The Design, Implementation and Performance Evaluation of Internet Services

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Announcement

- Summer Research Internships at U Waterloo
  – Several Different areas
  – Competing and possibly working with top students from around the world

See:

http://blizzard.cs.uwaterloo.ca/intern07/info.html

Introduction

- **Tim Brecht** (pronounced brek-t)
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  - http://cs.uwaterloo.ca/~brecht

    (see my 497 link for assignment due next lecture)
- Background
  - B.Sc. (Sask.), M.Math (Waterloo), Ph.D. (Toronto)
  - On faculty (York & Waterloo)
  - Visiting Scientist (IBM)
  - Sabbatical & Research Scientist (HP Labs) 1+2 yrs
- Research Interests: performance, operating systems, networking, parallel and distributed computing

Introduction

- My research described here done with many people:
- **Ugrads**: Craig Barkhouse (UW),
  Siddharth Gupta (IIT Guwahati)
- **UW grad students**: Michal Ostrowski, David Pariag,
  Amol Shukla, Jialin Song, Elad Lehav,
  Weihan Wong, Ashif Harji, Gary Yeung
- **UW Faculty**: Martin Karsten, Peter Buhr,
- **UW Staff**: Louay Gammo, Mark Groves
- **HP Labs**: Brian Lynn, John Janakiraman,
  Yoshio Turner
- **Intel Labs**: Greg Regnier, Vikram Saletore

Outline

- **Part I: Background**
  - **Web Server Example: HTTP/1.1**
  - **Server Architectures**
  - **Performance Evaluation**
- Part II: A Flavour of some Current Research
  - Performance of Different Server Architectures
  - Improving Operating System Support for I/O Centric Servers (if time permits)
  - Possible Avenues for Future Research

Outline

- **Part I: Background**
  - Web Server Example: HTTP/1.1
  - Server Architectures
  - Performance Evaluation

How to build a fast Internet Service

- Types of services
  - Web Servers
  - Streaming Audio/Video Services
  - Game Services
  - Domain Name System (DNS) (i.e., name lookups)
  - Mail: SMTP / IMAP / POP
  - Chat Servers (Text)
  - Voice over IP
  - File Sharing (i.e., music stealing)

Example Internet Service: Web Server

- Simple to understand
- Easy to implement
- Widely used:
  - **106,875,138** Web Sites [Netcraft, January 2007]
  - Dominant Internet Service/Application
  - UW traffic [ist.uwaterloo.ca/cn/Stats/extvol.html]
    - http 62%, other 18%, ssh 6% Jan 10, 2007
    - http 52%, other 38%, p2p 3% March, 2005
    - http 63%, other 20%, ftp 7% March, 1998

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- Part I: Background
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Simple Web Server Request/Response

Client sends to server:

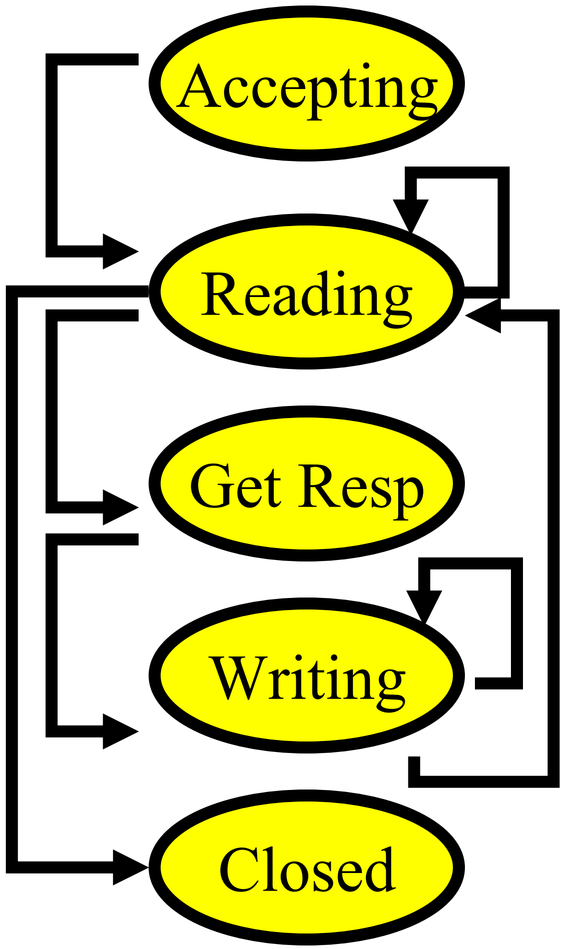
```
GET docs/10B.txt HTTP/1.1
User-Agent: httperf/0.8.4
Host: 127.0.0.1
<cr><lf>
```

Server replies to client:

```
HTTP/1.1 200 OK
Server: userver-0.5.2
Content-Length: 10

012345678
```

HTTP/1.1: State Machine



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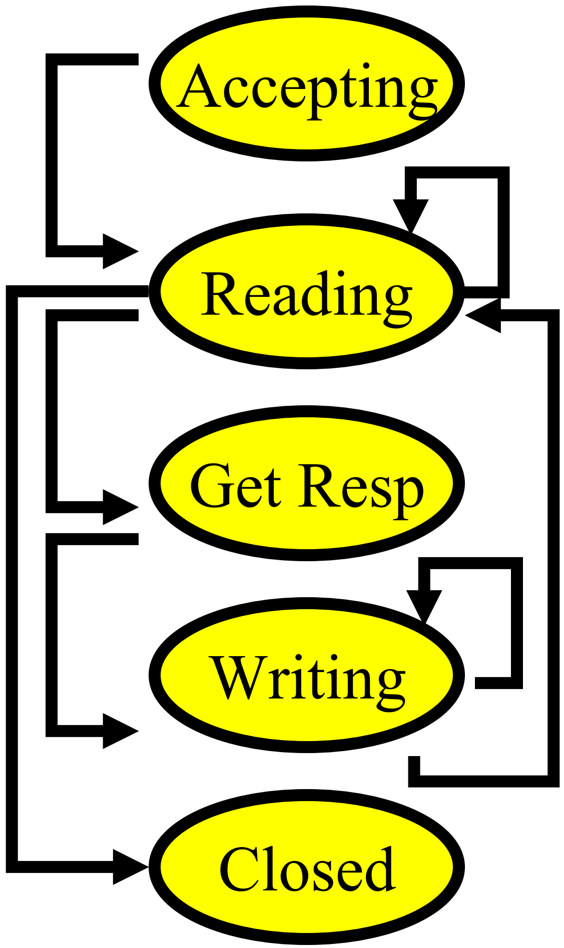

Fairly easy to translate this into a simple server

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  - Web Server Example: HTTP/1.1
  - **Server Architectures**
  - Performance Evaluation

A Simple Server

```
server_sd = socket(); bind(server_sd);
listen(server_sd);

for (;;) {
   // wait for new connection request
   sd = accept(server_sd);
   handle_requests(sd);
}

handle_requests(int sd)
{
   while(read_request(sd, inbuf)) {
       parse_request(inbuf);

       // get or compute response

       write_response(sd, outbuf);
   }
   close(sd);
}
```

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What's good about this approach?

What's bad about this approach?

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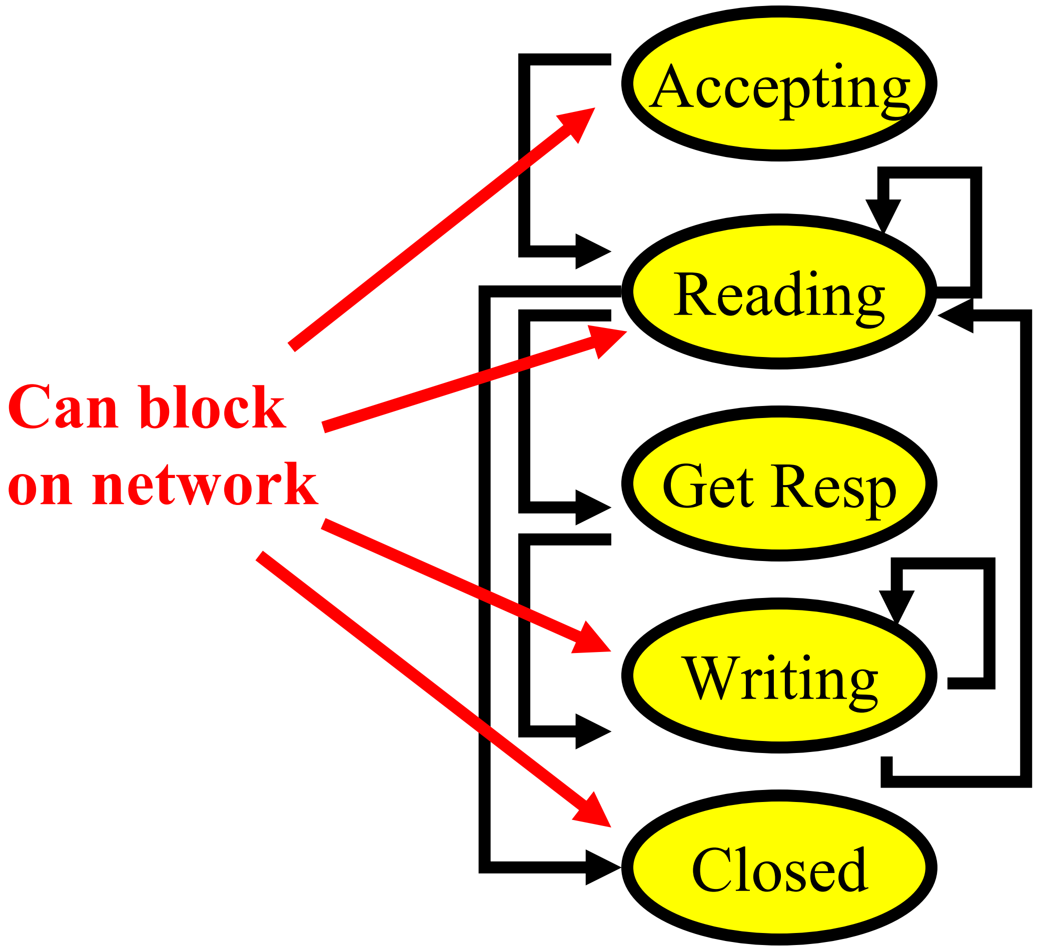

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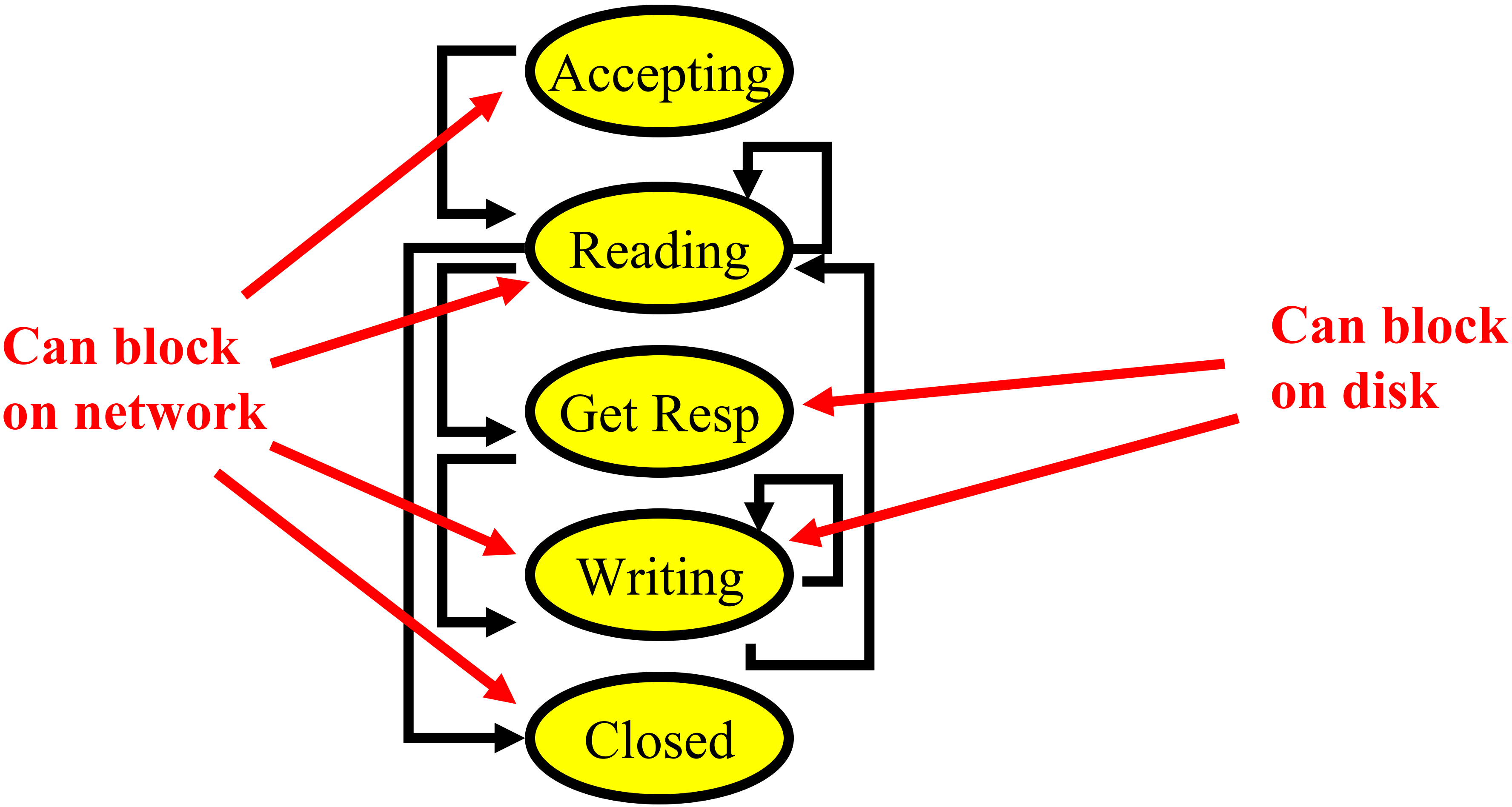

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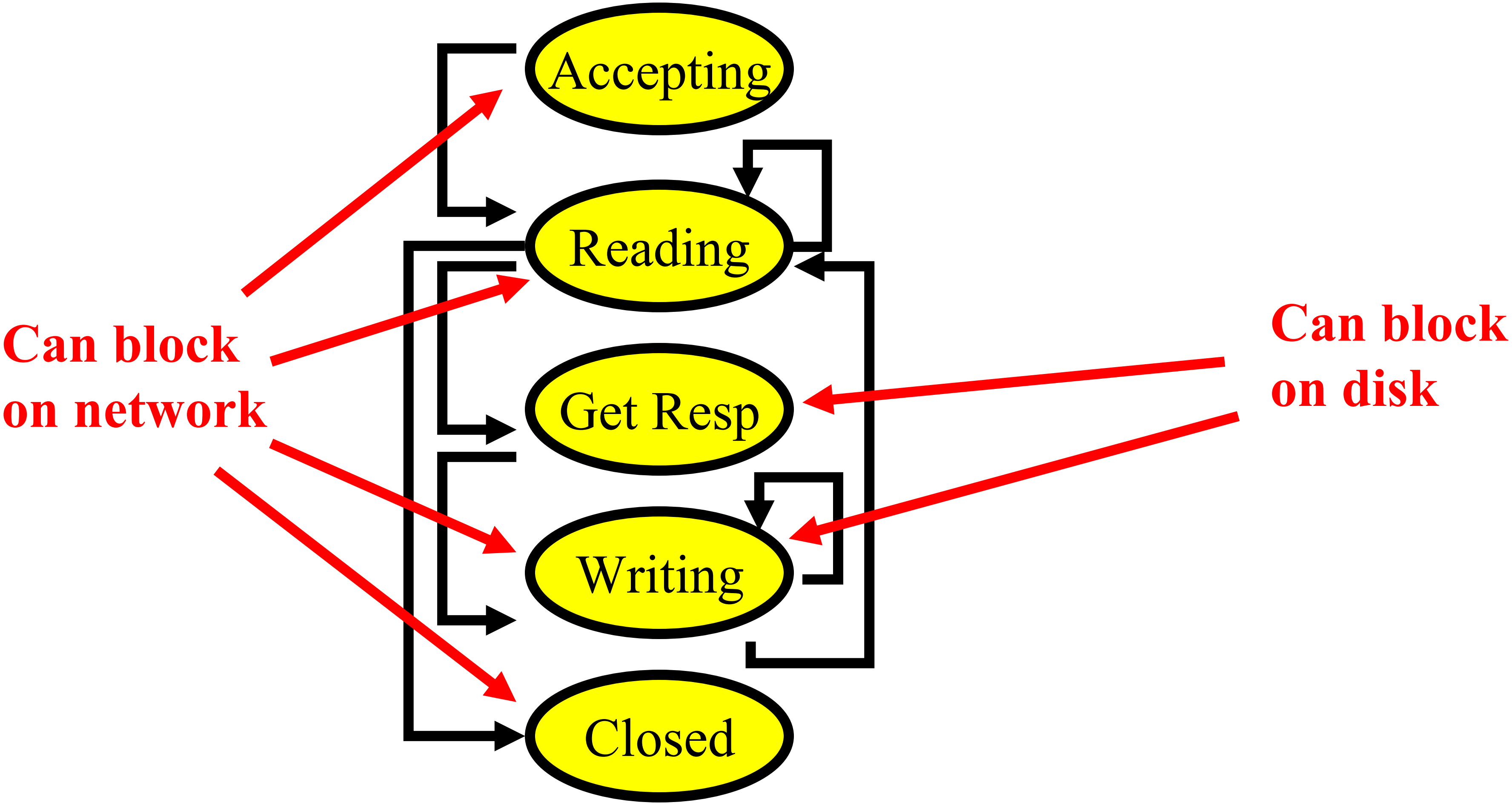
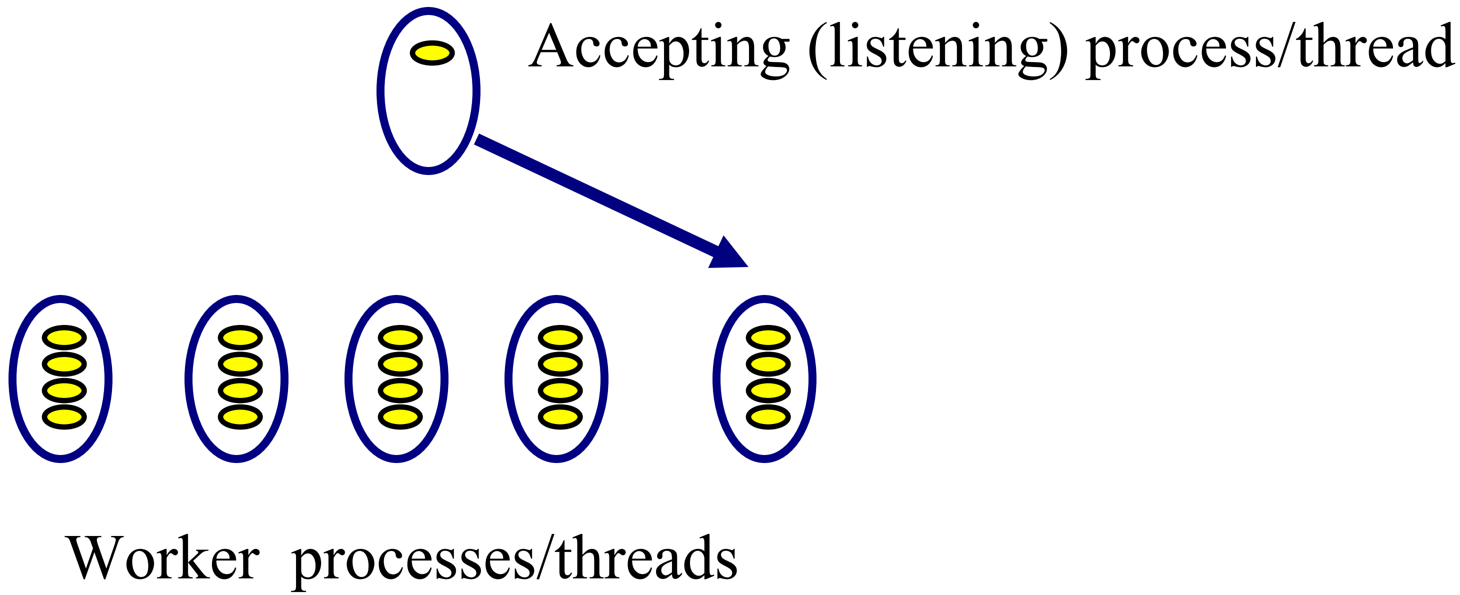


Possible Solutions?

A Forking Server



A Forking Server

```
for (;;) {
   // wait for connection
    sd = accept(server_sd);

   // fork/create child to handle request
   fork/create(handle_requests, sd);
}
```

A Forking Server

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for (;;) {
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How many simultaneous connections can be supported?

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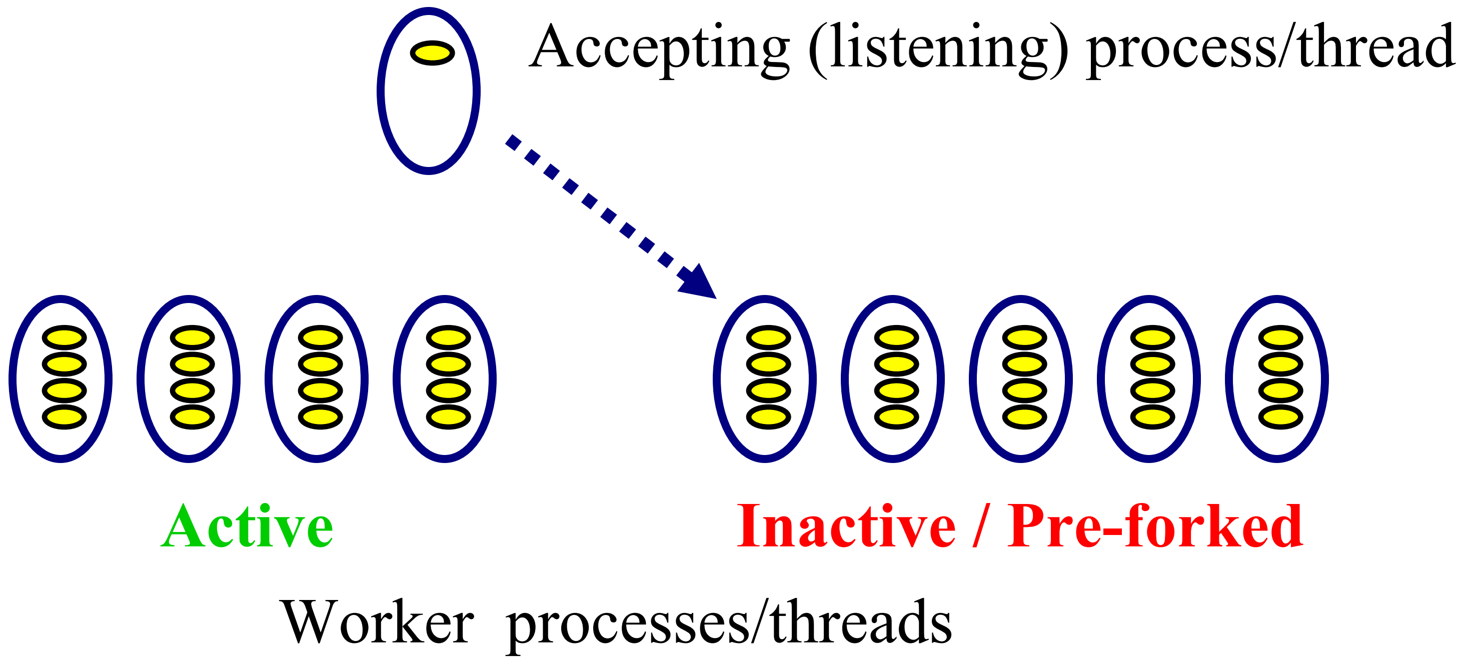
What's wrong with this approach?

How many simultaneous connections can be supported?

Should this server limit resource consumption? Which ones?

A Pre-Forking Server



A Pre-Forking Server

```
for (i=0; i<P; i++) {
   // fork/create a worker process
}

for (;;) {
   // wait for connection
    sd = accept(server_sd);

   // find idle worker to handle request
   pass_to_worker(sd);
}
```

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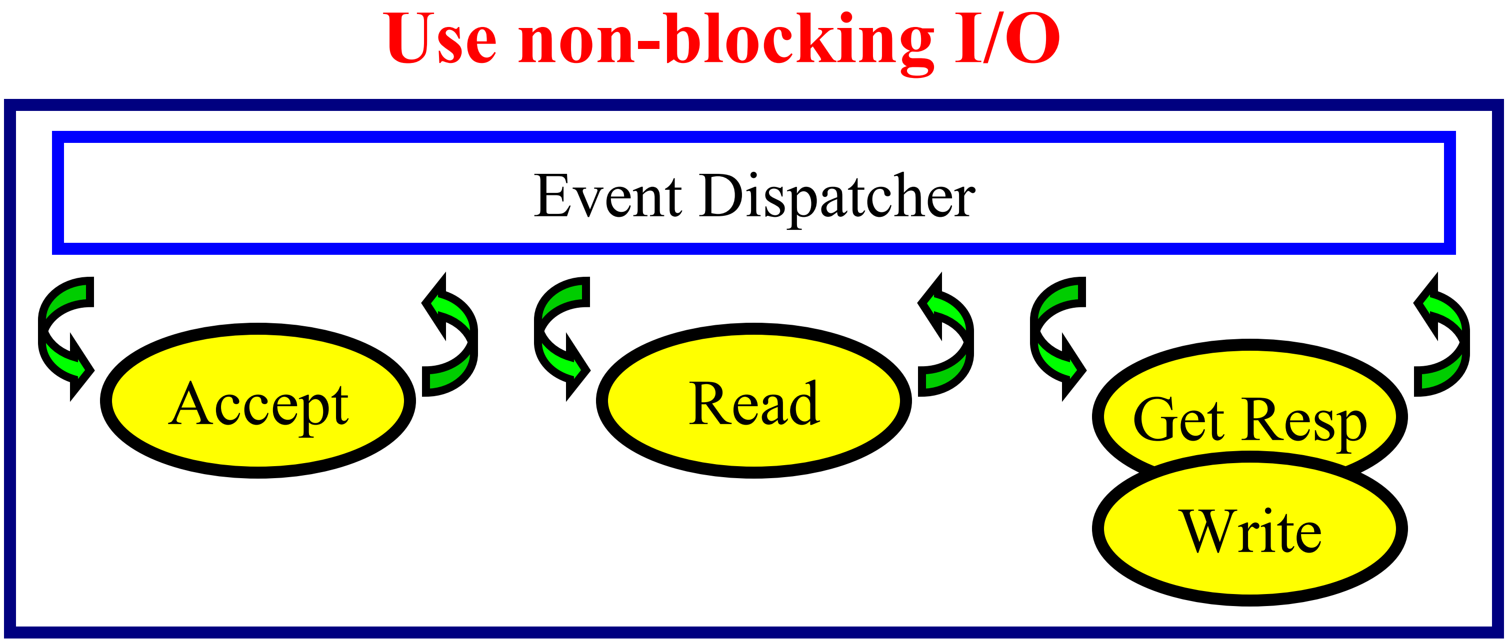
```

What's wrong with this approach?

What is a good value for P (# of workers)?

Single Process Event Driven (SPED)



Single Process Event Driven (SPED)

```
for (;;) {
  n = get_events(&eventlist);

  for (i=0; i<n; i++) {
    sd = eventlist[i].fd;
    if (is_read_event(eventlist[i])) {
      if (sd == server_sd) {
        // get new connection
        newsd = accept(server_sd);
      } else {
        read_request(sd); parse_request();
      }
    }
    if (is_write_event(eventlist[i])) {
      get_and_write_response(sd);
    }
  }
}
```

Single Process Event Driven (SPED)

```
for (;;) {
  readfdset = rdset; writefdset = wrset;
  n = select(max_sd, &readfdset, &writefdset,
             &exceptfds, &timeout);
  for (i=0; i<max_sd; i++) {
    if (FD_ISSET(i, &readfdset)) {
      if (i == server_sd) {
        // get new connection
        sd = accept(server_sd);
        FD_SET(sd, &rdset); FD_SET(sd, &wrset);
      } else {
        read_request(i); parse_request();
      }
    }
    if (FD_ISSET(i, &writefdset)) {
      get_and_write_response(i);
    }
  }
}
```

Single Process Event Driven (SPED)

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  readfdset = rdset; writefdset = wrset;
  n = select(max_sd, &readfdset, &writefdset,
             &exceptfds, &timeout);
  for (i=0; i<max_sd; i++) {
    if (FD_ISSET(i, &readfdset)) {
      if (i == server_sd) {
        // get new connection
        sd = accept(server_sd);
        FD_SET(sd, &rdset); FD_SET(sd, &wrset);
      } else {
        read_request(i); parse_request();
      }
    }
    if (FD_ISSET(i, &writefdset)) {
      get_and_write_response(i);
    }
  }
}
```
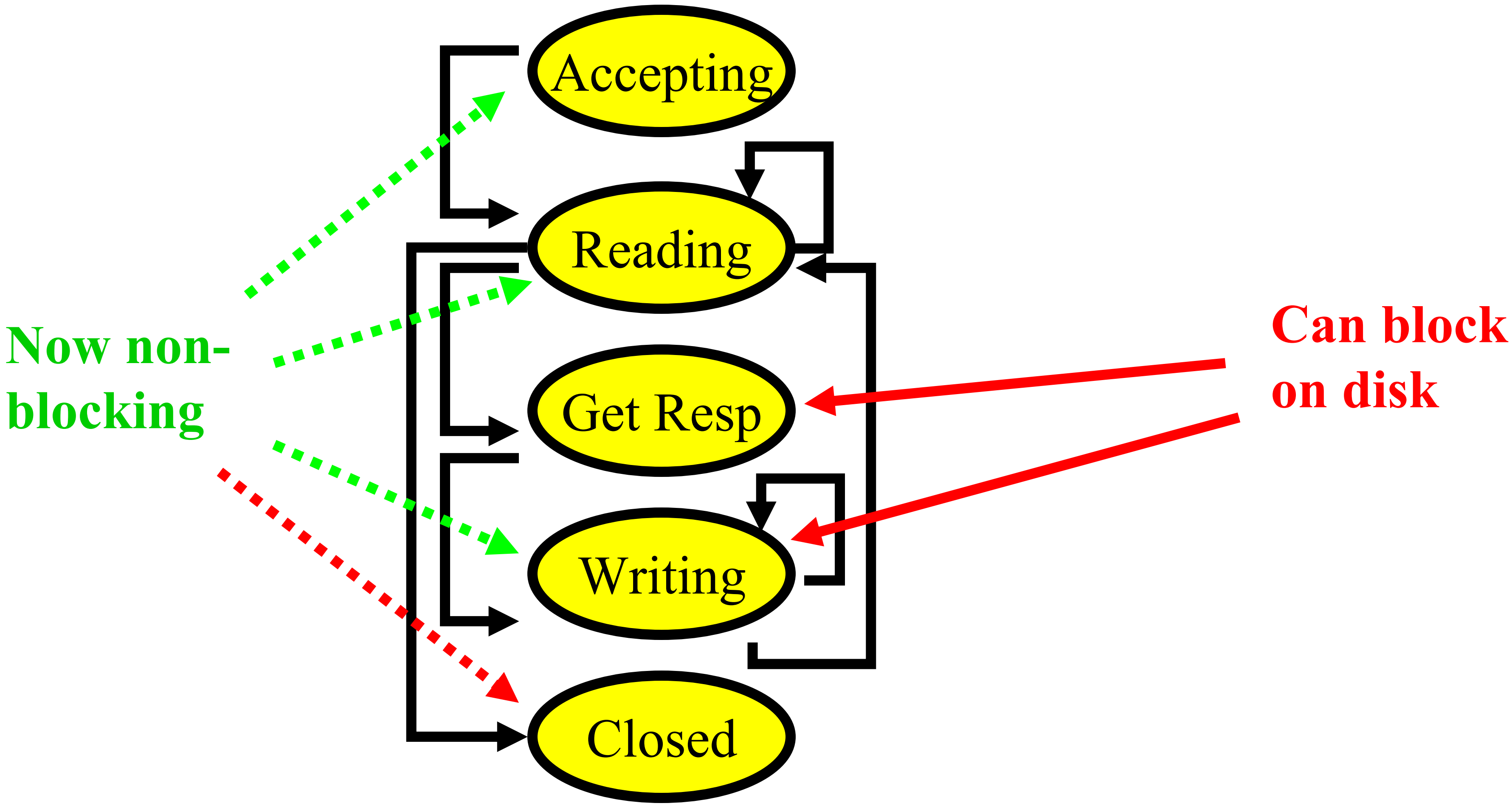

What are the pros and cons of this approach?

Single Process Event Driven (SPED)



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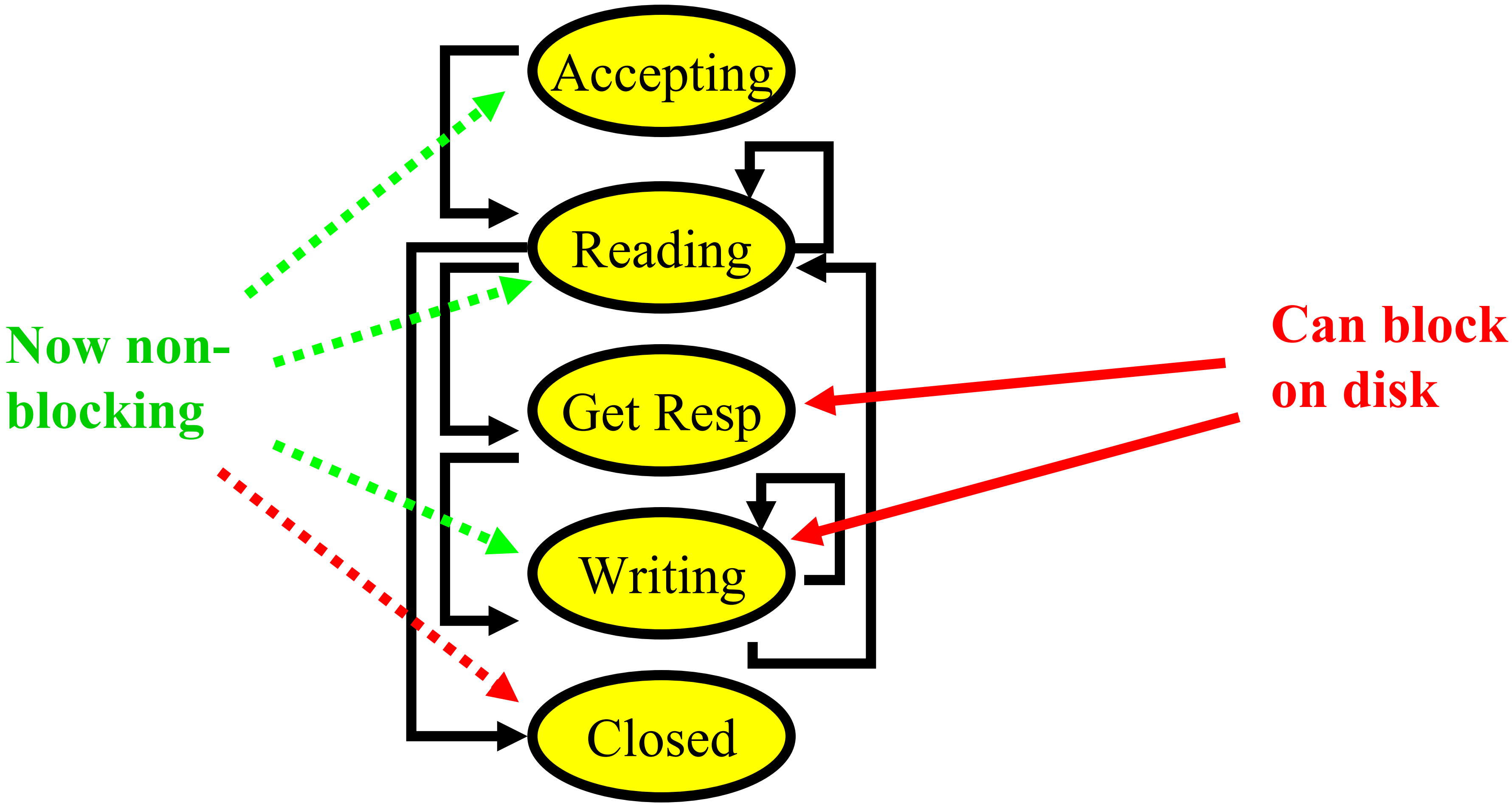
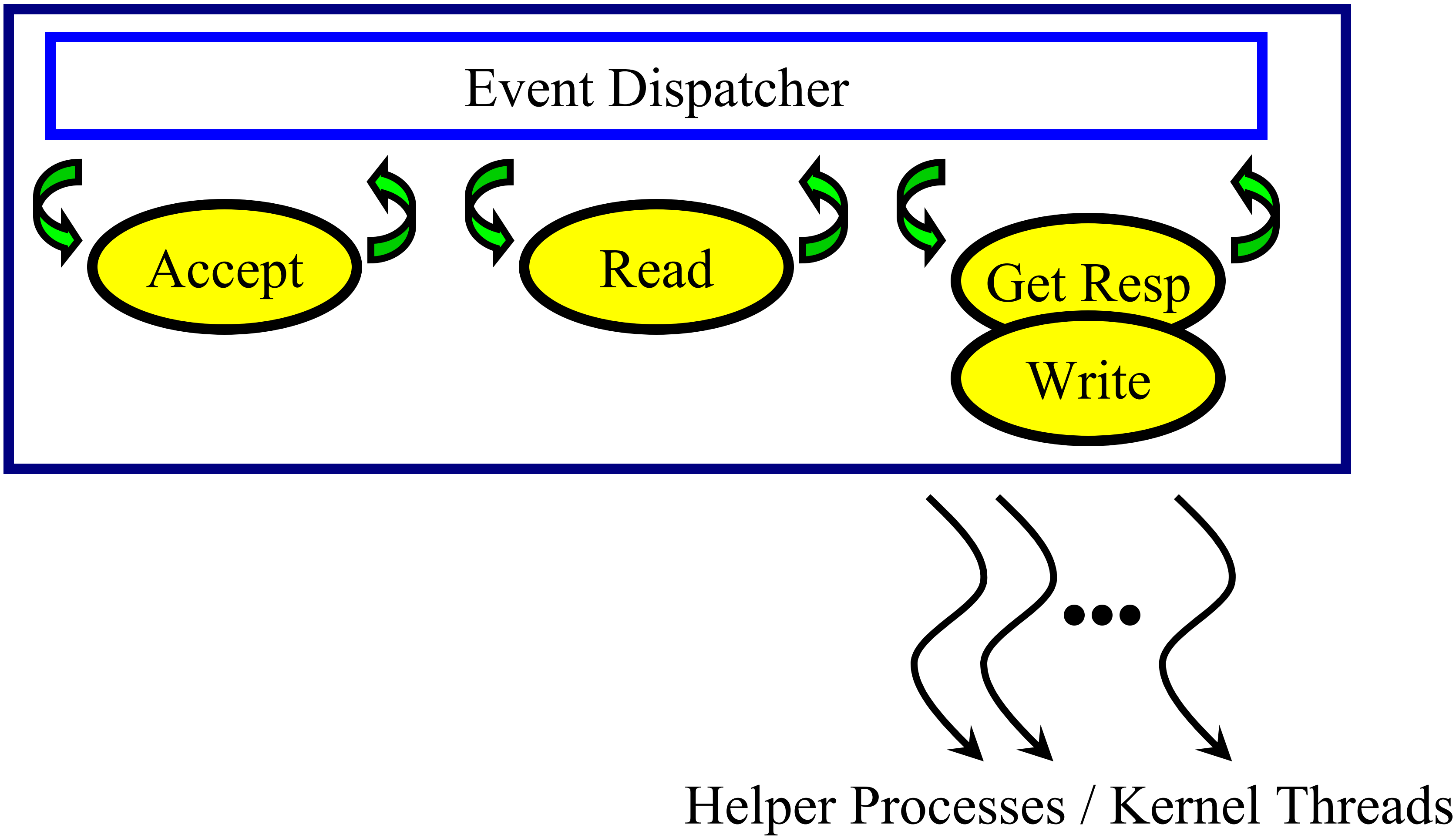


Possible Solutions?

Asymmetric MP Event Driven (AMPED)



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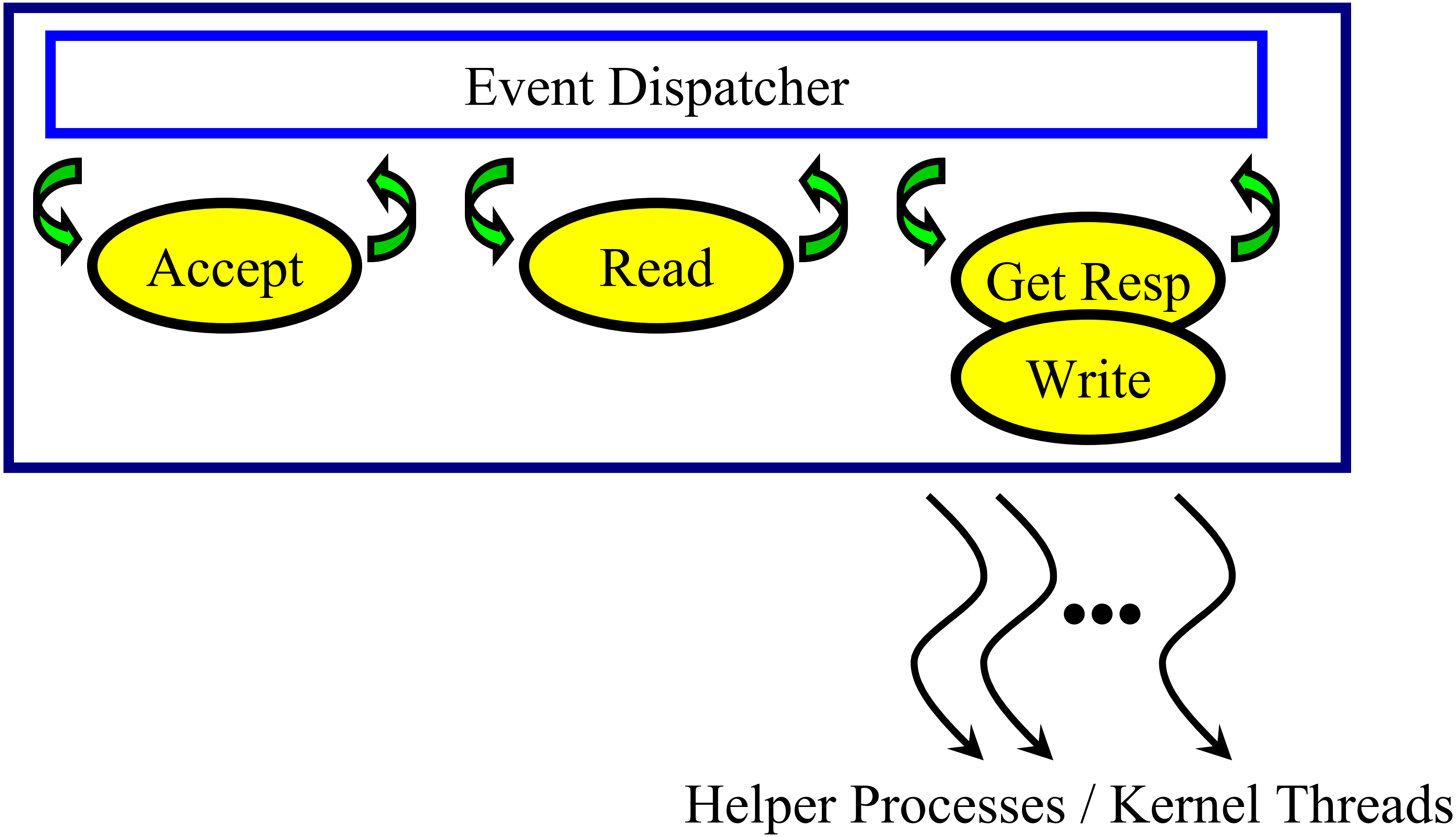
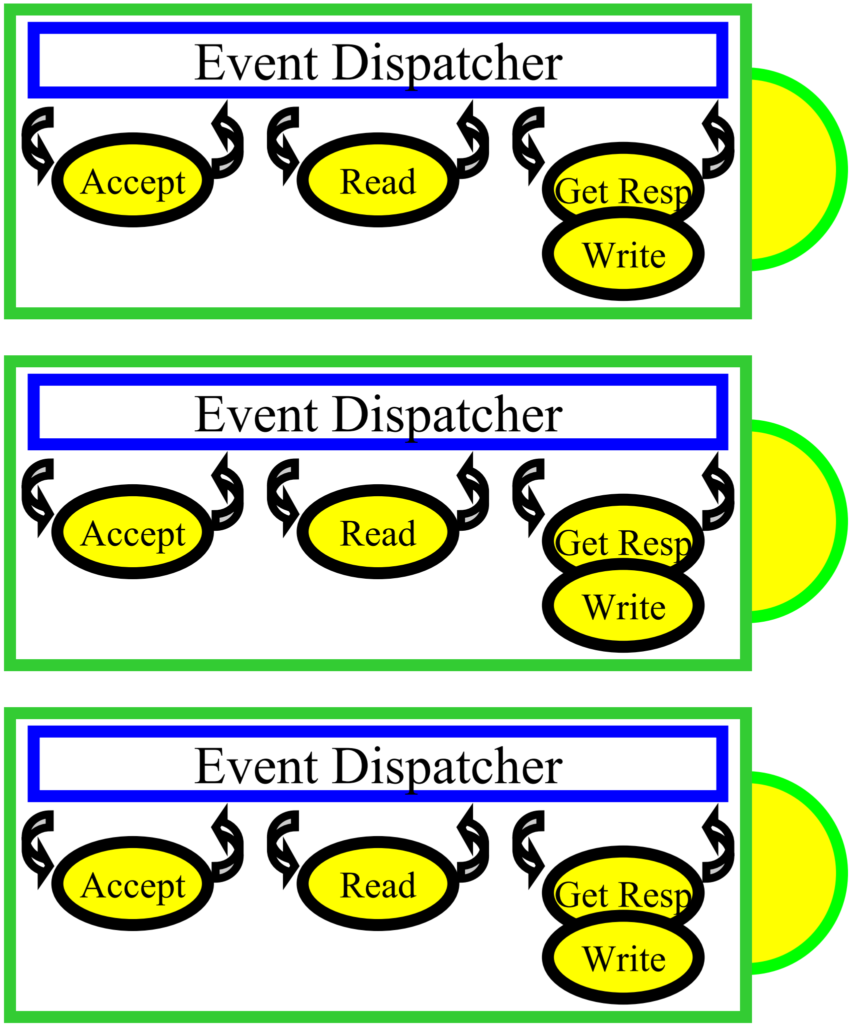


What are the pros and cons of this approach?

N-Copy: 1 SPED Server per CPU



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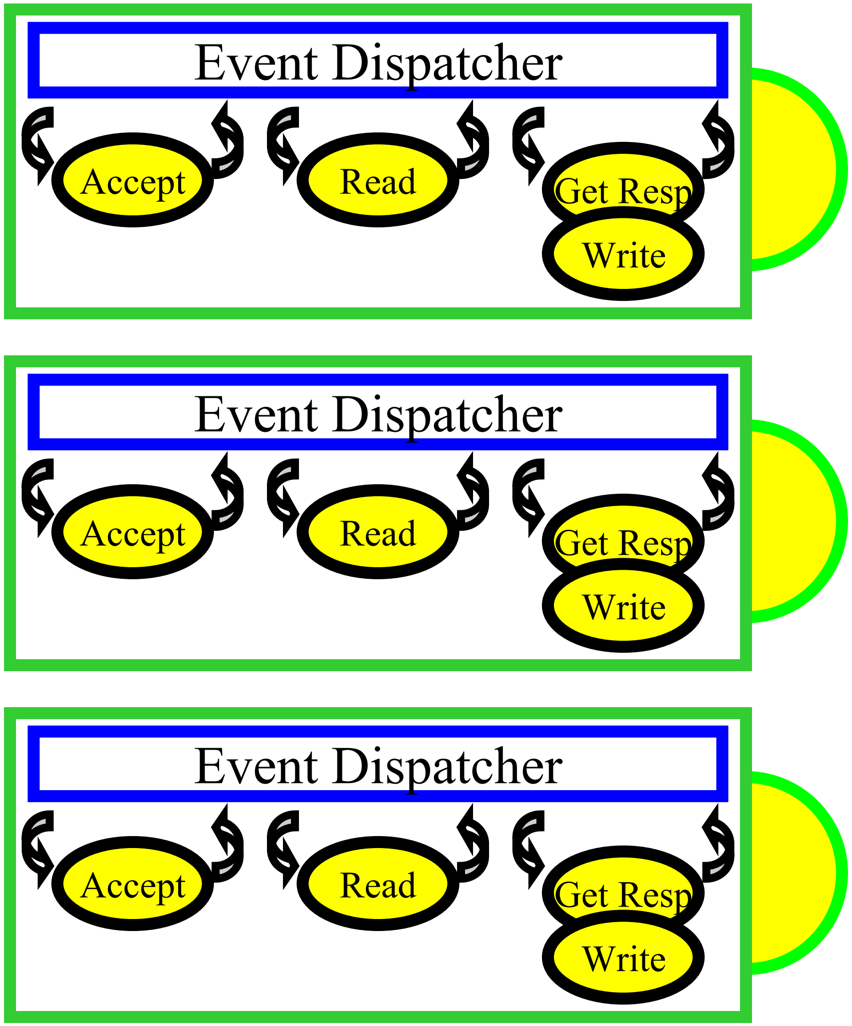

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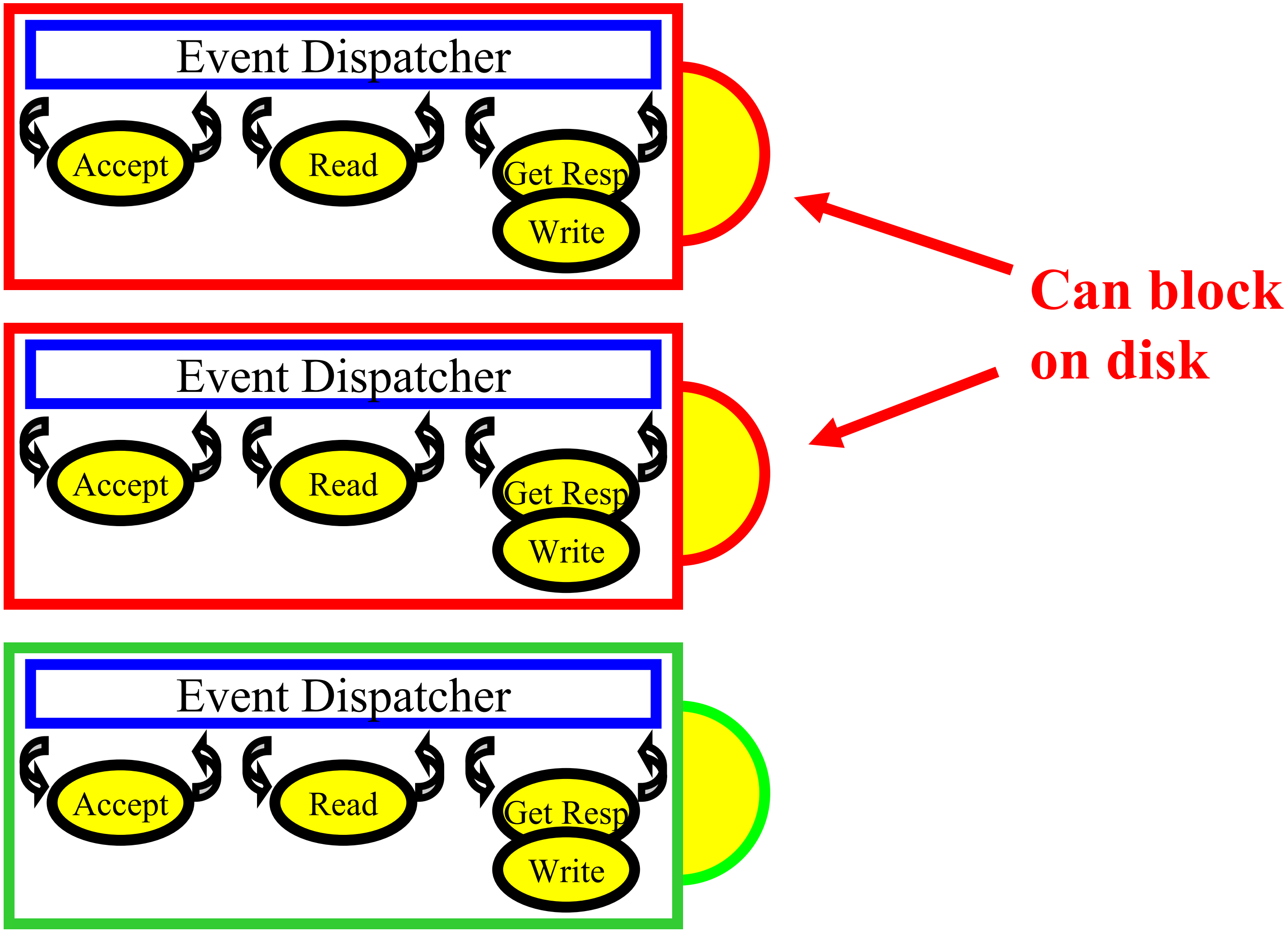
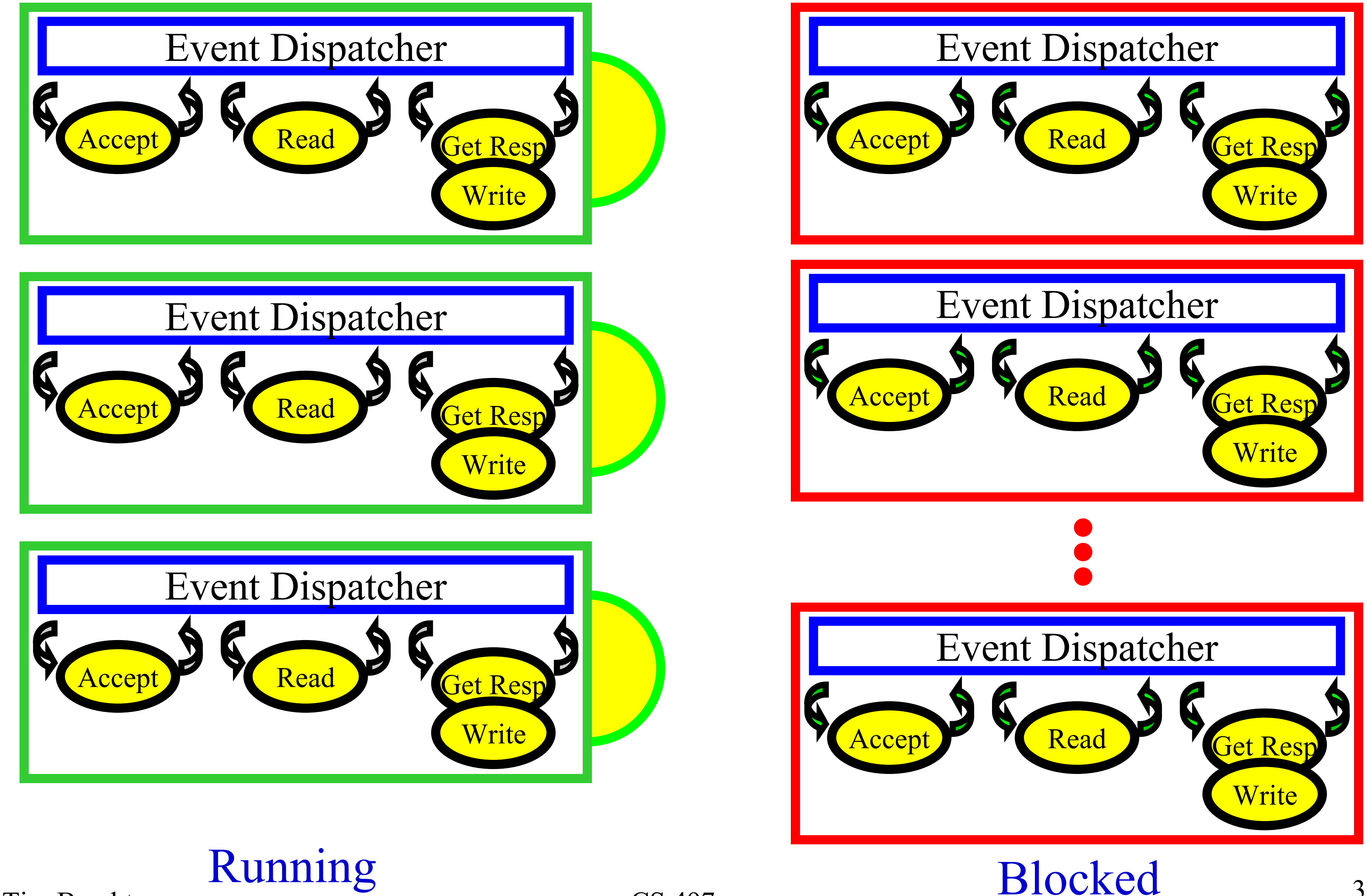


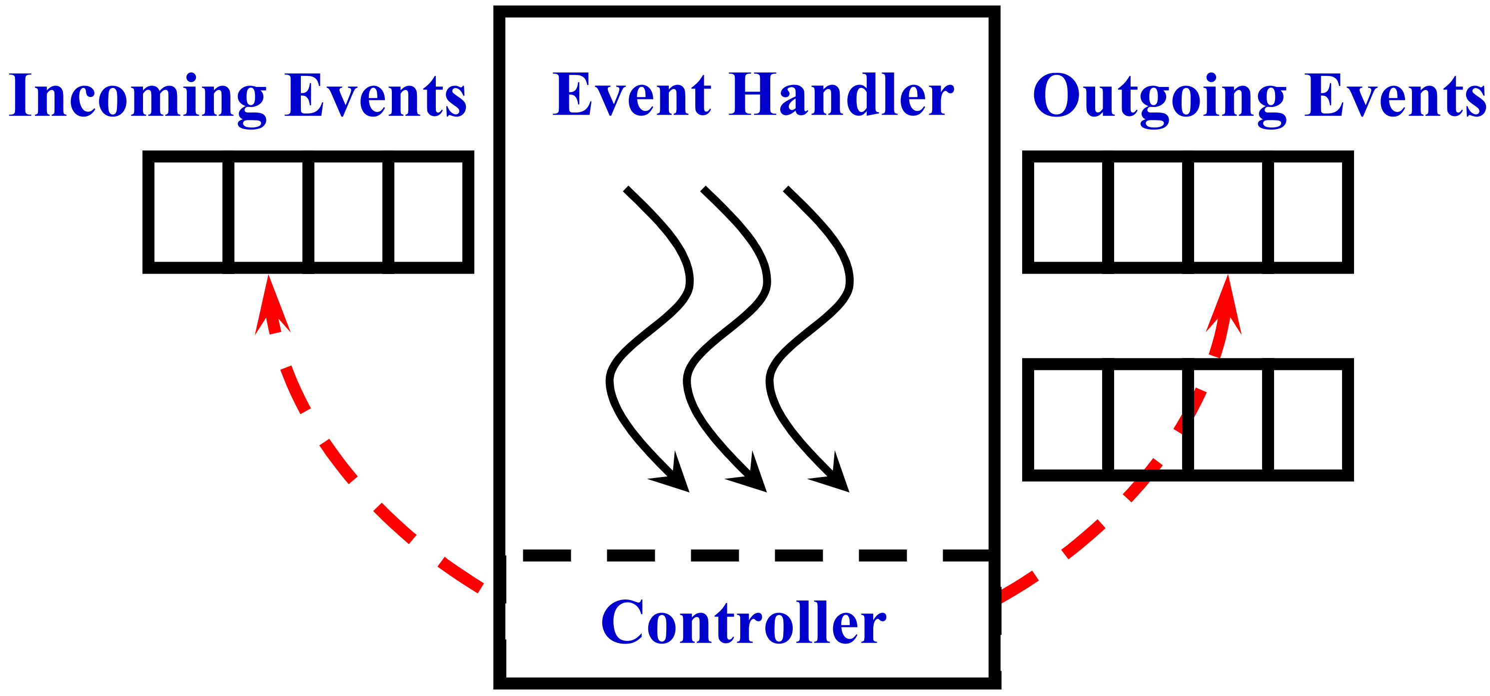
What are the pros and cons of this approach?

SYmmetric MP Event Driven (SYMPED)



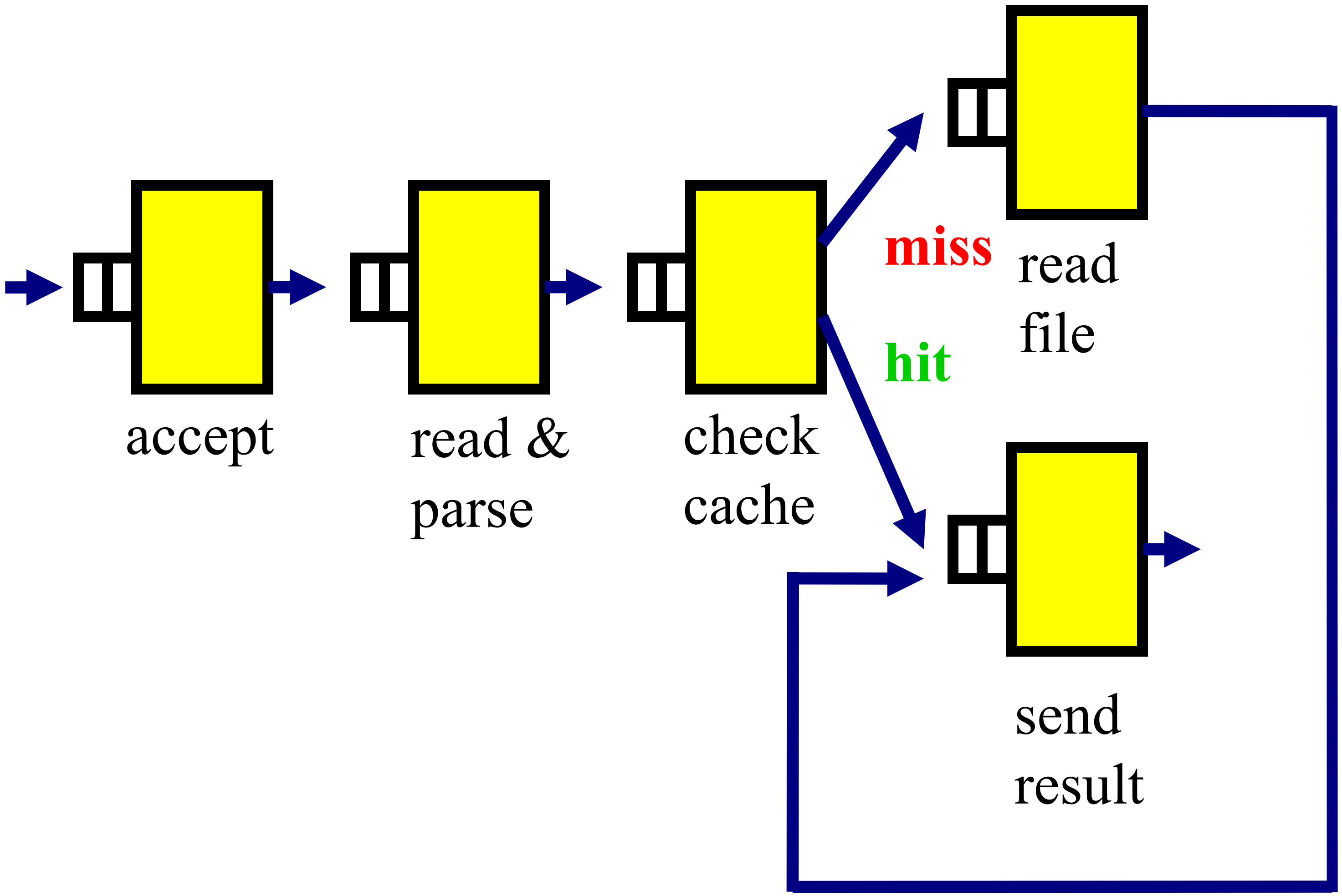
A Hybrid Server: Pipelined (SEDA)

An example of a stage:



- control # of threads
- shed load if needed

Hybrid Servers: Haboob / WatPipe



Overview of Some Servers

- Multi-Thread/Process: one thread/process per conn
  - (MT/MP) **Apache, Knot** [apache.org, von Behren et 03]
- Single Process Event Driven [www.zeus.com]
  - (SPED) **Zeus, Original Harvest/Squid** [Wessels, 96]
  - Asymmetric Multi-Process Event Driven
  - (AMPED) **Flash** [Pai et al, 99]
- One copy per CPU [Zeldovich et al, 03]
  - (N-Copy) **? Rock Web Server ?** [accoria.com]
- SYmmetric Multi-Process Event Driven
  - (SYMPED & Shared-SYMPED) **userver** [UW:Brecht et,]
- Hybrid: Staged Event Driven Architecture / Pipelined
  - (SEDA) **Haboob, WatPipe** [Welsh et 01, Pariag et 07]

Outline

- Part I: Background
  - Web Server Example: HTTP/1.1
  - Server Architectures
  - **Performance Evaluation**

How to Evaluate these Designs?

How to Evaluate these Designs?

- Performance?
- Ease of implementation?
- Ease of maintenance?
- Robustness?

What does Performance Mean?

"**We have improved performance by 48%.**"

What does Performance Mean?

"**We have improved performance by 48%.**"

- What is the performance metrics?
- What is the basis of comparision?
- Under what conditions is this statement true?
- Will this statement be true for you?

What does Performance Mean?

- How does one evaluate the performance of a car?

What does Performance Mean?

- How does one evaluate the performance of a car?
  - Horsepower, Torque?
  - 0-60 mph times? 60-0 times?
  - 0-100 mph times?
  - 0-200 mph times?
  - Track lap times?
  - Track lap times on an icy surface?
  - Number of speakers?
  - Crash test results?
  - Stereo decibel output?
  - Many others?

Which is the best?

What does Performance Mean?

- It means different things to different people
- What are some Web server performance metrics?

What does Performance Mean?

- It means different things to different people
- What are some Web server performance metrics?
  - **Throughput**: requests serviced per unit time
    (server operator / owner / hosting service provider)
  - **Response time**: how long to get response/result
    (user / client)
  - **Revenue**: e.g., dollars of income per unit time
    (owner, executives of the company)
  - **Reliability** (e.g., MTTF), **Recovery time** (crash recovery)
  - (owner, executives e.g., CFO, sys admins)
  - **Many others**

Q: mean, maximum, minimum, distributions?

How to Evaluate Performance?

- **Analytic Model** [Jain, The Art of Comp Sys Perf, 91]
  - mathematical model [CS 457]
  - high-level abstraction capturing the essence
  - (+) easy to change, (+) runs quickly,
    (-) may not capture important details
- **Simulation**
  - must capture key components of behaviour
  - (+) easy to change, (+/-) runtime,
    (-) may be difficult/expensive to capture important details
- **Experimental Evaluation**
  - run experiments on actual hardware
  - (-) hard to change, (-) can run for a long time,
    (+) captures details

Experimental Performance Evaluation

- Benchmark

Experimental Performance Evaluation

- Benchmark
  - A program or set of programs designed to be used to compare performance
  - Meant to be in some way representative of reality
  - Micro-benchmarks
    - small test of idea in isolation (outside of real application and environment)
  - Macro-benchmarks (benchmarks)
    - larger test of a real application in representative environment

Designing a Web Server Benchmark

- What is the goal?
- What is needed?

Benchmark: What is the goal?

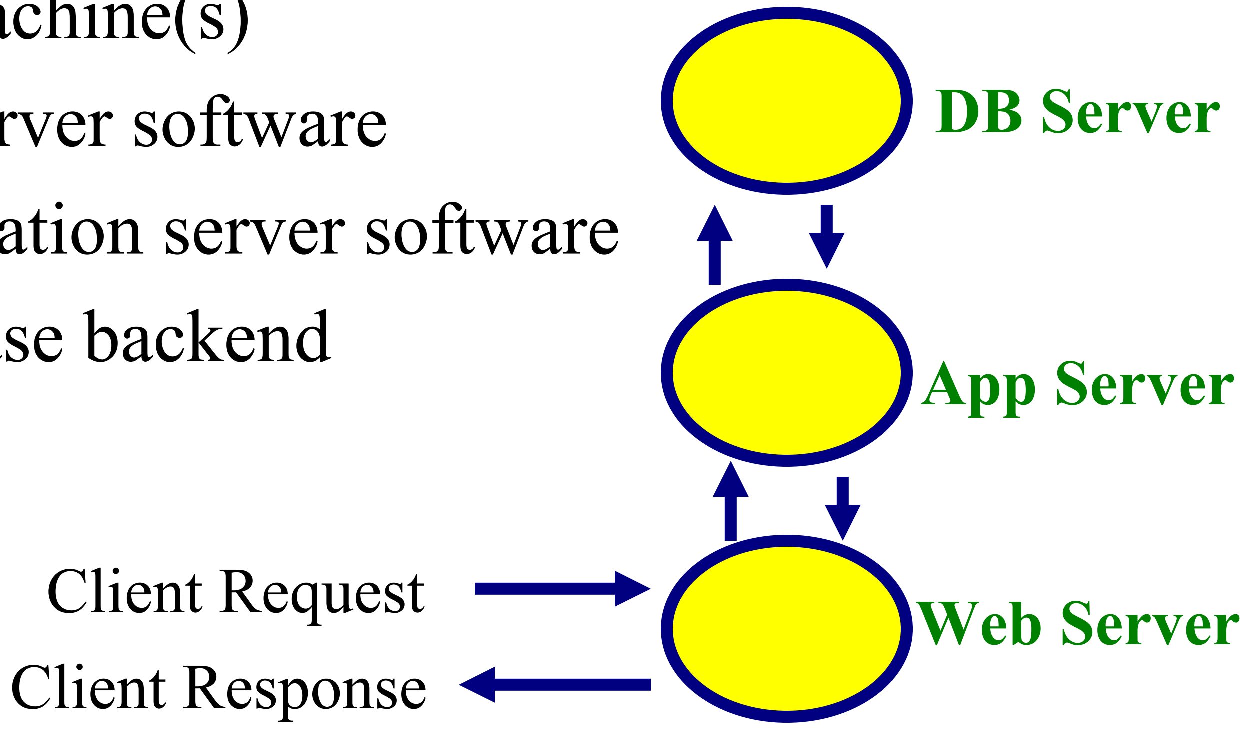
- Compare the performance of one or more of:
  - different machines
  - different web servers
  - different operating systems
  - improvements to web server implementation

Benchmark: What is the goal?

- Compare the performance of one or more of:
  - different machines
  - different web servers
  - different operating systems
  - improvements to web server implementation
- **HOW?**
  - **simulate real users accessing the web site**

Benchmark: What is needed?

- Experimental Environment:
  - **Server**
    - Host/machine(s)
    - Web Server software
    - ?Application server software
    - ?Database backend

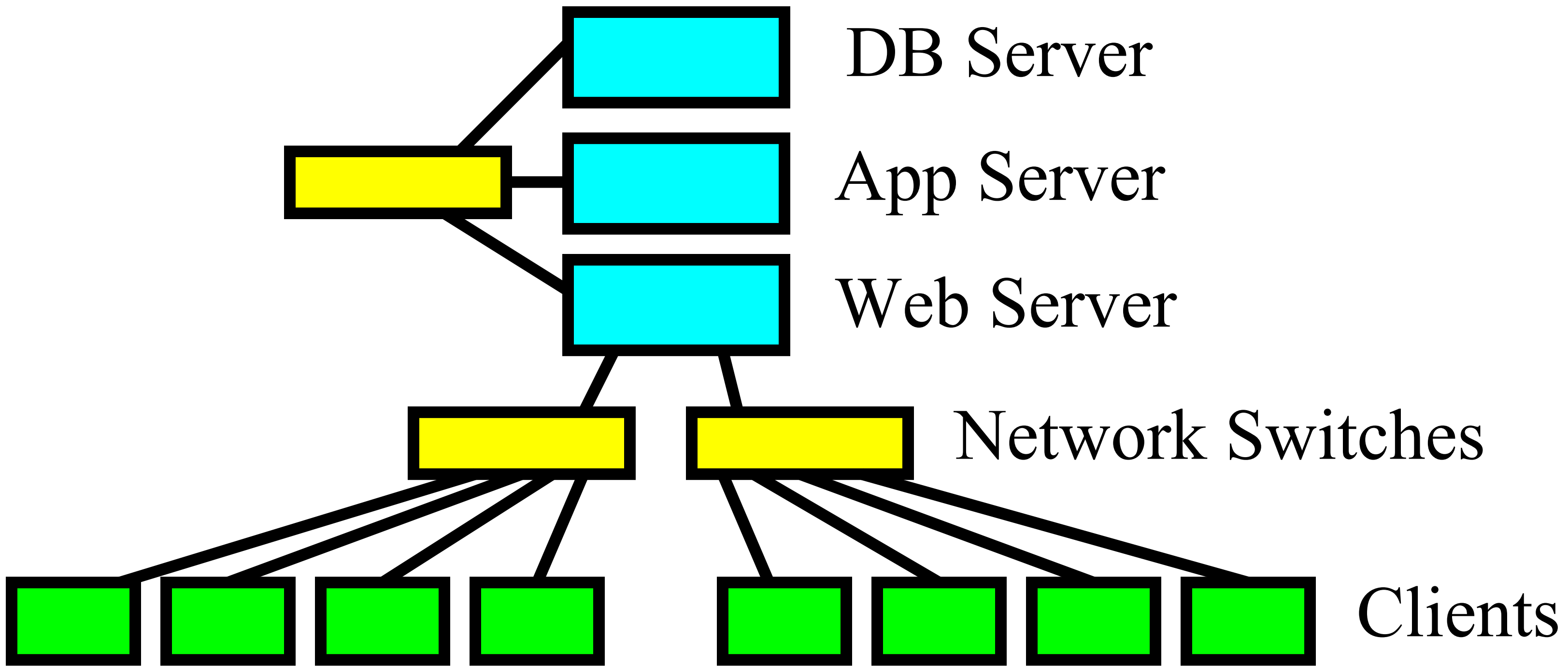


Benchmark: What is needed?

- Experimental Environment:
  - **Clients**
    - Hosts/Machines ... how many?
    - Client simulator software
  - **Networks(s)** to connect clients to servers
    - Server Network Interface Cards (NICs)
    - Client Network Interface Cards (NICs)
    - Network Switches and cables

Benchmark: What is needed?

Example Hardware Configuration/Environement



Benchmark: What is needed?

- Experimental Environment:
  - **Data required on the Server**
    - Files and info for clients to request
    - Data for the database (e.g., things to buy, cost)
  - **Data/Info required for simulated clients**
    - What to request?
    - Which Server NIC to talk to?
    - How long to wait for response?

Benchmark: What is needed?

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    - Which Server NIC to talk to?

Q: Where does this data and info come from?

Some Types of Benchmarks

- Trace driven
  - collect requests and times
  - play requests back by clients

    (+) real stream of requests

    (-) can be difficult to modify in meaningful ways
- Characterization driven
  - collect requests and times
  - compute useful stats, use stats to drive workload

Workload Characterization

- Study an environment to try to determine workload
  - Workload is the load inflicted on a service
- Capture the essence of the workload with parameters
- May do this by observing/monitoring
  - Server
  - Client / Users
  - Network traffic

Workload Characterization

- Want benchmarks representative of real environments
  – Modify software (add instrumentation) to track
    - files accessed, when, by who (log file)
    - post process to get relevant info/stats
  – Run this on a real server
    - Ideally a bunch of different servers
  – Collect & analyze data: use in representative bmark

Workload Characterization

- Some server side characteristics:
  - file/info request sequences, rates & distributions
  - number of embedded objects
  - object types (e.g., html, jpg, mpg, etc.)
  - file sizes and distributions (usually by file types)

[Arlitt & Williamson: Invariants 1996]
[Arlitt & Jin: World Cup Soccer 1998]
[Arlitt, Krshnamurthy & Rolia: Shopping 2001]
[Veloso, et al., Streaming media, 2006]

Workload Characterization

- Behaviours of clients:
  - How long does a user typically:
    - Wait for a response?
    - Spend looking at a page?
  - How does browser fetch embedded objects
    - HTTP/1.1 one at a time
    - HTTP/1.0 all in parallel
    - HTTP/1.1 (pipelined – 1 req for N files)

[Cunha, Bestavros & Crovella, Client-based traces, 1995]

Workload Characterization

- Behaviour of network:
  - Network link speeds?
  - How long for a request to reach the server?
  - How long for a response to reach the client?
  - Packet drop rates?
  - What gets dropped, when?

Some Benchmarks

- Standard Performance Evaluation Corporation (SPEC) [spec.org]
  - SPECWeb96 (Static)
  - SPECweb99/_SSL (70% Static, 30% Dynamic)
  - SPECweb2005
    - Banking, Ecommerce, Support
    - Multi-tiered
- Transaction Processing Performance Council
  - TPC-W (Database oriented) [www.tpc.org]

Some Benchmark Clients

- SPECweb clients [SPEC: 96, 99, 2005/6]
- httperf [Mosberger & Jin: 98]
- s-client [Banga & Drushel: 97]
- Surge [Barford & Crovella: 98]

Some Research (Past, Present, Future)

- Server design and implementation (understanding!!)
  - best architecture for performance
  - how to avoid server meltdown under overload
- Client workload generator design and implemenation
  - small # of hosts to simulate large # of users
- Workload characterization
  - What is a representative workload?
  - What does it represent? How do we know?
- Improving operating system support
  - spending large % of execution time in OS / Why?

Part I: The End