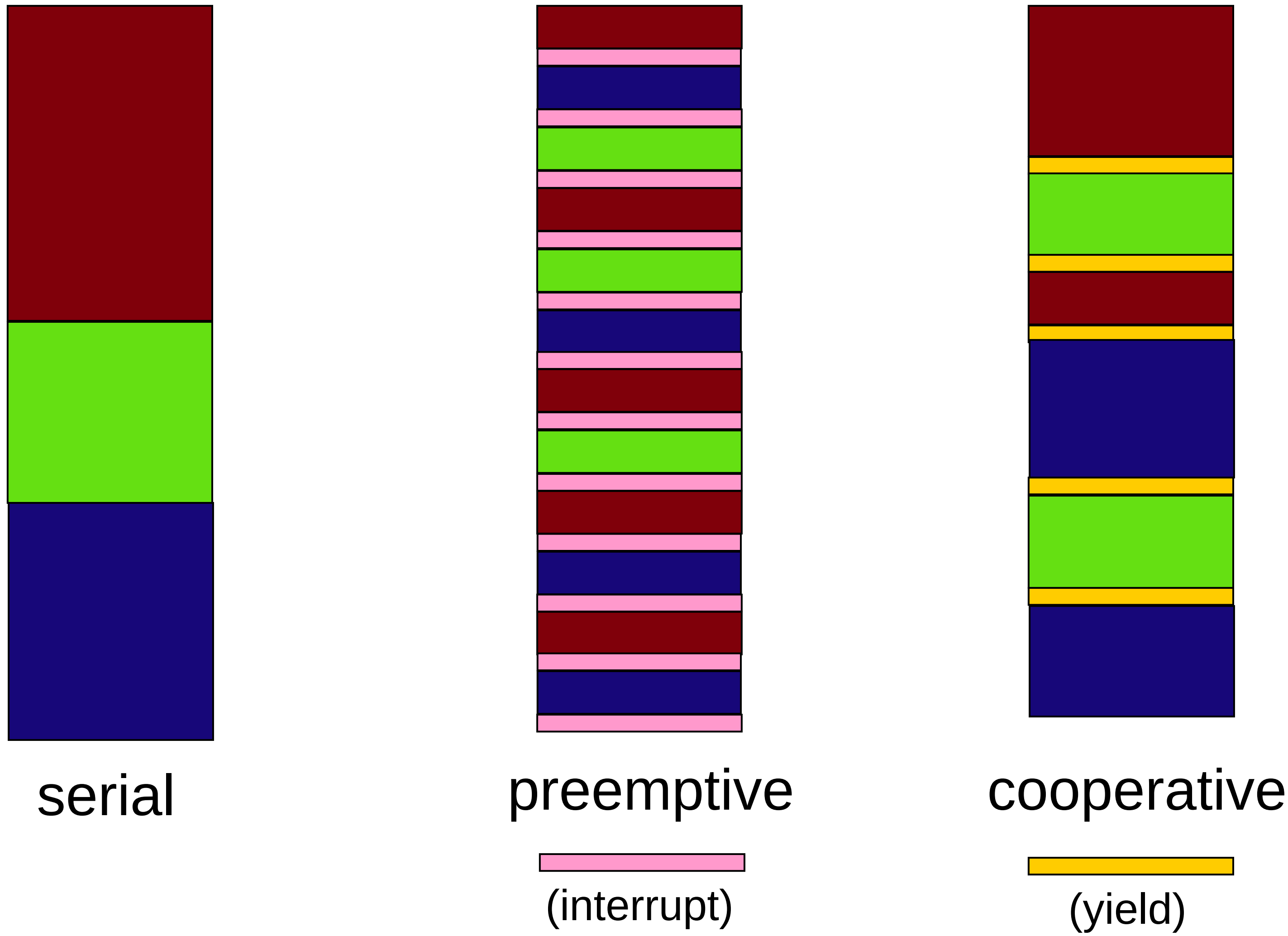
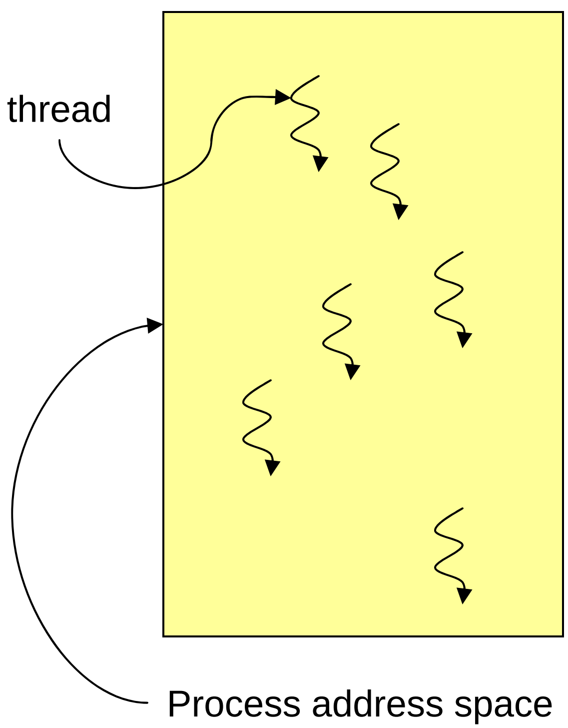
Threads vs. Events

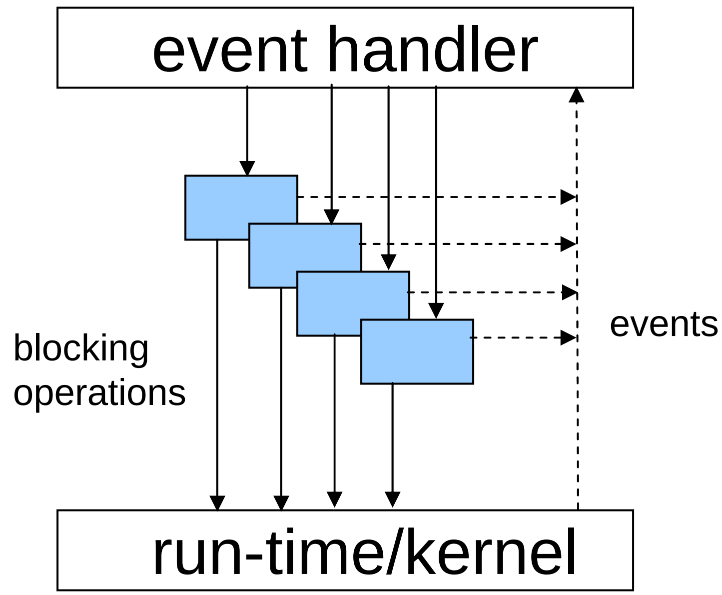
Forms of task management



Programming Models

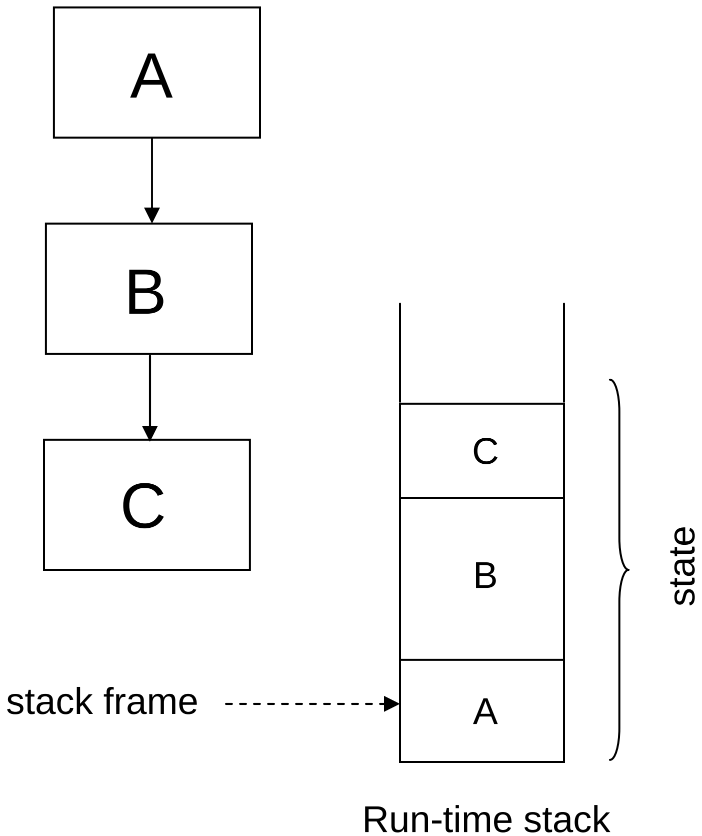


thread model

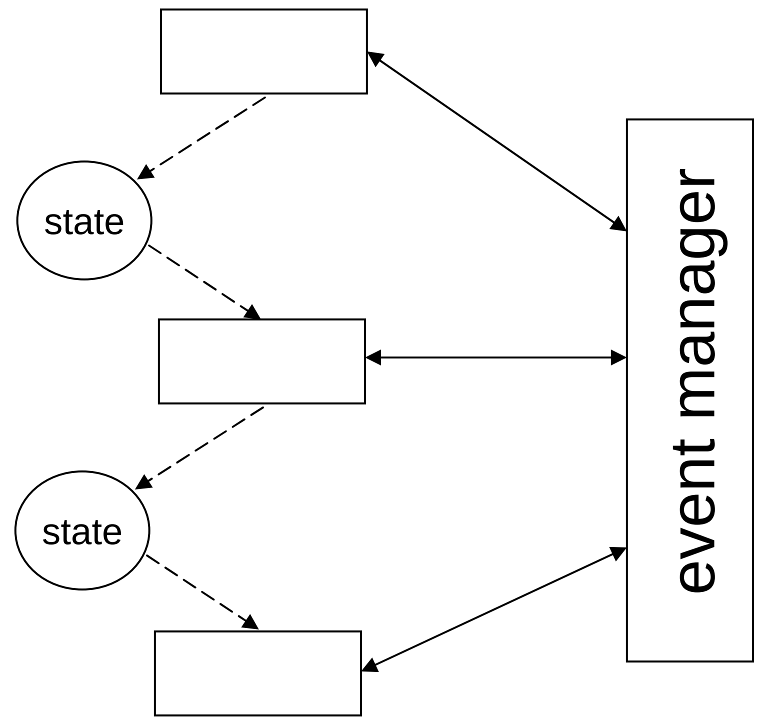


event model

Stack (really state) Management



automatic



manual

Threads are Bad

- Difficult to program
  - Synchronizing access to shared state
  - Deadlock
  - Hard to debug (race conditions, repeatability)
- Break abstractions
  - Modules must be designed “thread safe”
- Difficult to achieve good performance
  - simple locking lowers concurrency
  - context switching costs
- OS support inconsistent
  - semantics and tools vary across platforms/systems
- May not be right model
  - Window events do not map to threads but to events

Events are Bad- Threads are Good

- Thread advantages
  - Avoids "stack ripping" to maintain application context
  - Exception handling simpler due to history recorded in stack
  - Exploits available hardware concurrency
- Events and Threads are duals
  - Performance of well designed thread system equivalent to well designed event system (for high concurrency servers)
  - Each can cater to the common control flow patterns (a call/return pattern is needed for the acknowledgement required to build robust systems)
  - Each can accommodate cooperative multitasking
  - Stack maintenance problems avoided in event systems and can be mitigated in thread systems

Stack Ripping

```
CAInfo GetCAInfoBlocking(CAID caId) {
  CAInfo caInfo = LookupHashTable(caId);
  if (caInfo != NULL) {
    // Found node in the hash table
    return caInfo;
  }
  caInfo = new CAInfo();
  // DiskRead blocks waiting for
  // the disk I/O to complete.
  DiskRead(caId, caInfo);
  InsertHashTable(caId, CaInfo);
  return caInfo;
}
```

```
CAInfo GetCAInfoBlocking(CAID caId) {
  CAInfo caInfo = LookupHashTable(caId);
  if (caInfo != NULL) {
    // Found node in the hash table
    return caInfo;
  }
  caInfo = new CAInfo();
  // DiskRead blocks waiting for
  // the disk I/O to complete.
  DiskRead(caId, caInfo);
```

```
  InsertHashTable(caId, CaInfo);
  return caInfo;
}
```

Ripped Code

```
void GetCAInfoHandler1(CAID caId,
                       Continuation *callerCont)
{
  // Return the result immediately if in cache
  CAInfo *caInfo = LookupHashTable(caId);
  if (caInfo != NULL) {
    // Call caller's continuation with result
    (*callerCont->function)(caInfo);
    return;
  }

  // Make buffer space for disk read
  caInfo = new CAInfo();
  // Save return address & live variables
  Continuation *cont = new
    Continuation(&GetCAInfoHandler2,
           caId, caInfo, callerCont);
  // Send request
  EventHandle eh =
       InitAsyncDiskRead(caId, caInfo);
  // Schedule event handler to run on reply
  // by registering continuation
  RegisterContinuation(eh, cont);
}
```

```
void GetCAInfoHandler2(Continuation
*cont) {
  // Recover live variables
  CAID caId = (CAID) cont->arg1;
  CAInfo *caInfo = (CAInfo*) cont->arg2;
  Continuation *callerCont =
       (Continuation*) cont->arg3;
  // Stash CAInfo object in hash
  InsertHashTable(caId, caInfo);
  // Now "return" results to original caller
  (*callerCont->function)(callerCont);
}
```

Ousterhout’s conclusions

Why Threads Are A Bad Idea (for most purposes)

John Ousterhout
Sun Microsystems Laboratories

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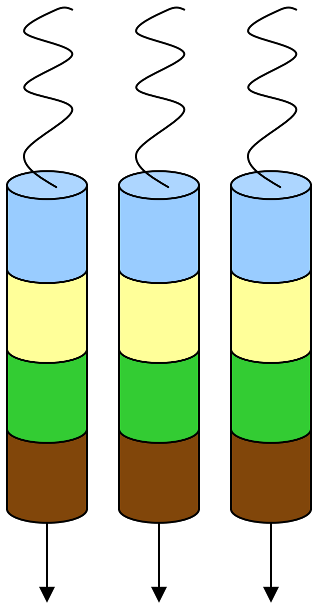
Conclusions

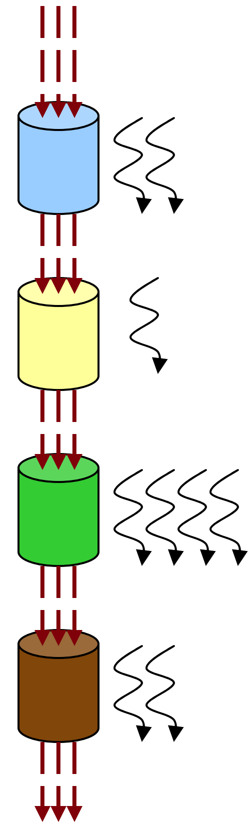
- Concurrency is fundamentally hard; avoid whenever possible.
- Threads more powerful than events, but power is rarely needed.
- **Threads much harder to program than events**; for experts only.
- Use events as primary development tool (both GUIs and distributed systems).
- Use threads only for performance-critical kernels.

Why Threads Are A Bad Idea — *September 28, 1995, slide 15*

Two approaches



- **Capriccio**
  - Each service request bound to an independent thread
  - Each thread executes all stages of the computation

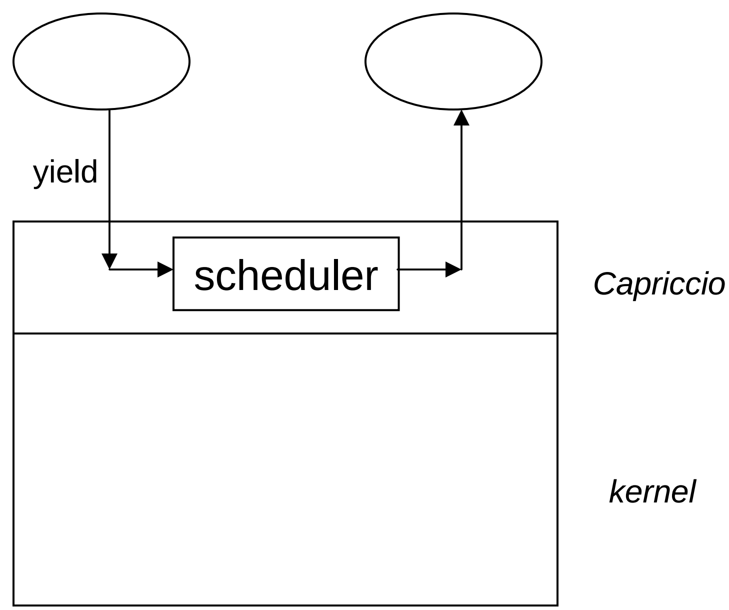


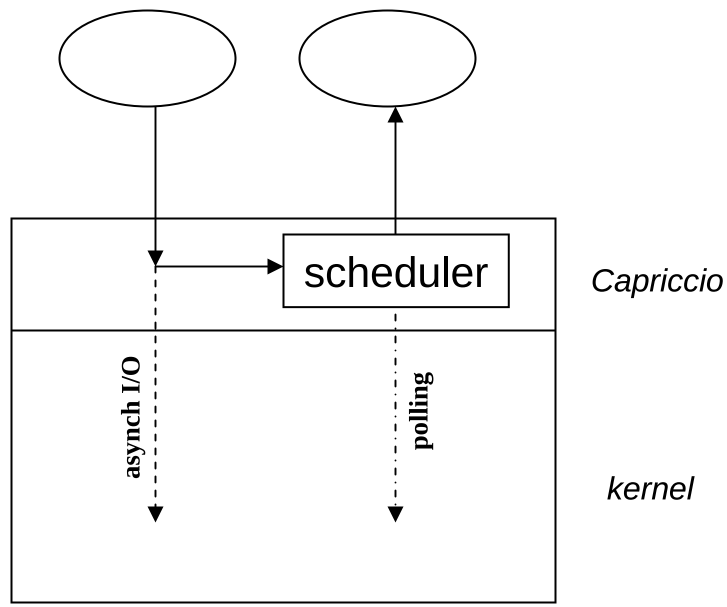
- **Seda**
  - Each thread bound to one stage of the computation
  - Each service request proceeds through successive stages

Cappricio

- Philosophy
  - Thread *model* is useful
  - Improve *implementation* to remove barriers to scalability
- Techniques
  - User-level threads
  - Linked stack management
  - Resource aware scheduling
- Tools
  - Compiler-analysis
  - Run-time monitoring

Capriccio – user level threads

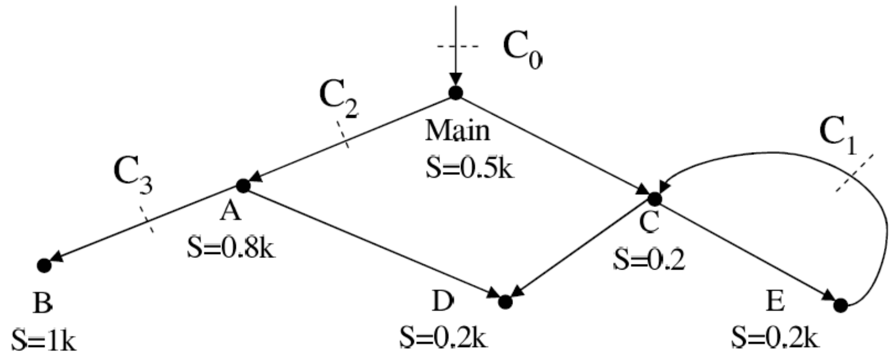




- User-level threading with fast context switch
- Cooperative scheduling (via yielding)
- Thread management costs independent of number of threads (except for sleep queue)

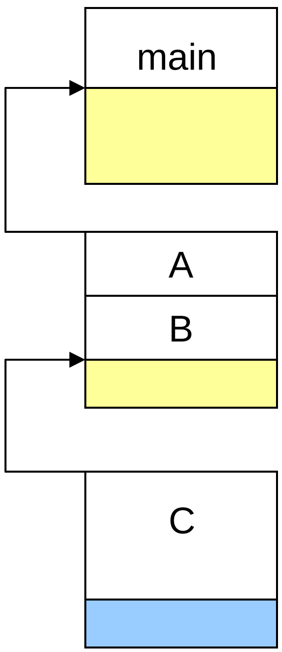
- Intercepts and converts blocking I/O into asynchronous I/O
- Does polling to determine I/O completion

Compiler Analysis - Checkpoints



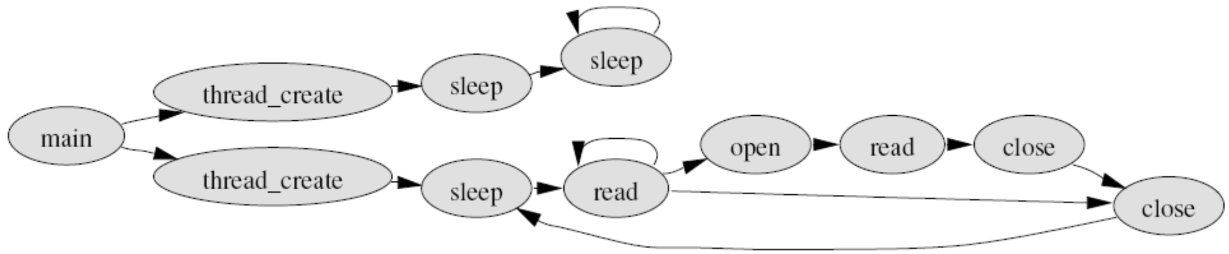
- Call graph – each node is a procedure annotated with maximum stack size needed to execute that procedure; each edge represents a call
- Maximum stack size for thread executing call graph cannot be determined statically
  - Recursion (cycles in graph)
  - Sub-optimal allocation (different paths may require substantially different stack sizes)
- Insert checkpoints to allocate additional stack space ("chunk") dynamically
  - On entry (e.g., C_O)
  - On each back-edge (e.g. C_1)
  - On each edge where the needed (maximum) stack space to reach a leaf node or the next checkpoints exceeds a given limit (*MaxPath*) (e.g., C_2 and C_3 if limit is 1KB)
- Checkpoint code added by source-source translation

Linked Stacks



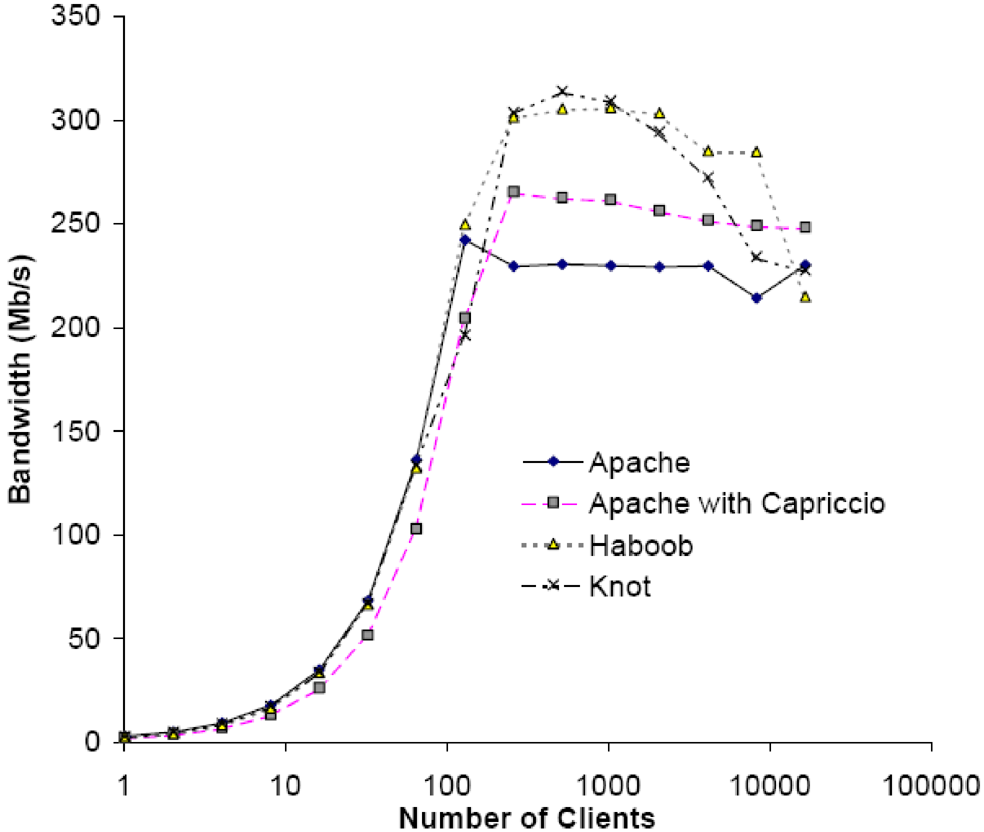
- Thread stack is collection of non-contiguous blocks (‘chunks”)
- *MinChunk:* smallest stack block allocated
- Stack blocks “linked” by saving stack pointer for “old” block in field of “new” block; frame pointer remains unchanged
- Two kinds of wasted memory
  - Internal (within a block) (yellow)
  - External (in last block) (blue)
- Two controlling parameters
  - MaxPath: tradeoff between amount of instrumentation and run-time overhead vs. internal memory waste
  - MinChunk: tradeoff between internal memory waste and external memory waste
- Memory advantages
  - Avoids pre-allocation of large stacks
  - Improves paging behavior by (1) leveraging LIFO stack usage pattern to share chunks among threads and (2) placing multiple chunks on the same page

Resource-aware scheduling



- Blocking graph
  - Nodes are points where the program blocks
  - Arcs connect successive blocking points
- Blocking graph formed dynamically
  - Appropriate for long-running program (e.g. web servers)
- Scheduling annotations
  - Edge – exponentially weighted average resource usage
  - Node – weighted average of its edge values (average resource usage of next edge)
  - Resources – CPU, memory, stack, sockets
- Resource-aware scheduling:
  - Dynamically prioritize nodes/threads based on whether the thread will increase or decrease its use of each resource
  - When a resource is scarce, schedule threads that release that resource
- Limitations
  - Difficult to determine the maximum capacity of a resource
  - Application-managed resources cannot be seen
  - Applications that do not yield

Performance comparison

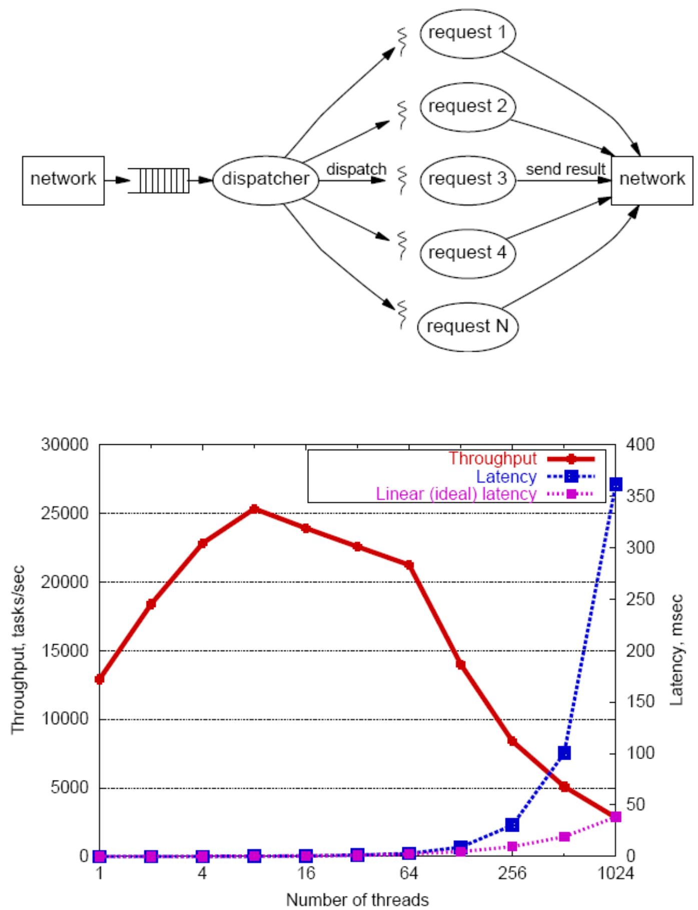


- Apache – standard distribution
- Haboob – event-based web server
- Knot – simple, threaded specially developed web server

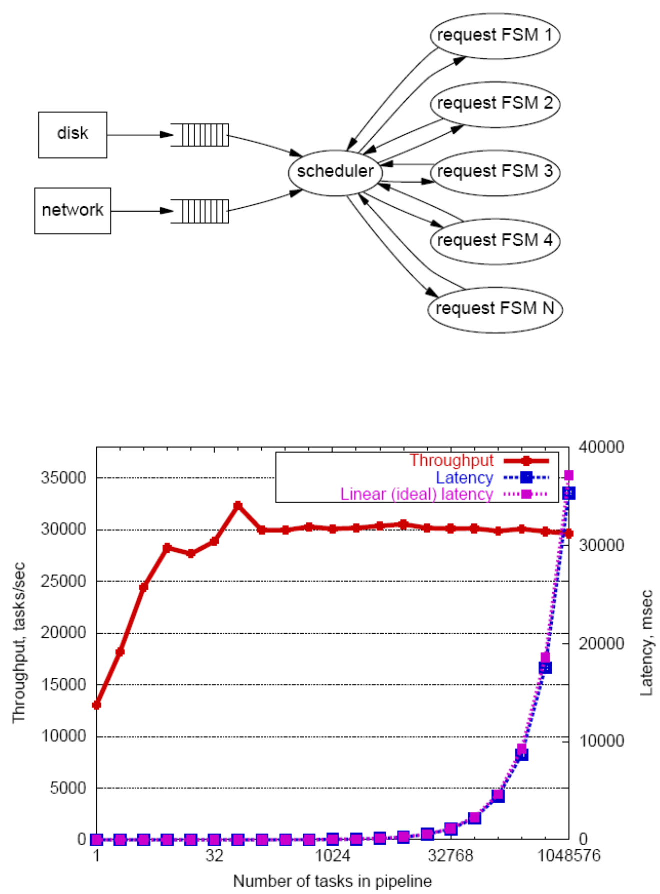
SEDA – Staged Event-Driven Architecture

- Goals
  - Massive concurrency
    - required for heavily used web servers
    - large spikes in load (100x increase in demand)
    - requires efficient, non-blocking I/O
  - Simplify constructing well-conditioned services
    - “well conditioned”: behaves like a simple pipeline
    - offers graceful degradation, maintaining high throughput as load exceeds capacity
    - provides modular architecture (defining and interconnecting “stages”)
    - hides resource management details
  - Introspection
    - ability to analyze and adapt to the request stream
  - Self-tuning resource management
    - thread pool sizing
    - dynamic event scheduling
- Hybrid model
  - combines threads (within stages) and events (between stages)

SEDA's point of view

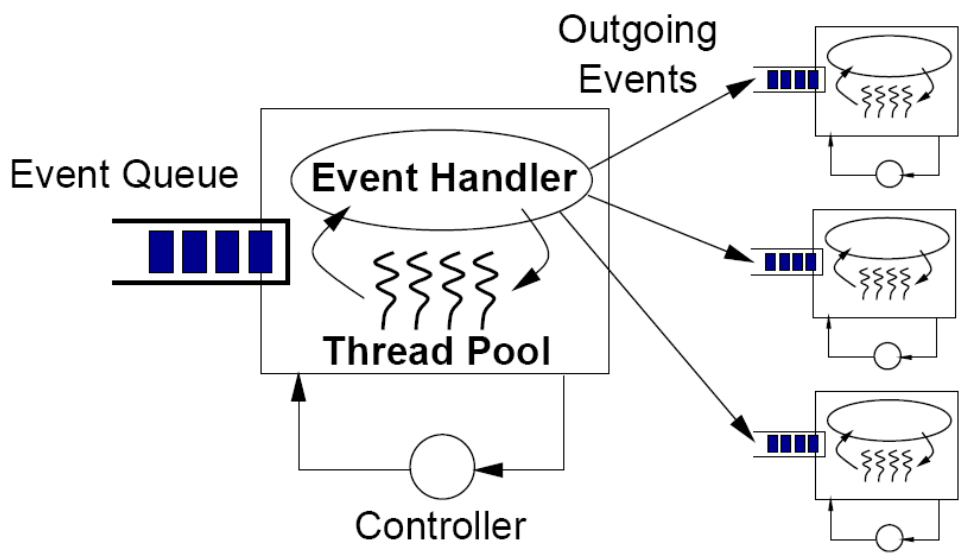


Thread model and performance



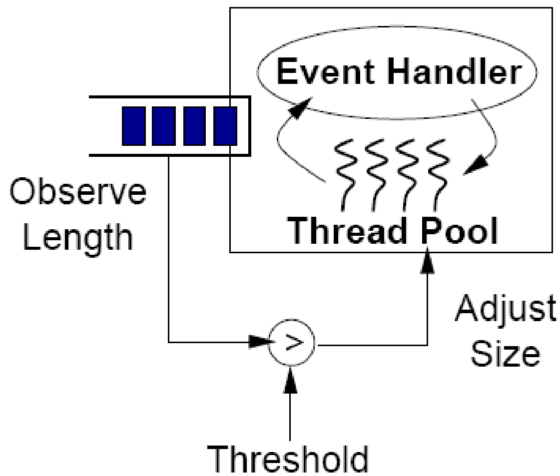
Event model and performance

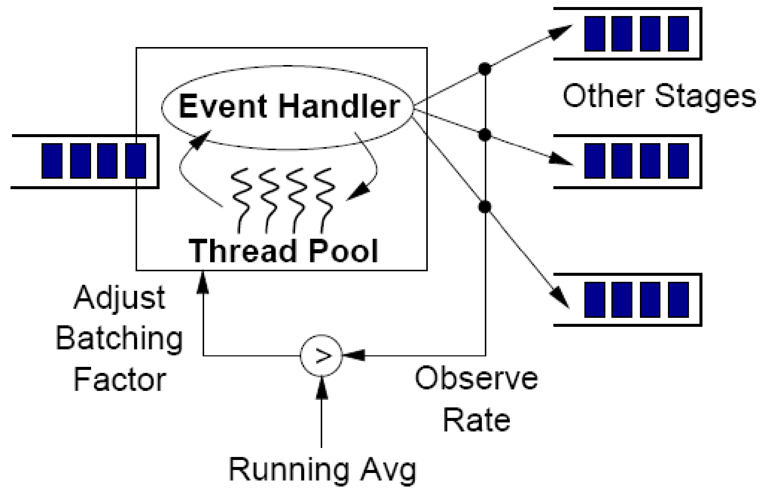
SEDA - structure



- Event queue – holds incoming requests
- Thread pool
  - takes requests from event queue and invokes event handler
  - Limited number of threads per stage
- Event handler
  - Application defined
  - Performs application processing and possibly generates events for other stages
  - Does not manage thread pool or event queue
- Controller – performs scheduling and thread management

Resource Controllers





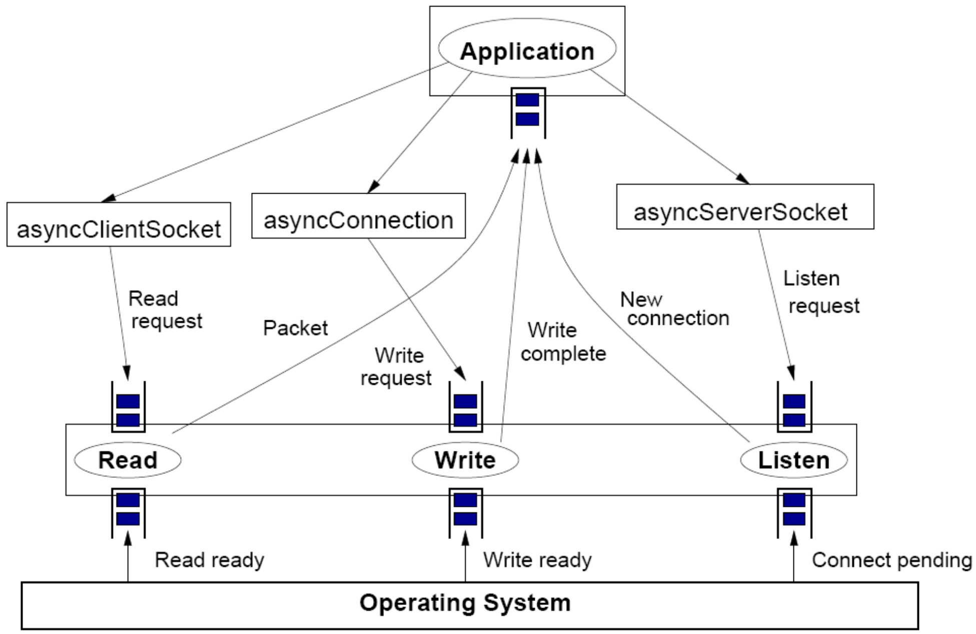
Thread pool controller

- Thread added (up to a maximum) when event queue exceeds threshold
- Thread deleted when idle for a given period

Batching controller

- Adjusts batching factor: the number of event processed at a time
- High batching factor improves throughput
- Low batching factor improves response time
- Goal: find lowest batching factor that sustains high throughput

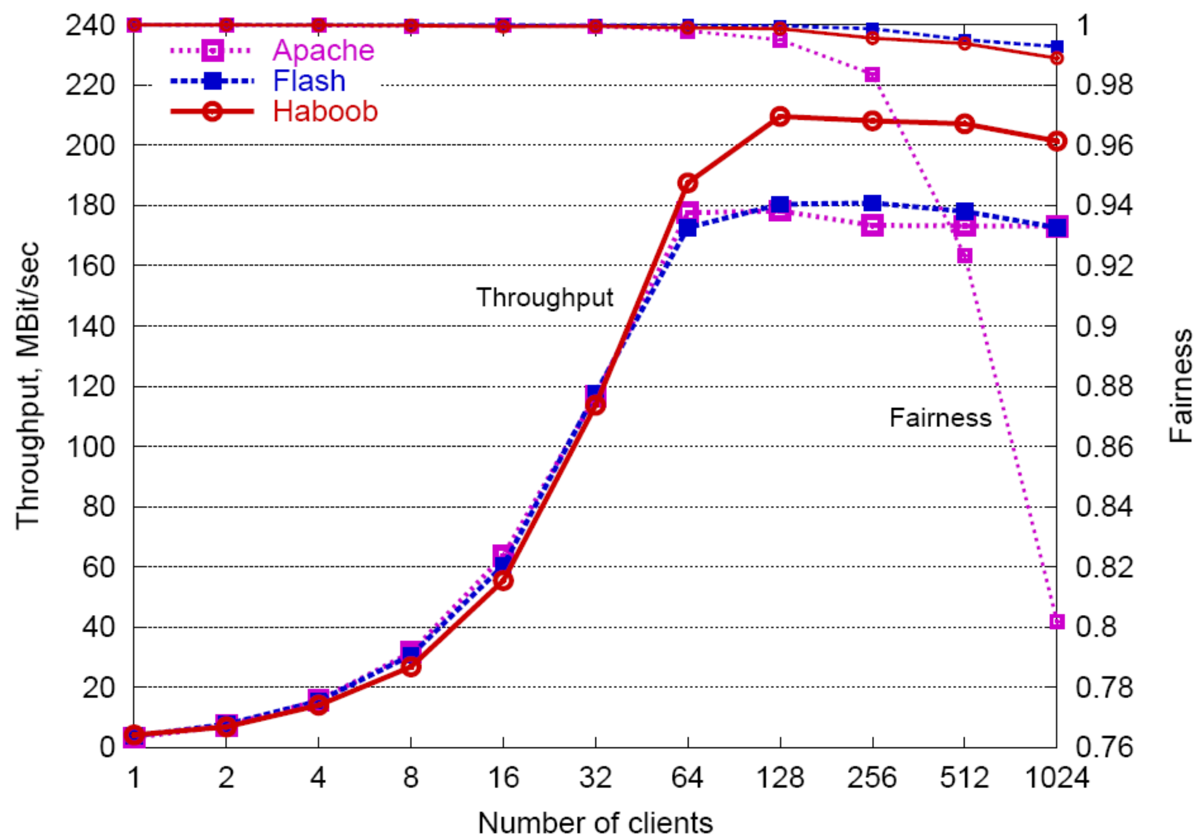
Asynchronous Socket layer



- Implemented as a set of SEDA stages
- Each asynchSocket stage has two event queues
- Thread in each stage serves each queue alternately based on time-out
- Similar use of stages for file I/O

Performance

- Apache
  - process-per-request design
- Flash
  - event-drived design
  - one process handling most tasks
- Haboob
  - SEDA-based design



Fairness

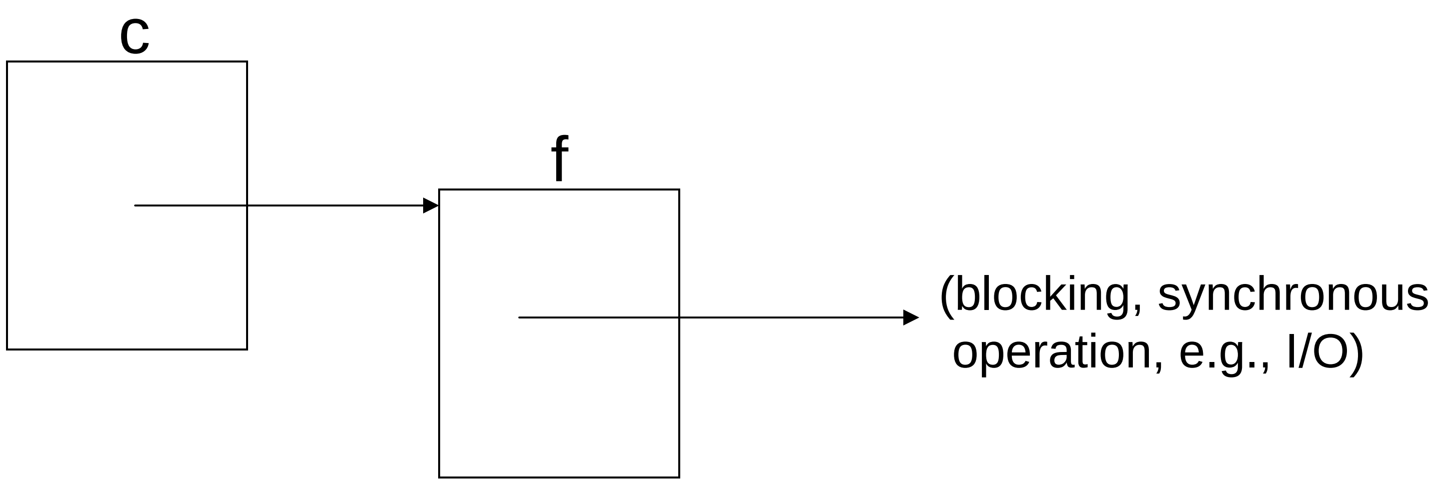
- Measure of number of requests completed per client
- Value of 1 indicates equal treatment of clients
- Value of k/N indicates k clients received equal treatment and n-k clients received no service

TAME

- expressive abstractions for event-based programming
- implemented via source-source translation
- avoids stack ripping
- type safety and composability via templates

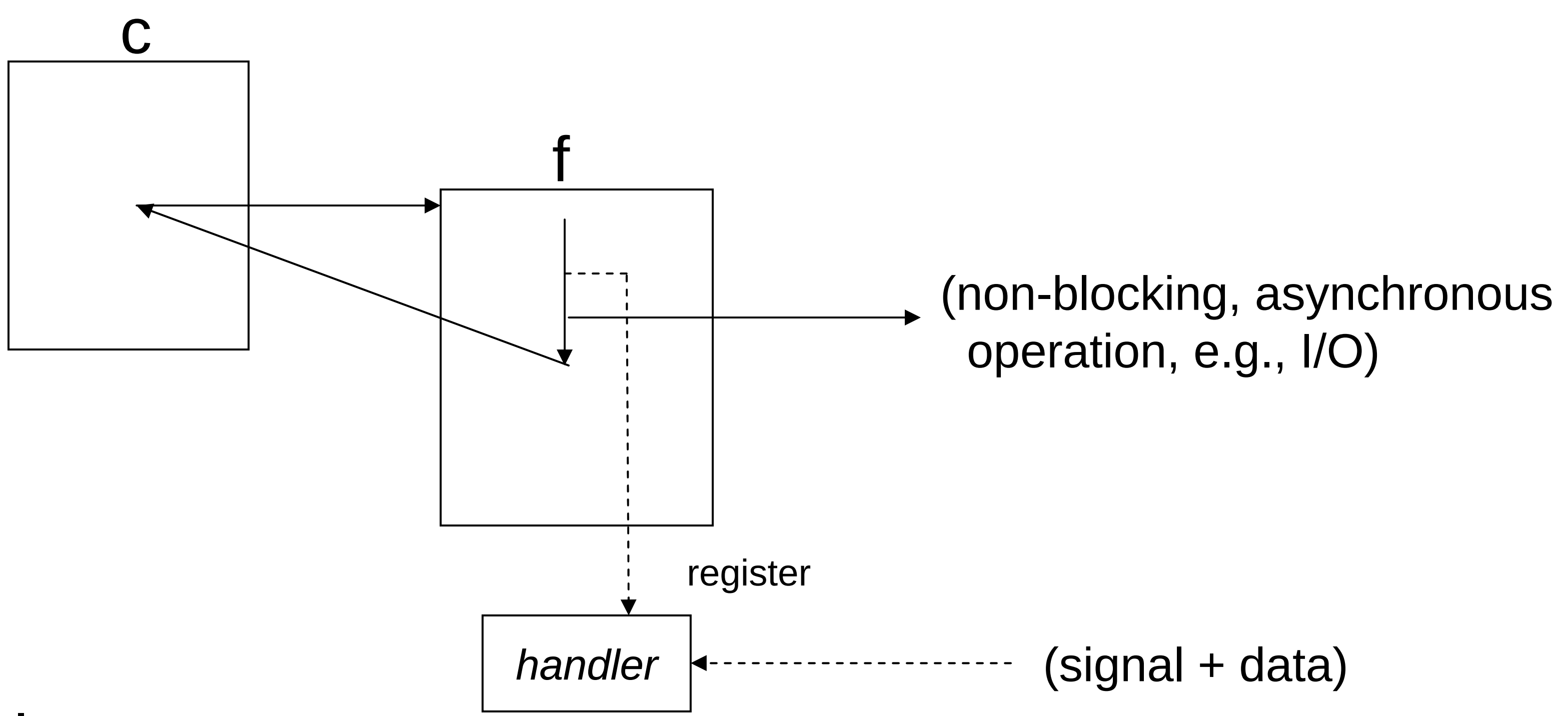
M. Krohn, E. Kohler, M.F. Kaashoek, “Events Can Make Sense,” USENIX Annual Technical Conference, 2007, pp. 87-100.

A typical thread programming problem



Problem: the thread becomes blocked in the called routine (f) and the caller (c) is unable to continue even if it logically is able to do so.

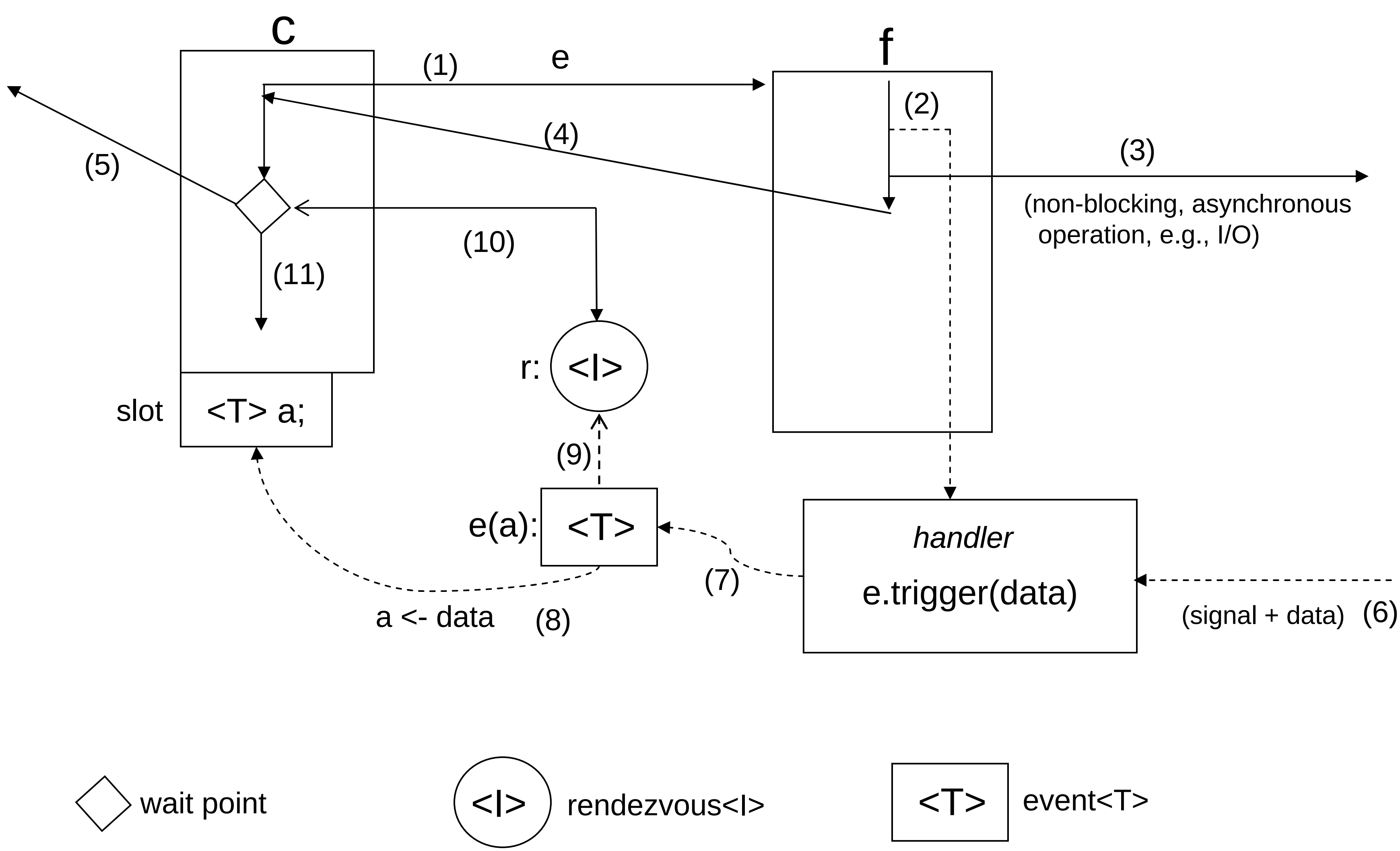
A partial solution



Issues

- Synchronization: how does the caller know when the signal has occurred without busy-waiting?
- Data: how does the caller know what data resulted from the operation?

A “Tame” solution



Tame Primitives

Classes	Keywords & Language Extensions	Functions & Methods

event<>
• A basic event.
event<T>
• An event with a single *trigger value* of type T. This value is set when the event occurs; an example might be a character read from a file descriptor. Events may also have multiple trigger values of types $T_1 \ldots T_n$.
rendezvous<I>
• Represents a set of outstanding events with event IDs of type I. Callers name a rendezvous when they block, and unblock on the triggering of any associated event.
	twait(r[,i]);
	• A wait point. Block on explicit rendezvous r, and optionally set the event ID i when control resumes.
	tamed
	• A return type for functions that use twait.
	tvars { ... }
	• Marks safe local variables.
	twait { *statements*; }
	• Wait point syntactic sugar: block on an implicit rendezvous until all events created in *statements* have triggered.
		mkevent(r,i,s);
		• Allocate a new event with event ID i. When triggered, it will awake rendezvous r and store trigger value in slot s.
		mkevent(s);
		• Allocate a new event for an implicit twait{} rendezvous. When triggered, store trigger value in slot s.
		e.trigger(v);
		• Trigger event e, with trigger value v.
		timer(to,e); wait_on_fd(fd,rw,e);
		• Primitive event interface for timeouts and file descriptor events, respectively.

Figure 2: Tame primitives for event programming in C++.

An example

```
void multidns(dnsname name[], ipaddr a[], int n) {
    for (int i = 0; i < n; i++)
        a[i] = gethostbyname(name[i]);
}
```

```
tamed multidns_tame(dnsname name[], ipaddr a[],
                    int n, event<> done) {
    tvars { int i; }
    for (i = 0; i < n; i++)
        twait { gethost_ev(name[i], mkevent(a[i])); }
    done.trigger();
}
```

```
tamed gethost_ev(dsname name, event<ipaddr> e);
```

Variations on control flow

```
tamed multidns_par(dnsname name[], ipaddr a[],
                    int n, event<> done) {
   twait {
      for (int i = 0; i < sz; i++)
         gethost_ev(name[i], mkevent(a[i]));
   }
   done.trigger();
}
```

parallel control flow

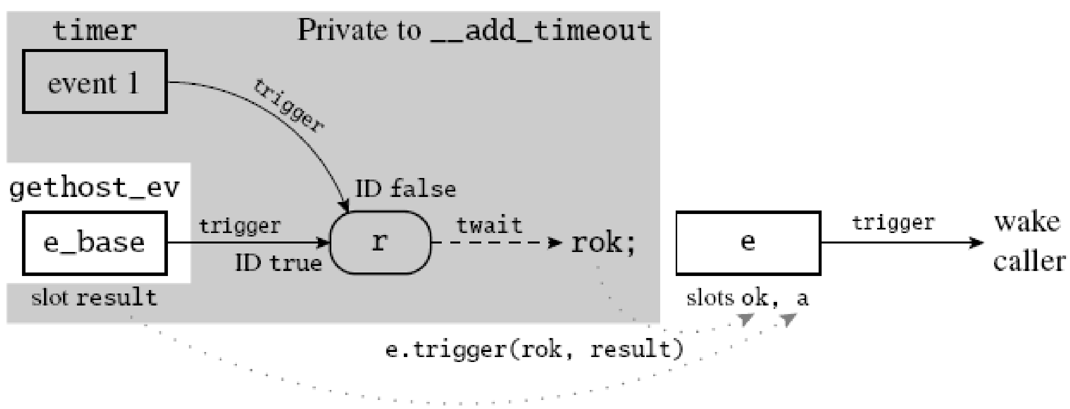
```
tamed multidns_win(dnsname name[], ipaddr a[],
                    int n, event<> done) {
  tvars { int sent(0), recv(0); rendezvous<> r; }
  while (recv < n)
     if (sent < n && sent - recv < WINDOWSIZE) {
        gethost_ev(name[sent], mkevent(r,a[sent]));
        sent++;
     } else {
        twait(r);
        recv++;
     }
  done.trigger();
}
```

window/pipeline control flow

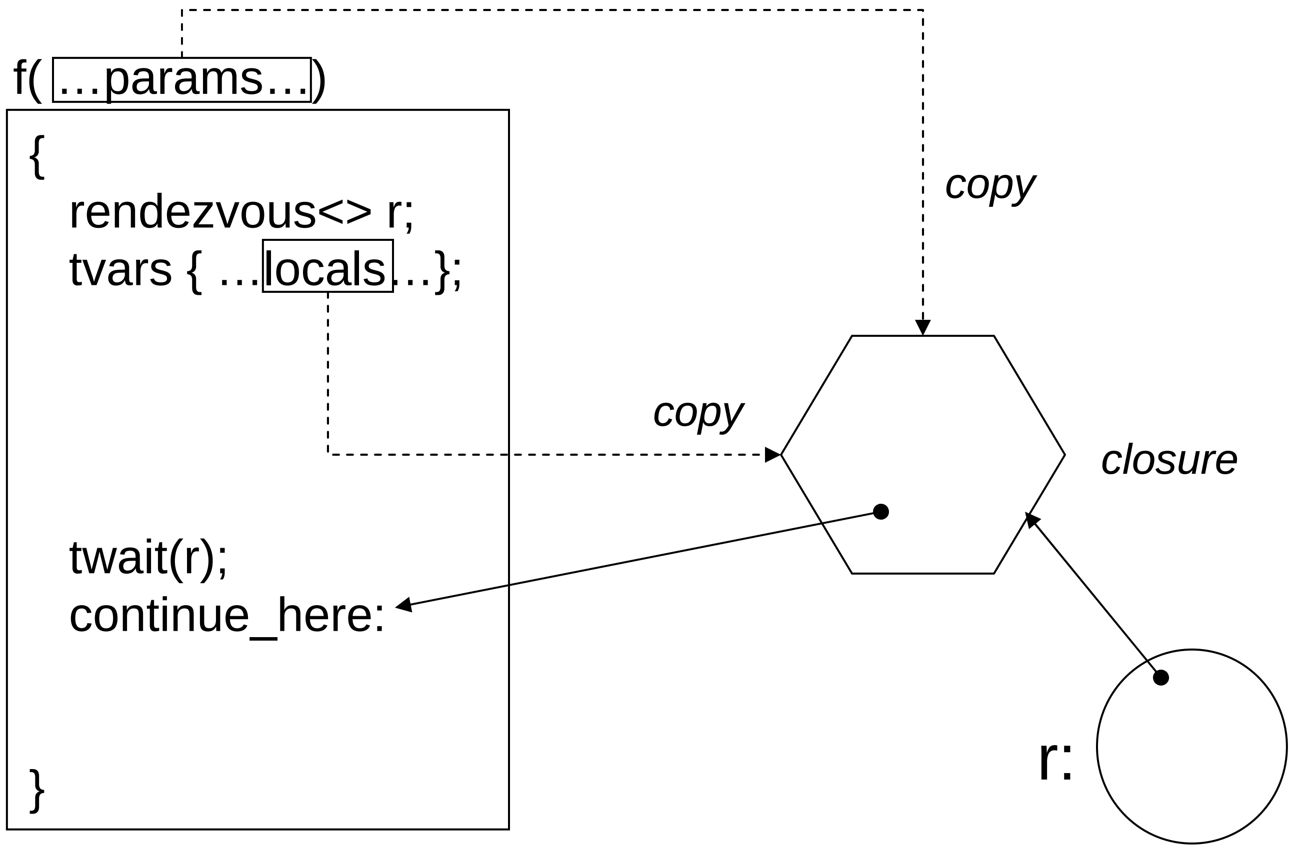
Event IDs & Composability

```
template <typename T> tamed
__add_timeout(event<T> &e_base, event<bool, T> e) {
    tvars { rendezvous<bool> r; T result; bool rok; }
    timer(TIMEOUT, mkevent(r, false));
    e_base = mkevent(r, true, result);
    twait(r, rok);
    e.trigger(rok, result);
    r.cancel();
}

template <typename T> event<T> add_timeout(event<bool, T> e) {
    event<T> e_base;
    __add_timeout(e_base, e);
    return e_base;
}
```



Closures



Smart pointers and reference counting insure correct deallocation of events, redezvous, and closures.

Performance
(relative to Capriccio)

	Capriccio	**Tame**
Throughput (connections/sec)	28,318	28,457
Number of threads	350	1
Physical memory (kB)	6,560	2,156
Virtual memory (kB)	49,517	10,740

Figure 7: Measurements of Knot at maximum throughput. Throughput is averaged over the whole one-minute run. Memory readings are taken after the warm-up period, as reported by ps.