SEDA: An Architecture for Scalable, Well-Conditioned Internet Services

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Internet Services Today

Massive concurrency demands

- Yahoo: 1.2 billion+ pageviews/day
- AOL web caches: 10 billion hits/day

Load spikes are inevitable (the ''Slashdot Effect'')

- Peak load is orders of magnitude greater than average
- Traffic on September 11, 2001 overloaded many news sites
- Load spikes occur exactly when the service is most valuable!
  - ▷ *In this regime,* **overprovisioning is infeasible**

Increasingly dynamic

- Days of the ''static Web'' are over
- Majority of services based on dynamic content:
  - ▷ *e-Commerce, stock trading, driving directions, etc.*
- Service logic evolves rapidly
  - ▷ *Increases complexity of engineering and deployment*

Problem Statement

Supporting massive concurrency is hard

- Threads/processes designed for timesharing
  - ▷ *High overheads and memory footprint*
- Don't scale to many thousands of tasks

Existing OS designs do not provide graceful management of load

- Standard OSs strive for maximum resource transparency
- Static resource containment is inflexible
  - ▷ *How to set a apriori resource limits for widely fluctuating loads?*
- Load management demands a *feedback loop*

Dynamics of services exaggerate these problems

- Much work on performance/robustness for specific services
  - ▷ *e.g., Fast, event-driven Web servers*
- As services become more dynamic, this engineering burden is excessive
- Replication alone does not solve the load management problem

Proposal: The Staged Event-Driven Architecture

SEDA: A new architecture for Internet services

- A general-purpose framework for high concurrency and load conditioning
- Decomposes applications into *stages* separated by *queues*
- Adopt a structured approach to event-driven concurrency

Enable load conditioning

- Event queues allow inspection of request streams
- Can perform prioritization or filtering during heavy load

Dynamic control for self-tuning resource management

- System observes application performance and tunes runtime parameters
- Apply control for graceful degradation
  - ▷ *Perform load shedding or degrade service under overload*

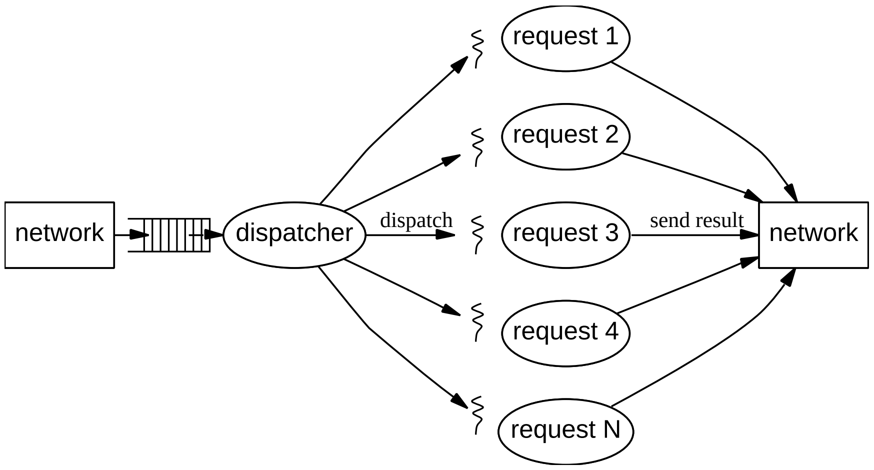
Simplify task of building highly-concurrent services

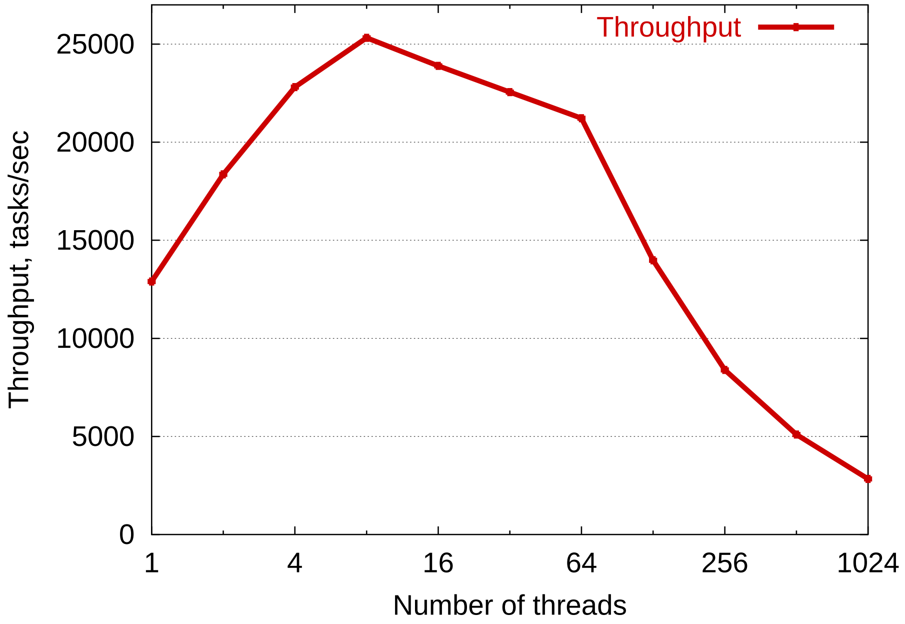
- *Decouple load management from service complexity*
- Use of stages supports modularity, code reuse, debugging
- Dynamic control shields apps from complexity of resource management

Outline

- Problems with Threads and Event-Driven Concurrency
- The Staged Event-Driven Architecture
- SEDA Implementation
- Application Study: High-Performance HTTP Server
- Using Control for Overload Prevention
- Ongoing Work and Conclusions

Problems with Thread-Based Concurrency

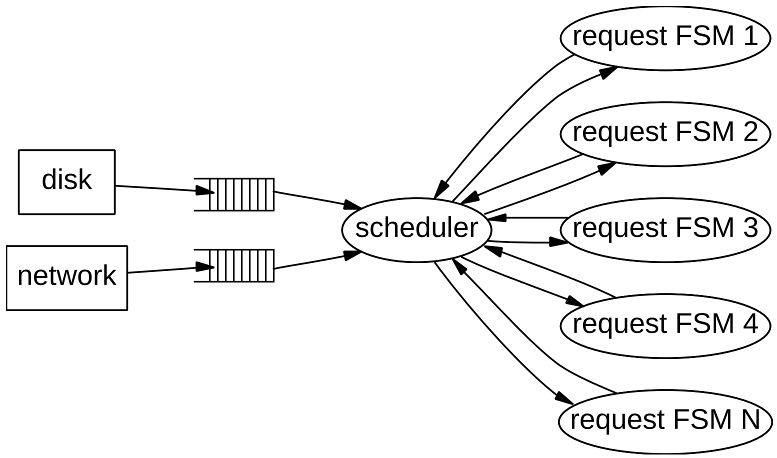


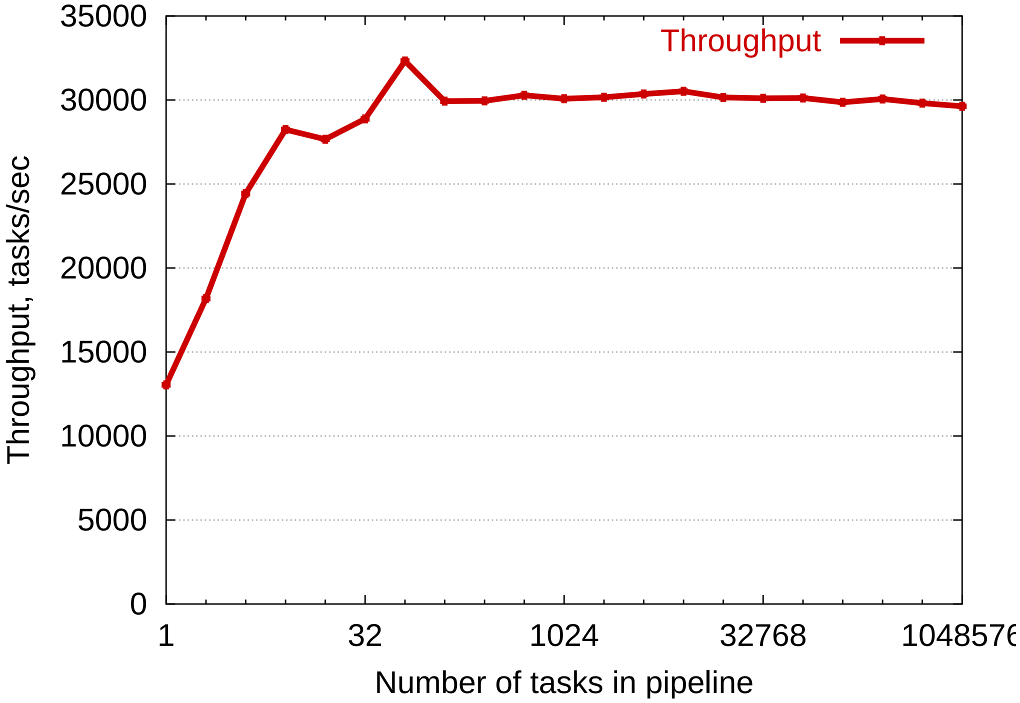


(937 MHz x86, Linux 2.2.14, each thread reading 8KB file)

- High resource usage, context switch overhead, contended locks
- Too many threads → throughput meltdown, response time explosion
- Traditional solution: Bound total number of threads
  - ▷ *But, how do you determine the ideal number of threads?*
- Regardless of performance, **threads are fundamentally the wrong interface**
  - ▷ *Request stream hidden within scheduler*
  - ▷ *Transparency masks resource contention*

Event-driven Concurrency





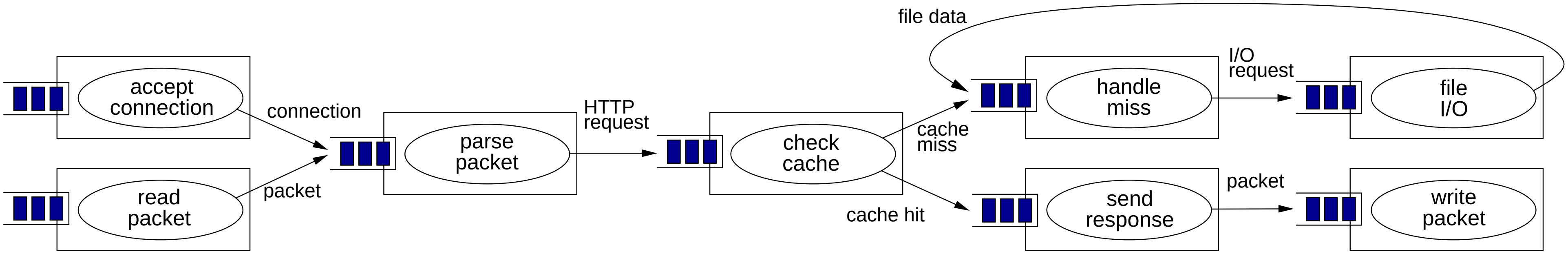
Small number of event-processing threads with many FSMs

- Yields efficent and scalable concurrency
- Many examples: Click router, Flash web server, TP Monitors, etc.

Difficult to engineer, modularize, and tune

- Little OS and tool support: ‘‘roll your own’’
- No performance/failure isolation between FSMs
- FSM code can never block (but page faults, garbage collection force a block)

Staged Event-Driven Architecture (SEDA)



Decompose service into *stages* separated by *queues*

- Each stage performs a subset of request processing
- Stages internally event-driven, typically nonblocking
- Queues introduce execution boundary for isolation and conditioning

Each stage contains a *thread pool* to drive stage execution

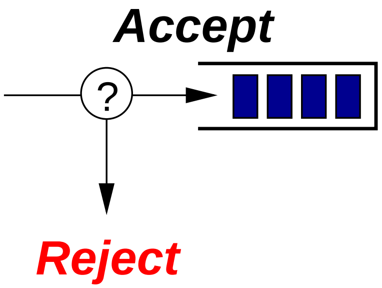
- However, threads are not exposed to applications
- Dynamic control grows/shrinks thread pools with demand
  - ▷ *Stages may block if necessary*

Best of both threads and events:

- Programmability of threads with explicit flow of events

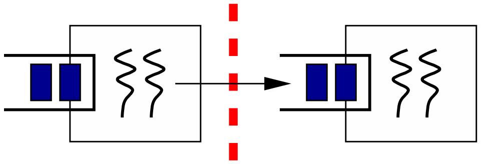
Queues for Control and Composition

Queues subject to *admission control policy*



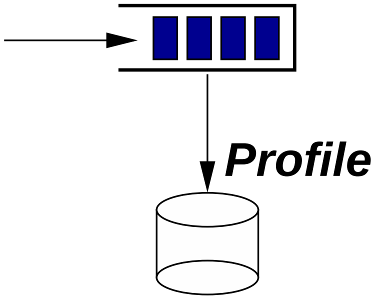
- e.g., Thresholding, rate control, credit-based flow control
  - ▷ *Applications must expect enqueue failures!*
- Block on full queue → backpressure
- Drop rejected events → load shedding
  - ▷ *May also take alternate action, e.g., degraded service*

Queues introduce explicit execution boundary



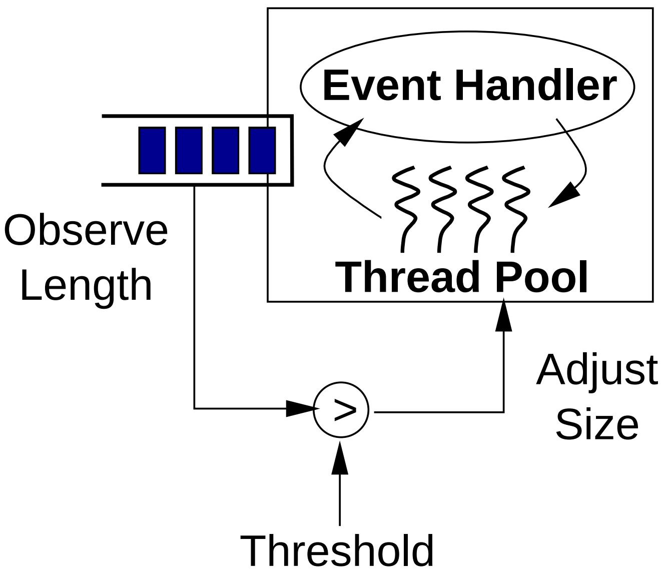
- Threads may only execute within a single stage
- Performance isolation, modularity, independent load management

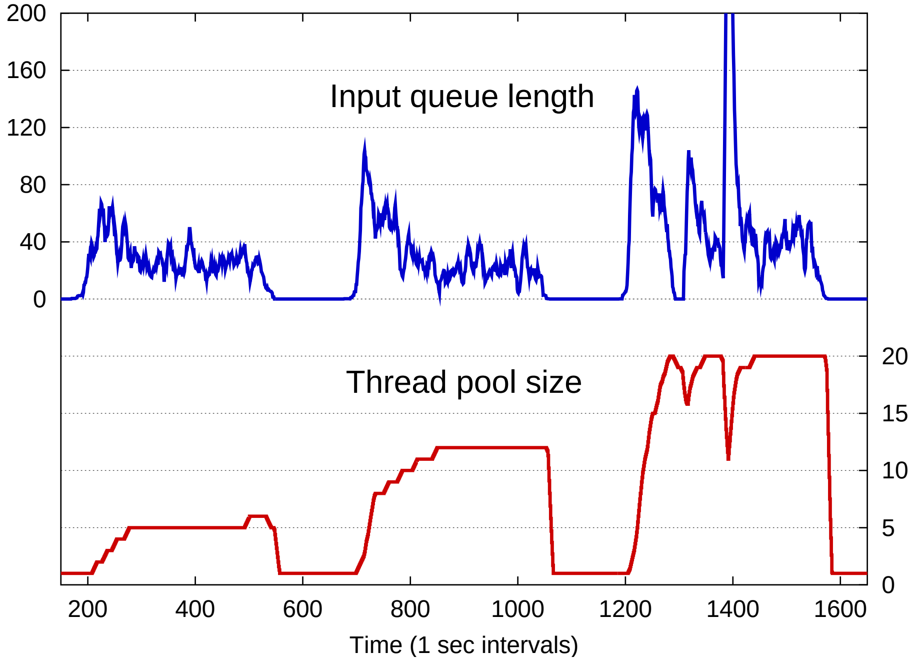
Explicit event delivery supports inspection



- Trace flow of events through application
- Monitor queue lengths to detect bottleneck

SEDA Thread Pool Controller





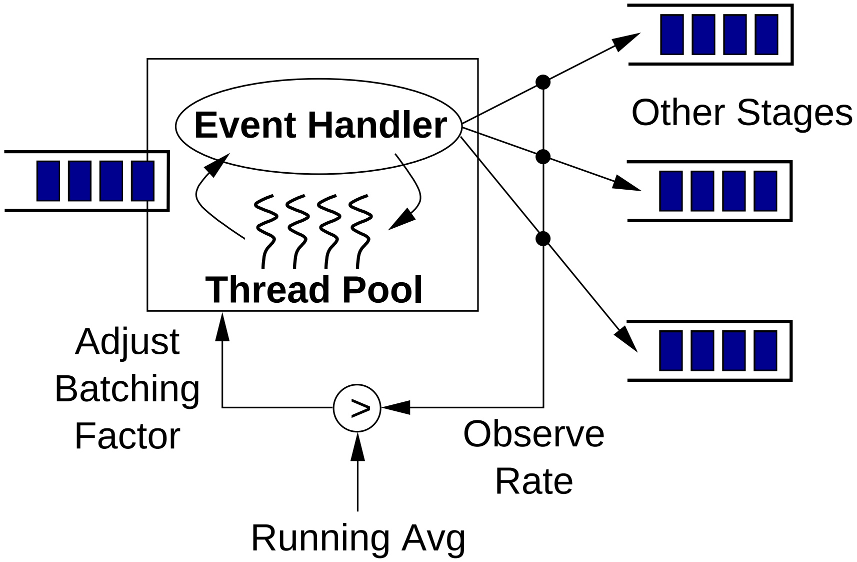
Goal: *Determine ideal degree of concurrency for a stage*

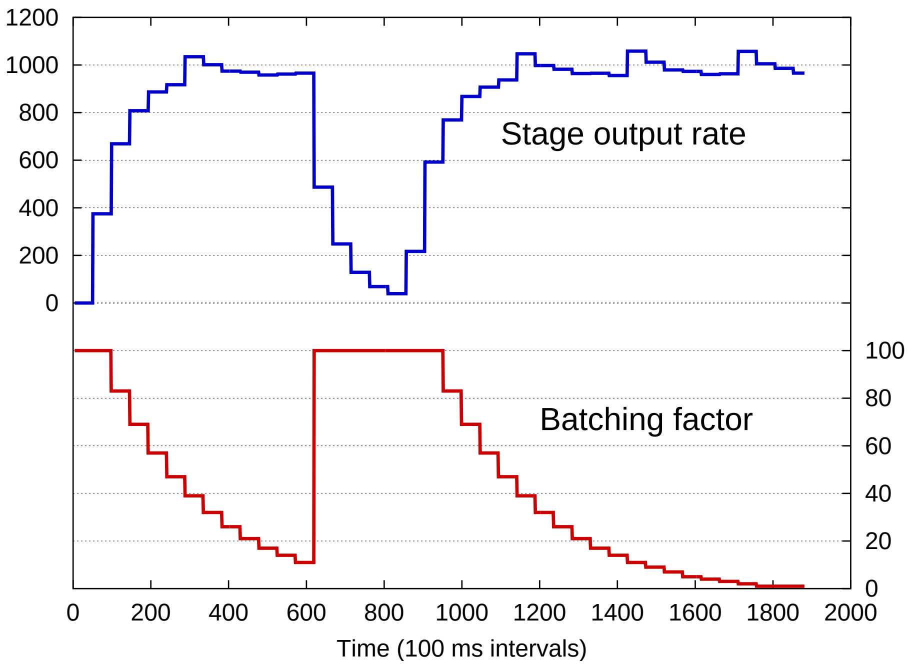
- Dynamically adjust number of threads allocated to each stage
- Avoid wasting threads when unneeded

Controller operation

- Observes input queue length, adds threads if over threshold
- Idle threads removed from pool

SEDA Batching Controller





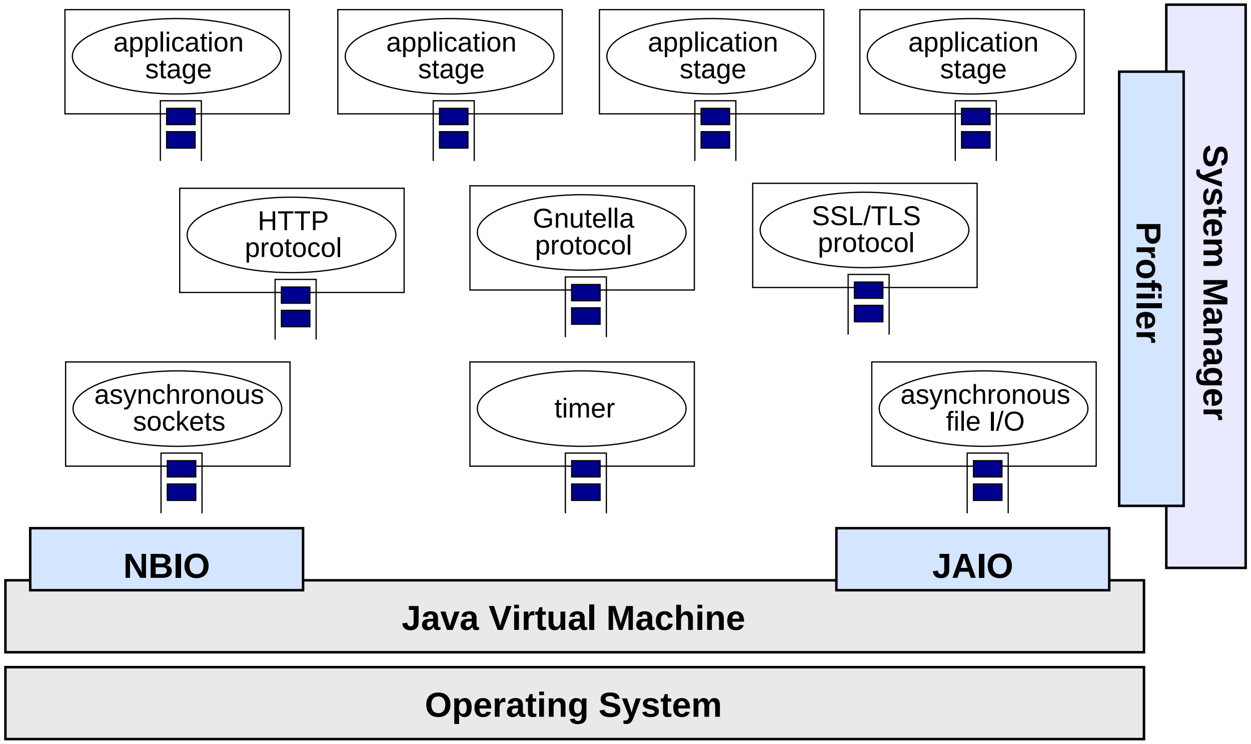
Goal: *Schedule for low response time and high throughput*

- **Batching factor:** number of events consumed by each thread
- Large batching factor → more locality, higher throughput
- Small batching factor → lower response time

Attempt to find smallest batching factor with stable throughput

- Reduces batching factor when throughput high, increases when low

SEDA Prototype: Sandstorm



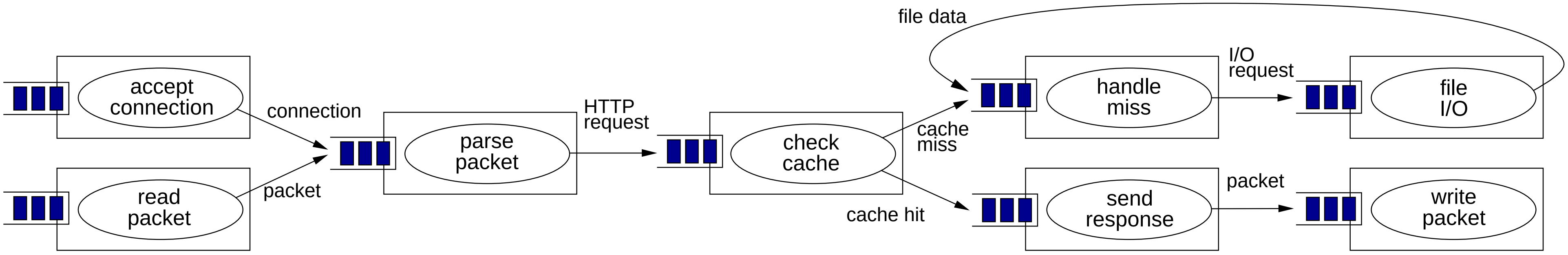
Implemented in Java with nonblocking I/O interfaces

- Scalable network performance up to 10,000 clients per node
- Influenced design of JDK 1.4 `java.nio` APIs

Java viable as service construction language

- Built-in threading, automatic memory management, cross-platform
  - ▷ *Java-based SEDA Web server outperforms Apache and Flash*

Haboob: A SEDA-Based Web Server



Measured *static file load* from SpecWEB99 benchmark

- Realisitic, industry-standard benchmark
- 1 to 1024 clients making repeated requests, think time 20ms
- Total fileset size is 3.31 GB ; page sizes range from 102 Bytes to 940 KB

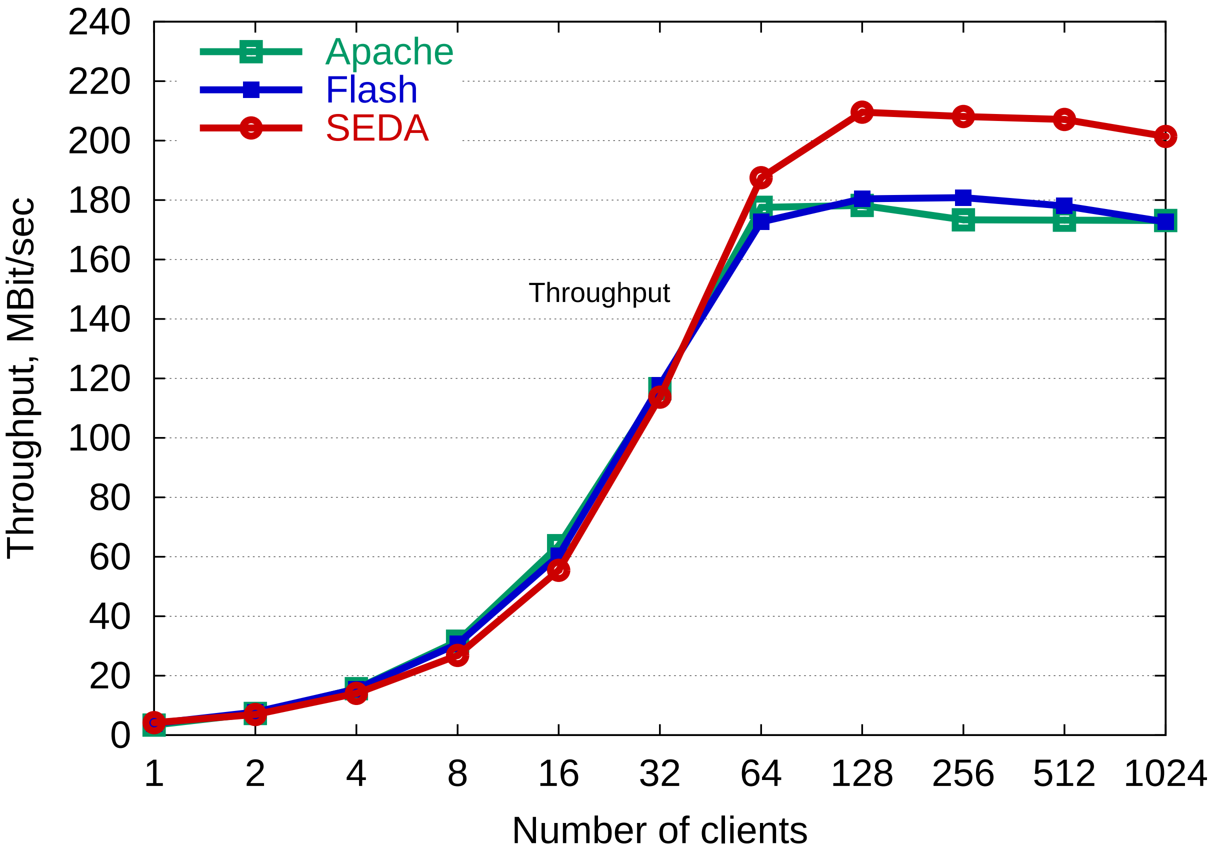
Maintains memory cache of recently accessed pages (200 MB)

- Significant fraction of page accesses require disk I/O

Comparison with Apache and Flash

- **Apache**: Process-based concurrency, 150 processes
  - ▷ *Does not accept new TCP connections when all processes busy*
- **Flash** (Vivek Pai, Princeton): Event-driven w/ 4 processes
  - ▷ *Accepts only 506 simultaneous connections due to fd limits*

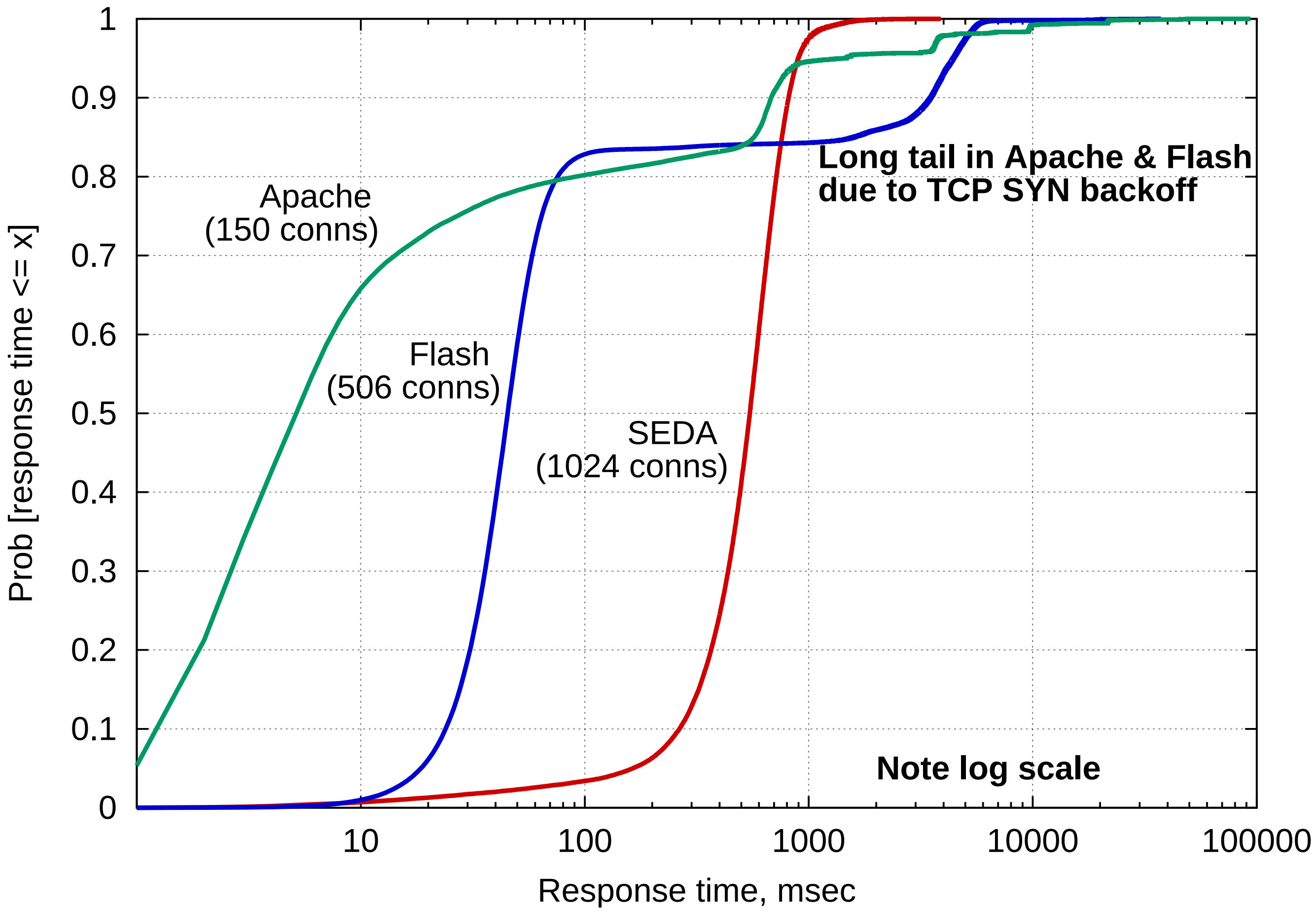
Haboob Throughput vs. Apache and Flash



4-way Pentium III 500 MHz, Gigabit Ethernet, 2 GB RAM, Linux 2.2.14, IBM JDK 1.3

- SEDA throughput **10% higher** than Apache and Flash (which are in C!)
  - ▷ *Some degradation due to Linux socket inefficiencies*
- Apache accepts only 150 clients at once - no overload despite thread model
  - ▷ *But as we will see, this penalizes many clients*

Response Time Distribution - 1024 Clients



Long tail in Apache & Flash due to TCP SYN backoff

Note log scale

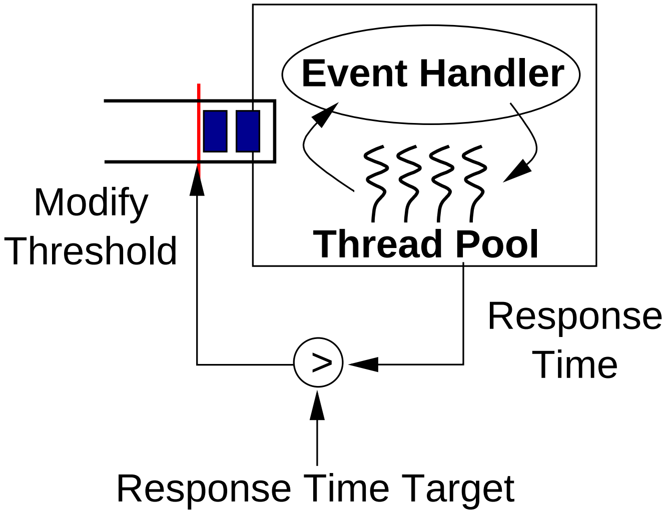
	SEDA	Flash	Apache
Mean RT	547 ms	665 ms	475 ms
Max RT	3.8 sec	37 sec	1.7 minutes

- SEDA yields **predictable performance** - Apache and Flash are very **unfair**
  - ▷ *''Unlucky'' clients see long TCP retransmit backoff times*
  - ▷ *Everyone is ''unlucky'': multiple HTTP requests to load one page!*

Dynamic Control for Overload Prevention

Arashi: Web-based e-mail service (Yahoo! Mail clone)

- Complex dynamic page generation, SSL encryption
- Mail stored in back-end MySQL database
- SEDA middle-tier conditions load on MySQL!



Adaptive admission control policy to meet performance target

- Dynamically adjust queue thresholds to maintain low response time
- Rejected clients sent friendly error message
  - ▷ *Could degrade service or redirect request instead*
- Goal: 90th percentile response time of 1 sec
- Controller is **ignorant of service logic**

Performance with 128 clients:

	90th percentile RT	% requests rejected
No control	7.5 sec	0%
With overload control	0.978 sec	49%

Ongoing Work

Formalize control-theoretic approach to resource management

- Large body of prior work in control of physical systems
- Internet services highly nonlinear, difficult to derive models
- Adaptive and fuzzy control as possible approaches

Generalize load conditioning mechanisms

- Extend resource control to memory, other resources
- General-purpose system overload monitor
- Explore degradation vs. load-shedding tradeoff

Ongoing implementation and application work

- Gnutella packet router
  - ▷ *Peer-to-peer file sharing network*
- Distributed, cluster-based SEDA *(Berkeley Ninja Project)*
  - ▷ *Event queues implemented as network pipes*
- Berkeley OceanStore Project using SEDA as a base
  - ▷ *Global, secure file store and archival system*

Summary

Support for massive concurrency requires new design techniques

- SEDA introduces service design as a *network of stages*
- Decouple load management from service complexity
- Expose request streams to applications for load conditioning

Observation and control as key to service design

- Dynamic control to keep stages within operating regime
- Controllers operate independent of application logic
- Bring body of work on control systems to bear on Internet services

Implications for OS and language design

- What would a ‘‘native’’ SEDA operating system look like?
- Language and tool support for event-driven computing
- SEDA opens up new questions in the service design space!

For more information, software, and (soon) my PhD thesis:

`http://www.cs.berkeley.edu/~mdw/`

Backup Slides Follow

Related Work

High-performance Web servers

- Many systems realizing the benefit of event-driven design
- *[Flash, Harvest, Squid, JAWS, ...]*
- Specific applications - no general-purpose framework
- Little work on load conditioning, event scheduling

StagedServer (Microsoft Research)

- Core design similar to SEDA
- Primarily concerned with cache locality
- Wavefront thread scheduler: last in, first out

Click Modular Router, Scout OS, Utah Janos

- Various systems making use of structured event queues
- Packet processing decomposed as stages
- Threads call through multiple stages
- Major goal is latency reduction

Related Work 2

Resource Containers *[Banga]*

- Similar to Scout ‘‘path’’ and Janos ‘‘flow’’
- Vertical resource management for data flows
- SEDA applies resource management at per-stage level

Scalable I/O and Event Delivery

- *[ASHs, IO-Lite, fbufs, /dev/poll, FreeBSD kqueue, NT completion ports]*
- Structure I/O system to scale with number of clients
- We build on this work

Large body of work on scheduling

- Interesting thread/event/task scheduling results
- e.g., Use of SRPT and SCF scheduling in Web servers *[Crovella, Harchol-Balter]*
- Alternate performance metrics *[Bender]*
- We plan to investigate their use within SEDA

How Complex is SEDA?

Code size and complexity

- Sandstorm runtime: 19934 LOC, 7871 NCSS
- 2566 NCSS for core runtime, 3023 NCSS for async I/O
- HTTP protocol library: 676 NCSS
- Haboob web server: 2607 NCSS

Some learning curve for event-driven programming

- Managing continuations, tracking events
- But, note that stages can block (for difficult code or lazy programmers)

Decomposition into stages helps greatly!

- Applications tend to map cleanly onto a pipeline of stages
- Each stage is a self-contained, well-conditioned module
- Typically little or no direct data sharing between stages
- Interposition of new stages is trivial
  - ▷ *We have found SEDA to be much simpler and easier to reason about than other event-driven server frameworks*