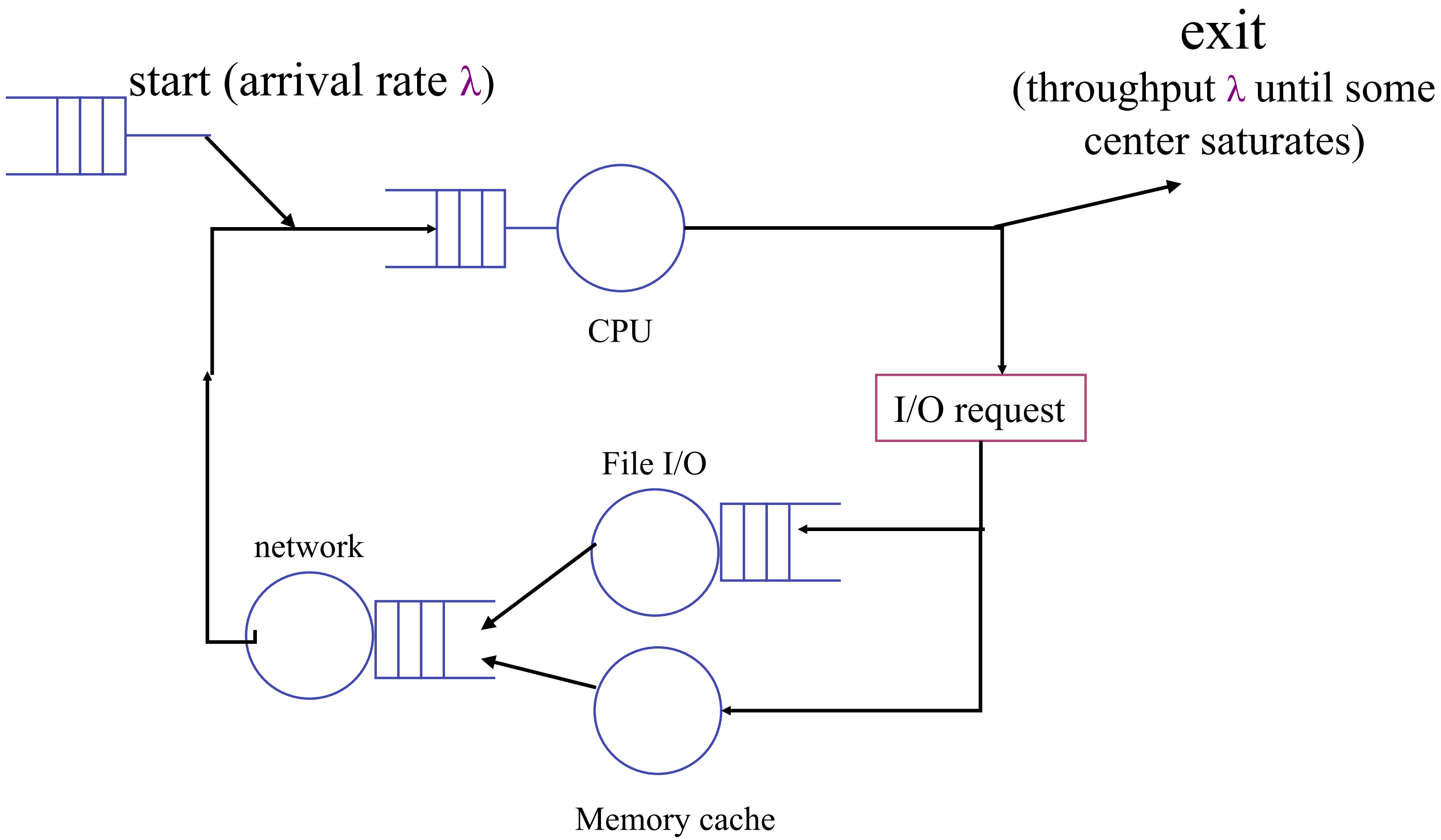
- These questions drive network server architecture design

Operational Analysis

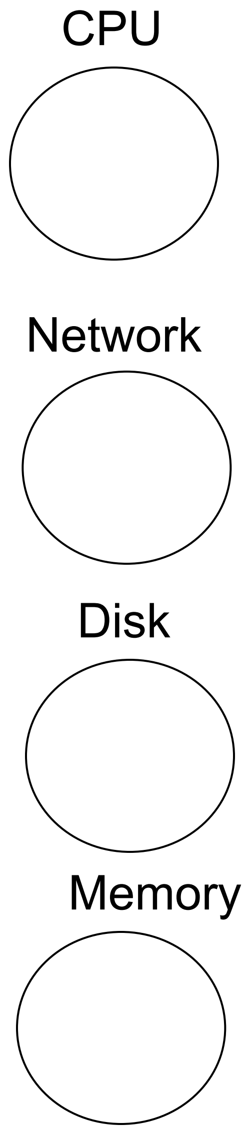
- Relationships that do not require any assumptions about the distribution of service times or inter-arrival times.
- Identified originally by Buzen (1976) and later extended by Denning and Buzen (1978).

- We touch only some techniques/results
  - In particular, bottleneck analysis
- More details see linked reading

Under the Hood (An example FSM)



Operational Analysis: Resource Demand of a Request



V_{CPU} visits for S_{CPU} units of resource time per visit

V_{Net} visits for S_{Net} units of resource time per visit

V_{Disk} visits for S_{Disk} units of resource time per visit

V_{Mem} visits for S_{Mem} units of resource time per visit

Operational Quantities

- T: observation interval
- Bi: busy time of device i
- i = 0 denotes system

Ai: # arrivals to device i

Ci: # completions at device i

$$\text{arrival rate } \lambda_i = \frac{A_i}{T}$$

$$\text{Throughput } X_i = \frac{C_i}{T}$$

$$\text{Utilization } U_i = \frac{B_i}{T}$$

$$\text{Mean service time } S_i = \frac{B_i}{C_i}$$

Utilization Law

$$\text{Utilization } U_i = \frac{B_i}{T}$$

$$= \frac{C_i}{T}\frac{B_i}{C_i}$$

$$= X_i S_i$$

- The law is independent of any assumption on arrival/service process
- Example: Suppose NIC processes 125 pkts/sec, and each pkt takes 2 ms. What is utilization of the network NIC?

Deriving Relationship Between R, U, and S for one Device

- Assume flow balanced (arrival=throughput), Little's Law:

$$Q = \lambda R = XR$$

- Assume PASTA (Poisson arrival--memory-less arrival--sees time average), a new request sees Q ahead of it, and FIFO

$$R = S + QS = S + XRS$$

- According to utilization law, U = XS

$$R = S + UR \longrightarrow R = \frac{S}{1-U}$$