C++ Network Programming with Patterns, Frameworks, and ACE

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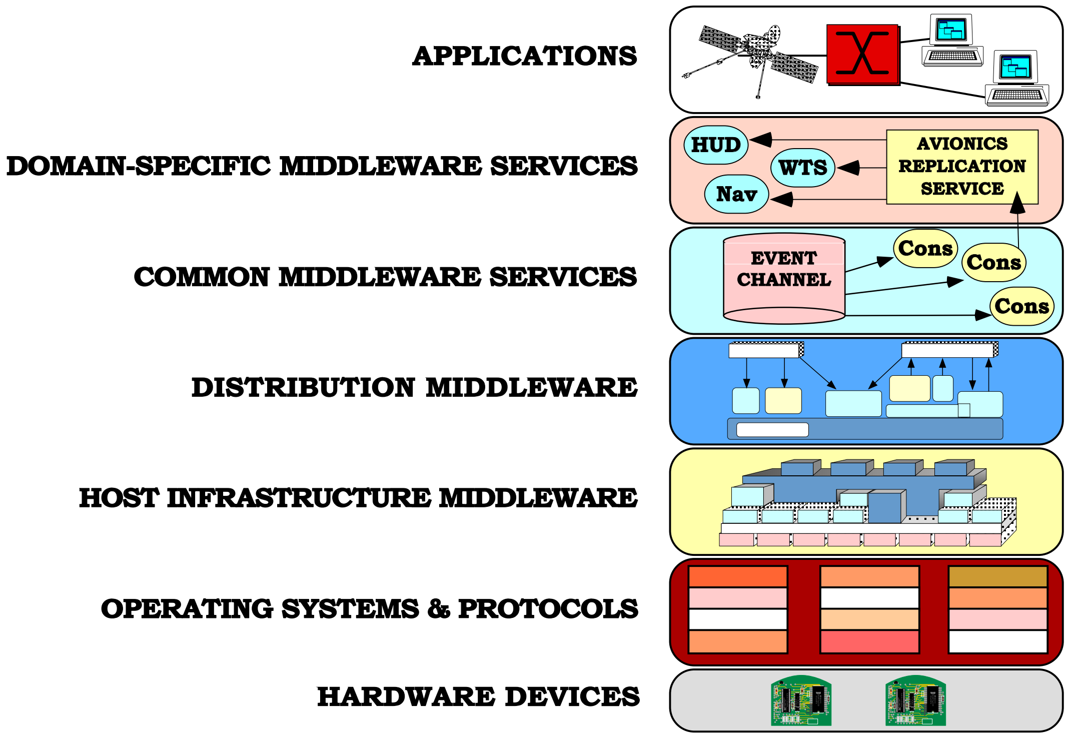
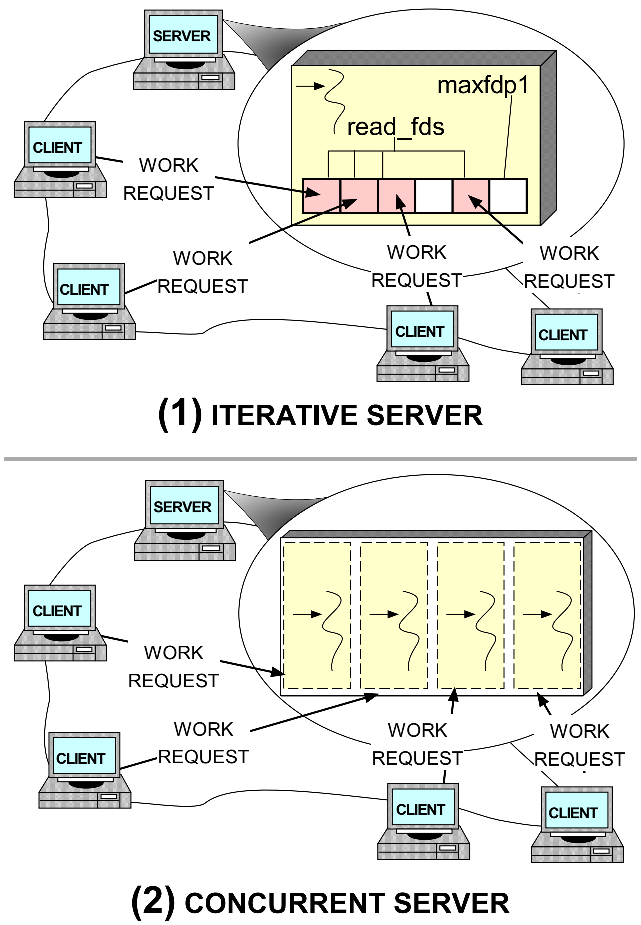
Roadmap to Levels of Middleware



www.cs.wustl.edu/~schmidt/PDF/middleware-chapter.pdf

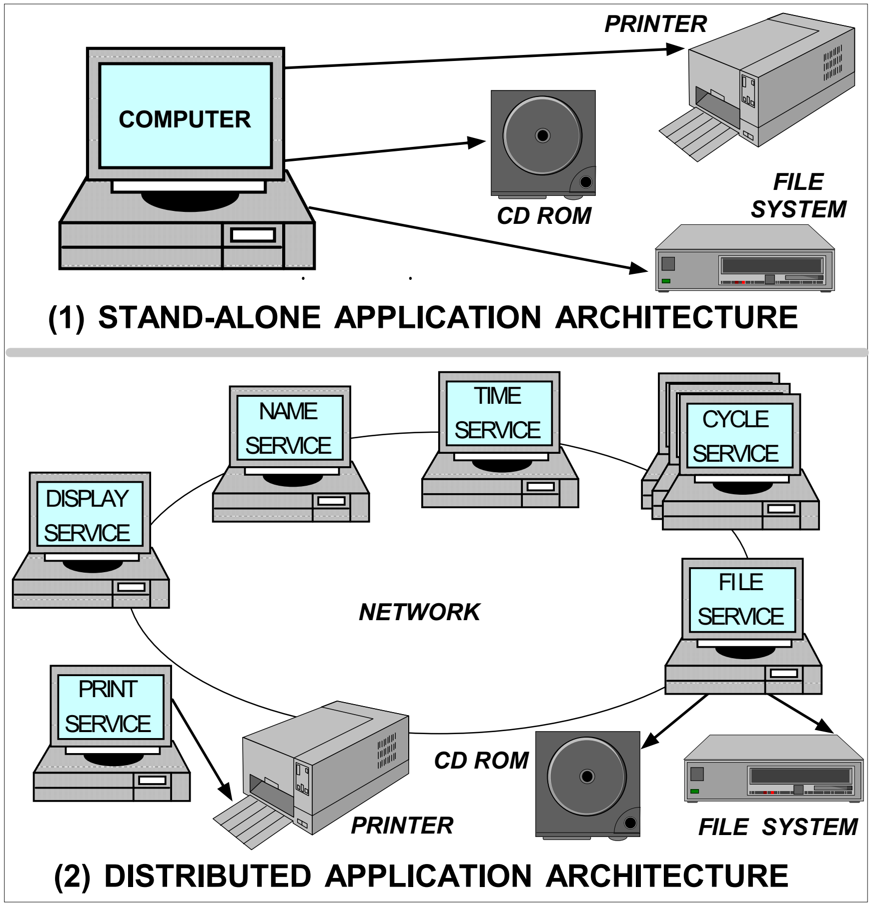
- **Observations**
  - Historically, apps built atop OS
  - Today, apps built atop *middleware*
  - Middleware has multiple layers
    * Just like network protocol stacks

Motivation for Concurrency



- *Leverage hardware/software*
  - *e.g.*, multi-processors and OS thread support
- *Increase performance*
  - *e.g.*, overlap computation and communication
- *Improve response-time*
  - *e.g.*, GUIs and network servers
- *Simplify program structure*
  - *e.g.*, sync vs. async

Motivation for Distribution



- Collaboration $\rightarrow$ *connectivity* and *interworking*
- Performance $\rightarrow$ *multi-processing* and *locality*
- Reliability and availability $\rightarrow$ *replication*
- Scalability and portability $\rightarrow$ *modularity*
- Extensibility $\rightarrow$ *dynamic configuration and reconfiguration*
- Cost effectiveness $\rightarrow$ *open systems* and *resource sharing*

Challenges and Solutions

- Developing *efficient*, *robust*, and *extensible* concurrent networking applications is hard
  - *e.g.*, must address complex topics that are less problematic or not relevant for non-concurrent, stand-alone applications
- OO techniques and OO language features help to enhance software quality factors
  - Key OO techniques include *patterns* and *frameworks*
  - Key OO language features include *classes*, *inheritance*, *dynamic binding*, and *parameterized types*
  - Key software quality factors include *modularity*, *extensibility*, *portability*, *reusability*, and *correctness*

Caveats

- OO is *not* a panacea
  - Though when used properly it helps minimize "accidental" complexity and improve software quality factors
- It's also essential to understand advanced OS features to enhance functionality and performance, *e.g.*,
  - *Multi-threading*
  - *Multi-processing*
  - *Synchronization*
  - *Shared memory*
  - *Explicit dynamic linking*
  - *Communication protocols and IPC mechanisms*

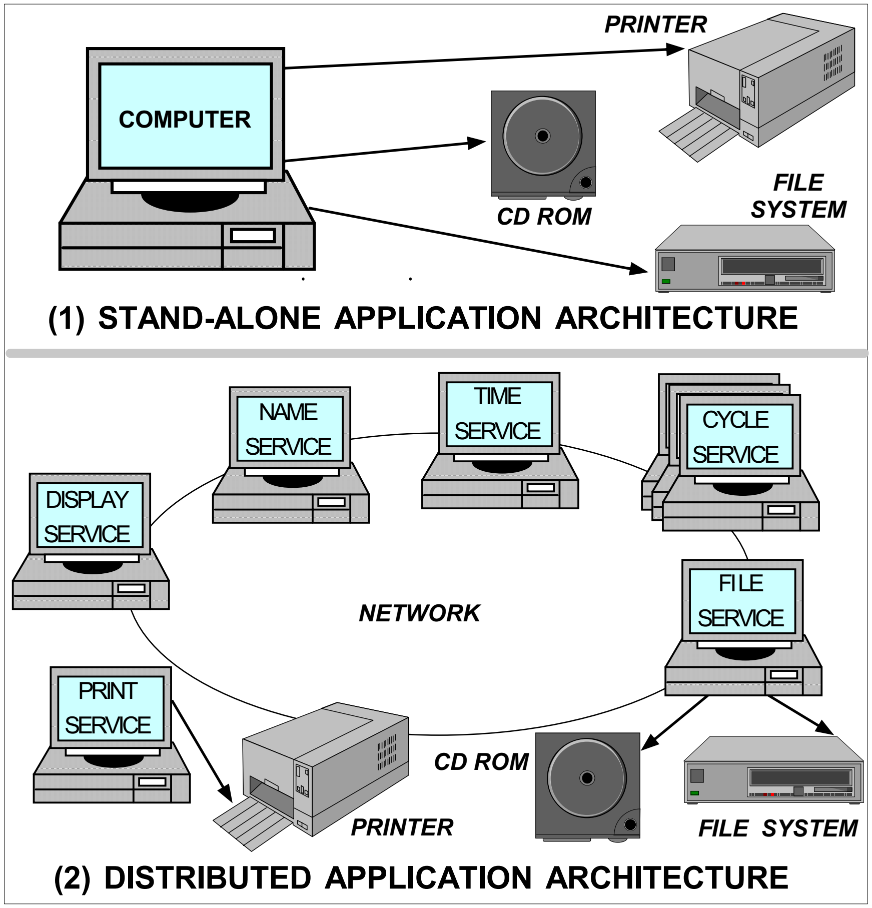
Tutorial Outline

- Brief overview of key OO networking and concurrency concepts and OS platform mechanisms
  - Emphasis is on *practical* solutions
- Examine a range of examples in detail
  - *Networked Logging Service*
  - *Concurrent Web Server*
  - *Application-level Telecom Gateway*
  - *Call Center Manager Event Server*
- Discuss general concurrent programming strategies
- Provide URLs for further reading on the topic

Software Development Environment

- The topics discussed here are largely independent of OS, network, and programming language
  - Currently used successfully on UNIX/POSIX, Windows, and RTOS platforms, running on TCP/IP networks using C++
- Examples are illustrated using freely available ADAPTIVE Communication Environment (ACE) OO framework components
  - Although ACE is written in C++, the principles covered in this tutorial apply to other OO languages
  - *e.g.*, Java, Eiffel, Smalltalk, etc.
- In addition, other networks and backplanes can be used, as well

Sources of Complexity



- **Inherent complexity**
  - Latency
  - Reliability
  - Synchronization
  - Deadlock
- **Accidental Complexity**
  - Low-level APIs
  - Poor debugging tools
  - Algorithmic decomposition
  - Continuous re-invention

Sources of Inherent Complexity

Inherent complexity results from fundamental domain challenges, *e.g.*:

Concurrent programming

- Eliminating "race conditions"
- Deadlock avoidance
- Fair scheduling
- Performance optimization and tuning

Distributed programming

- Addressing the impact of latency
- Fault tolerance and high availability
- Load balancing and service partitioning
- Consistent ordering of distributed events

Sources of Accidental Complexity

Accidental complexity results from limitations with tools and techniques used to develop concurrent applications, *e.g.*,

- Lack of portable, reentrant, type-safe and extensible system call interfaces and component libraries
- Inadequate debugging support and lack of concurrent and distributed program analysis tools
- Widespread use of *algorithmic* decomposition
  - Fine for *explaining* concurrent programming concepts and algorithms but inadequate for *developing* large-scale concurrent network applications
- Continuous rediscovery and reinvention of core concepts and components

OO Contributions to Concurrent and Distributed Applications

Concurrent network programming is traditionally performed using low-level OS mechanisms, *e.g.*,

- *fork/exec*
- *Shared memory and semaphores*
- *Memory-mapped files*
- *Signals*
- *sockets/select*
- *Low-level thread APIs*

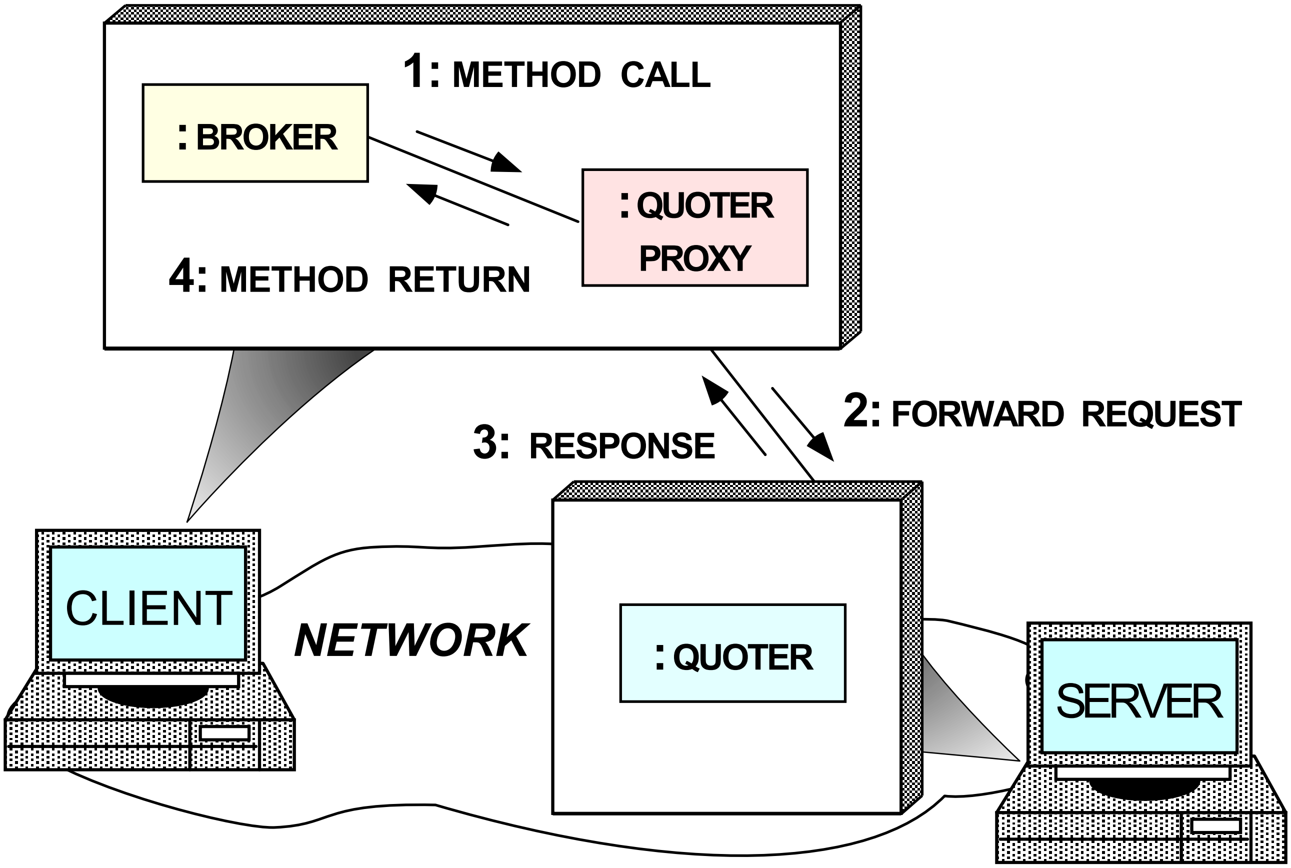
Patterns and *frameworks* elevate development level to focus on application concerns, *e.g.*,

- *Service functionality and policies*
- *Service configuration*
- *Concurrent event demultiplexing and event handler dispatching*
- *Service concurrency and synchronization*

Overview of Patterns

- Patterns represent *solutions* to *problems* that arise when developing software within a particular *context*
  - *i.e.*, “Patterns == problem/solution pairs within a context”
- Patterns capture the *static* and *dynamic structure* and *collaboration* among key *participants* in software designs
  - They are particularly useful for articulating how and why to resolve *non-functional forces*
- Patterns facilitate reuse of successful software architectures and designs

Example: the Proxy Pattern

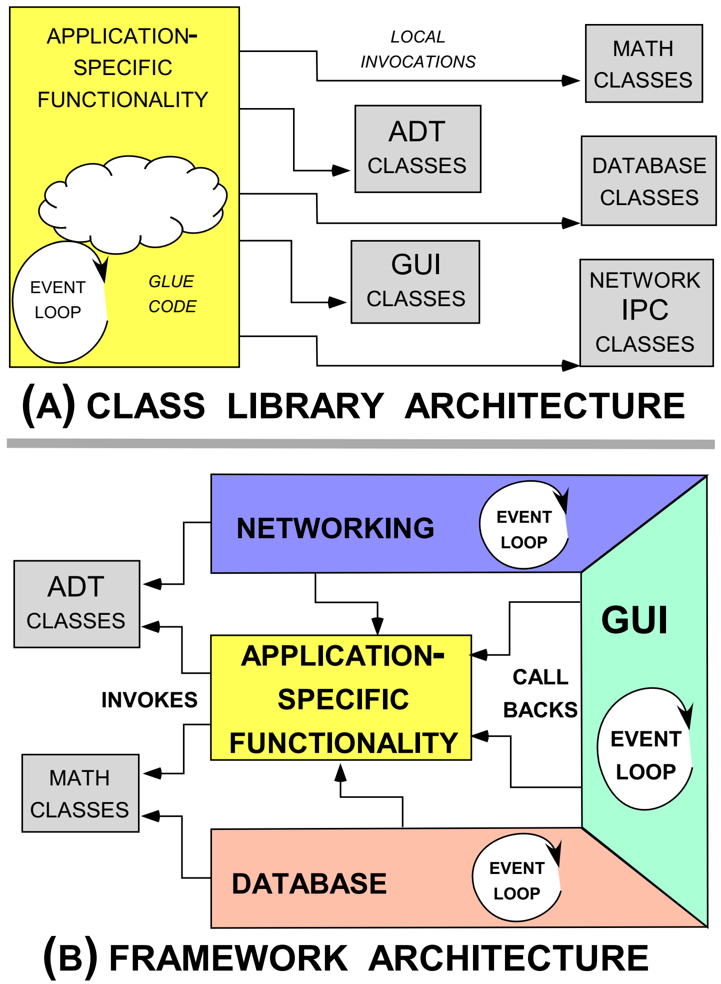


Intent: Provide a surrogate for another object that controls access to it

Overview of Frameworks and Components

- A framework is:
  - "An integrated collection of components that collaborate to produce a reusable architecture for a family of related applications"
- Frameworks differ from conventional class libraries:
  1. Frameworks are "semi-complete" applications
  2. Frameworks address a particular application domain
  3. Frameworks provide "inversion of control"
- Frameworks facilitate reuse of successful networked application software designs and implementations
  - Applications *inherit* from and *instantiate* framework components

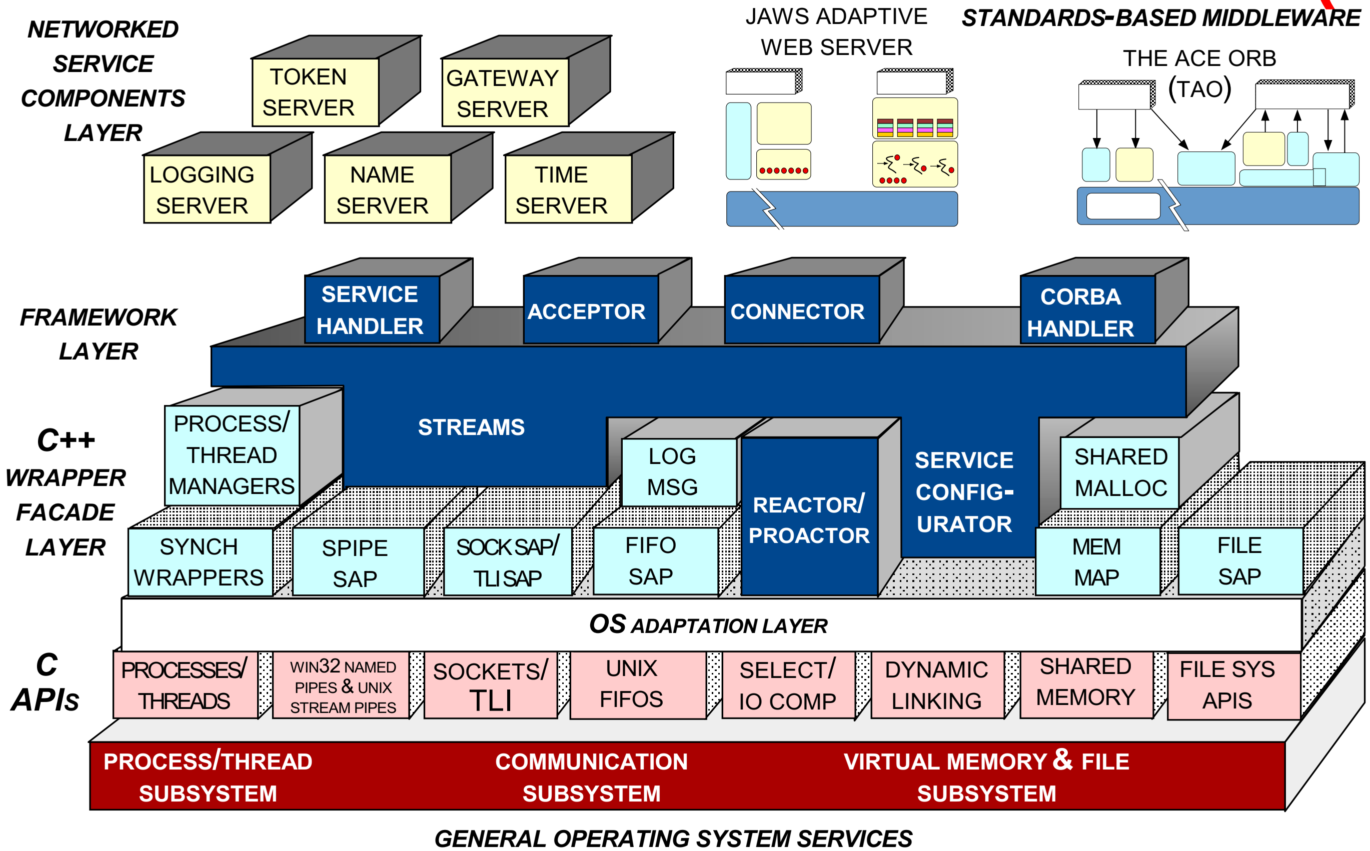
Class Libraries versus Frameworks



Key distinctions

- *Class libraries*
  – Reusable building blocks
  – Domain-independent
  – Limited in scope
  – Passive
- *Frameworks*
  – Reusable, “semi-complete” applications
  – Domain-specific
  – Broader in scope
  – Active

The ADAPTIVE Communication Environment (ACE)

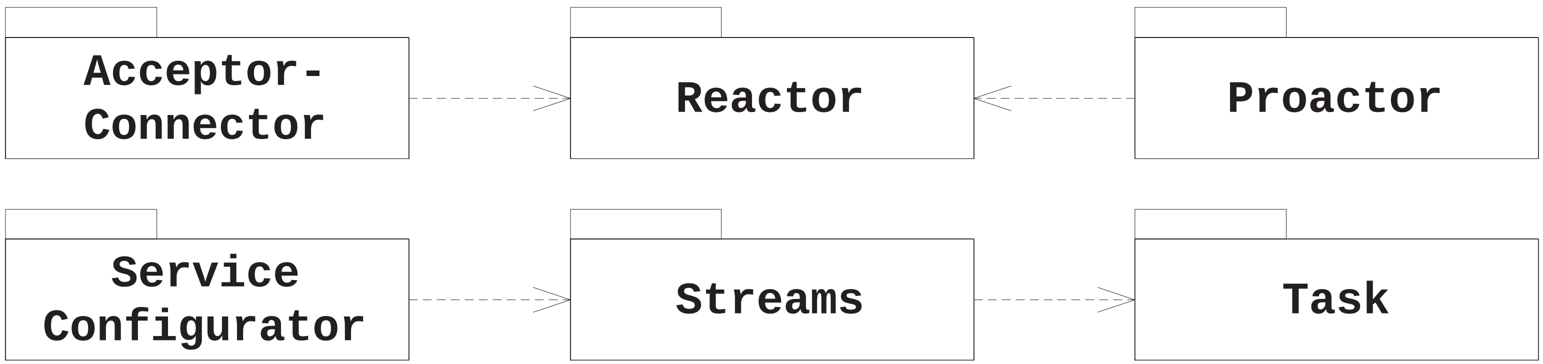


`www.cs.wustl.edu/~schmidt/ACE.html`

ACE Statistics

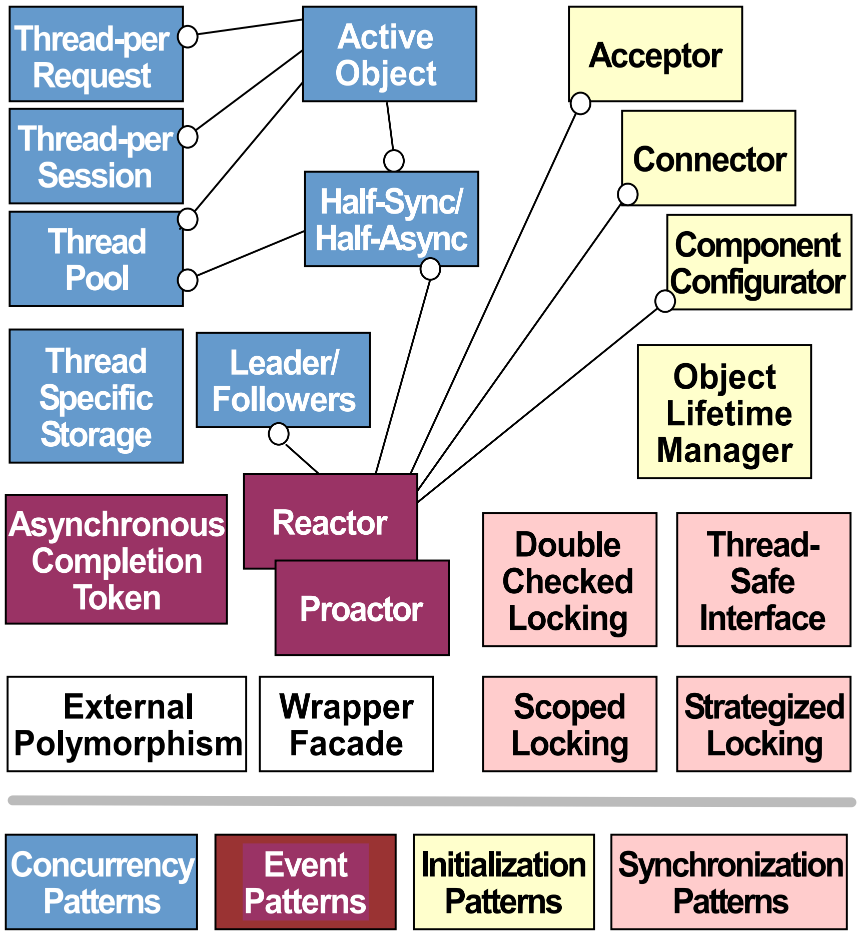
- ACE library contains $\sim$ 250,000 lines of C++
  - Over 40 person-years of effort
- Ported to UNIX, Windows, MVS, and RT/embedded platforms
  - *e.g.*, VxWorks, LynxOS, Chorus
- Large user and open-source developer community
  - `~schmidt/ACE-users.html`
- Currently used by dozens of companies
  - Bellcore, BBN, Boeing, Ericsson, Hughes, Kodak, Lockheed, Lucent, Motorola, Nokia, Nortel, Raytheon, SAIC, Siemens, etc.
- Supported commercially by Riverace
  - www.riverace.com

The Key Frameworks in ACE



- ACE contains a number of frameworks that can be used separately or together
- This design permits fine-grained subsetting of ACE components
  - Subsetting helps minimize ACE's memory footprint
  - `$ACE_ROOT/doc/ACE-subsets.html`

Patterns for Communication Middleware



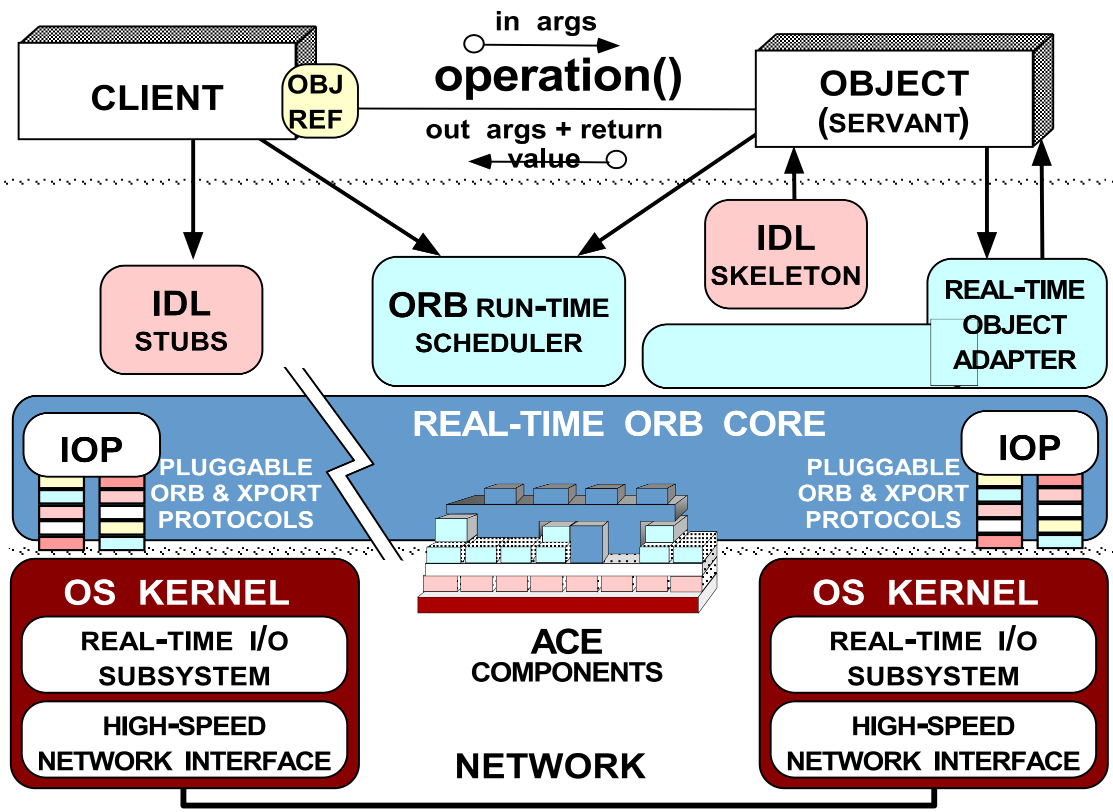
Observation

- *Failures rarely result from unknown scientific principles, but from failing to apply proven engineering practices and patterns*

Benefits of Patterns

- Facilitate design reuse
- Preserve crucial design information
- Guide design choices

The ACE ORB (TAO)



`www.cs.wustl.edu/~schmidt/TAO.html`

TAO Overview →

- A real-time, high-performance ORB
- Leverages ACE
  - Runs on POSIX, Windows, RTOSs

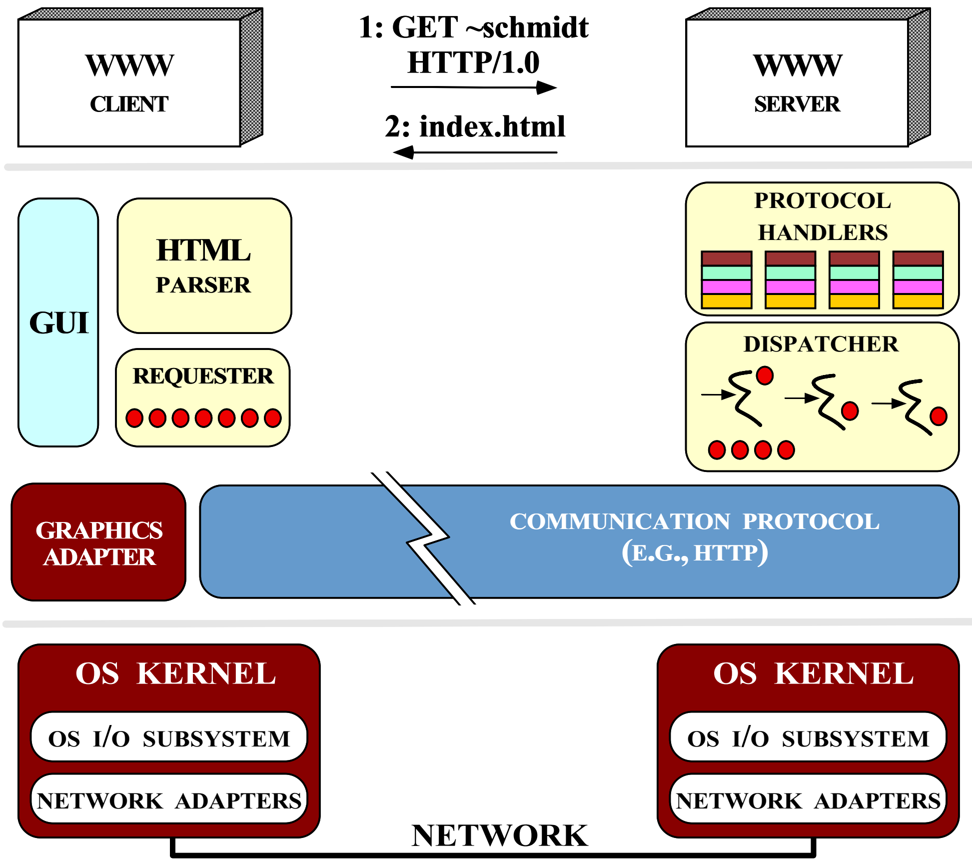
Related efforts →

- QuO at BBN
- MIC/GME at Vanderbilt
- XOTS

TAO Statistics

- TAO order of magnitude
  - Core ORB $>$ 300,000 LOC
  - IDL compiler $>$ 200,000 LOC
  - CORBA Object Services $>$ 250,000 LOC
  - Leverages ACE heavily
- Ported to UNIX, Windows, & RT/embedded platforms
  - *e.g.*, VxWorks, LynxOS, Chorus, WinCE
- $\sim$ 50 person-years of effort
- Currently used by many companies
  - *e.g.*, Boeing, BBN, Lockheed, Lucent, Motorola, Raytheon, SAIC, Siemens, etc.
- Supported commercially by OCI and PrismTech
  - www.ociweb.com
  - www.prismtechnologies.com

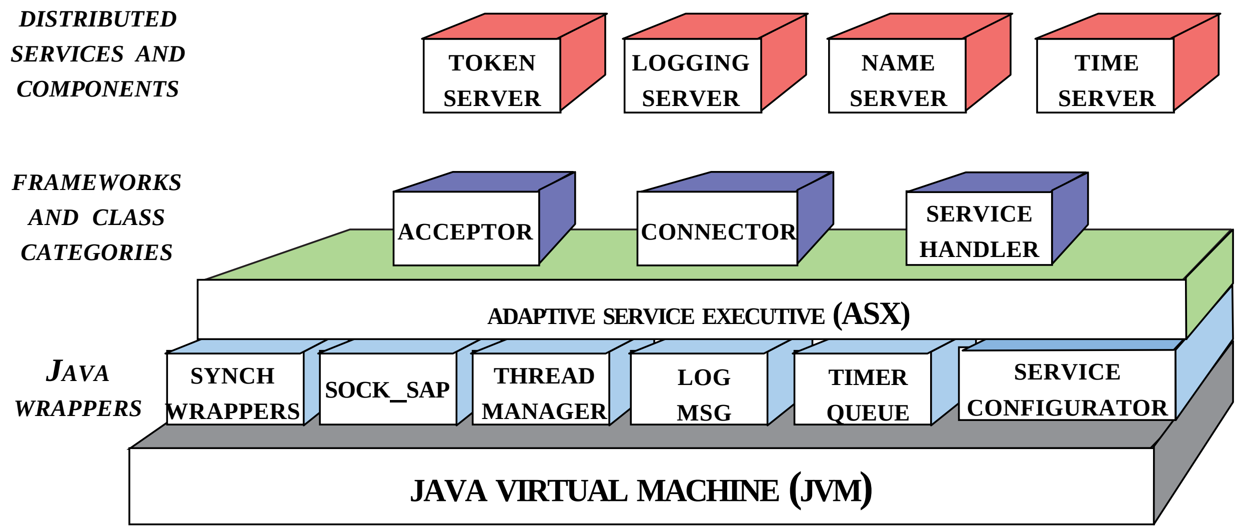
JAWS Adaptive Web Server



www.cs.wustl.edu/~jxh/research/

- **JAWS Overview**
  - A high-performance Web server
    - ∗ Flexible concurrency and dispatching mechanisms
  - Leverages the ACE framework
    - ∗ Ported to most OS platforms
  - Used commercially by CacheFlow
    - ∗ www.cacheflow.com

Java ACE

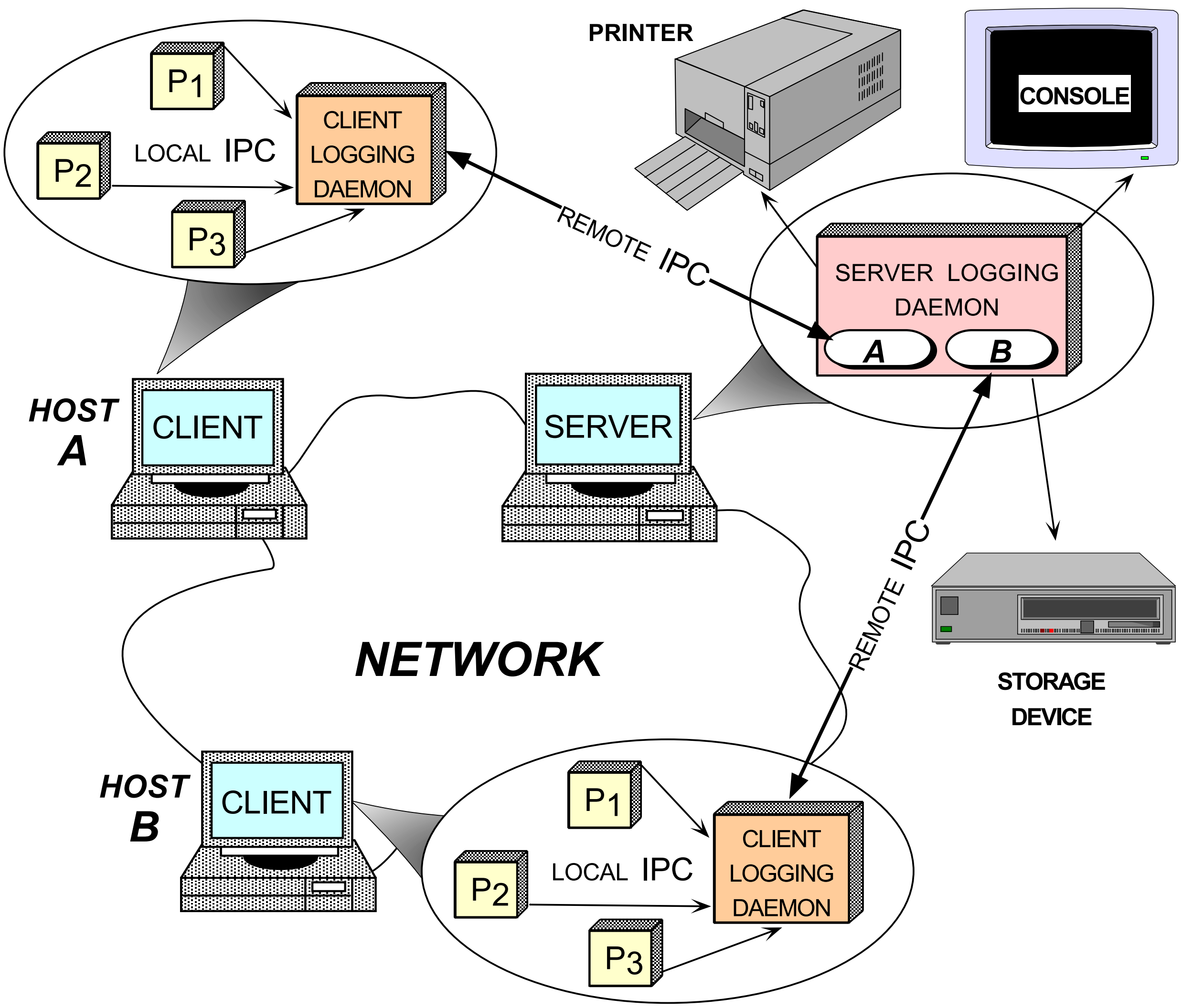


www.cs.wustl.edu/˜schmidt/JACE.html
www.cs.wustl.edu/˜schmidt/C++2java.html
www.cs.wustl.edu/˜schmidt/PDF/MedJava.pdf

Java ACE Overview

- A Java version of ACE
  - Used for medical imaging prototype

Networked Logging Service



Intent: *Server logging daemon* collects, formats, and outputs logging records forwarded from *client logging daemons* residing throughout a network or Internet

Networked Logging Service Programming API

The logging API is similar to `printf()`, *e.g.*:

```
ACE_ERROR ((LM_ERROR, "(%t) fork failed"));
```

Generates on logging server host:

```
Oct 31 14:50:13 1992@tango.ics.uci.edu@2766@LM_ERROR@client
::(4) fork failed
```

and

```
ACE_DEBUG ((LM_DEBUG,
            "(%t) sending to server %s", server_host));
```

generates on logging server host:

```
Oct 31 14:50:28 1992@zola.ics.uci.edu@18352@LM_DEBUG@drwho
::(6) sending to server bastille
```

Conventional Logging Server Design

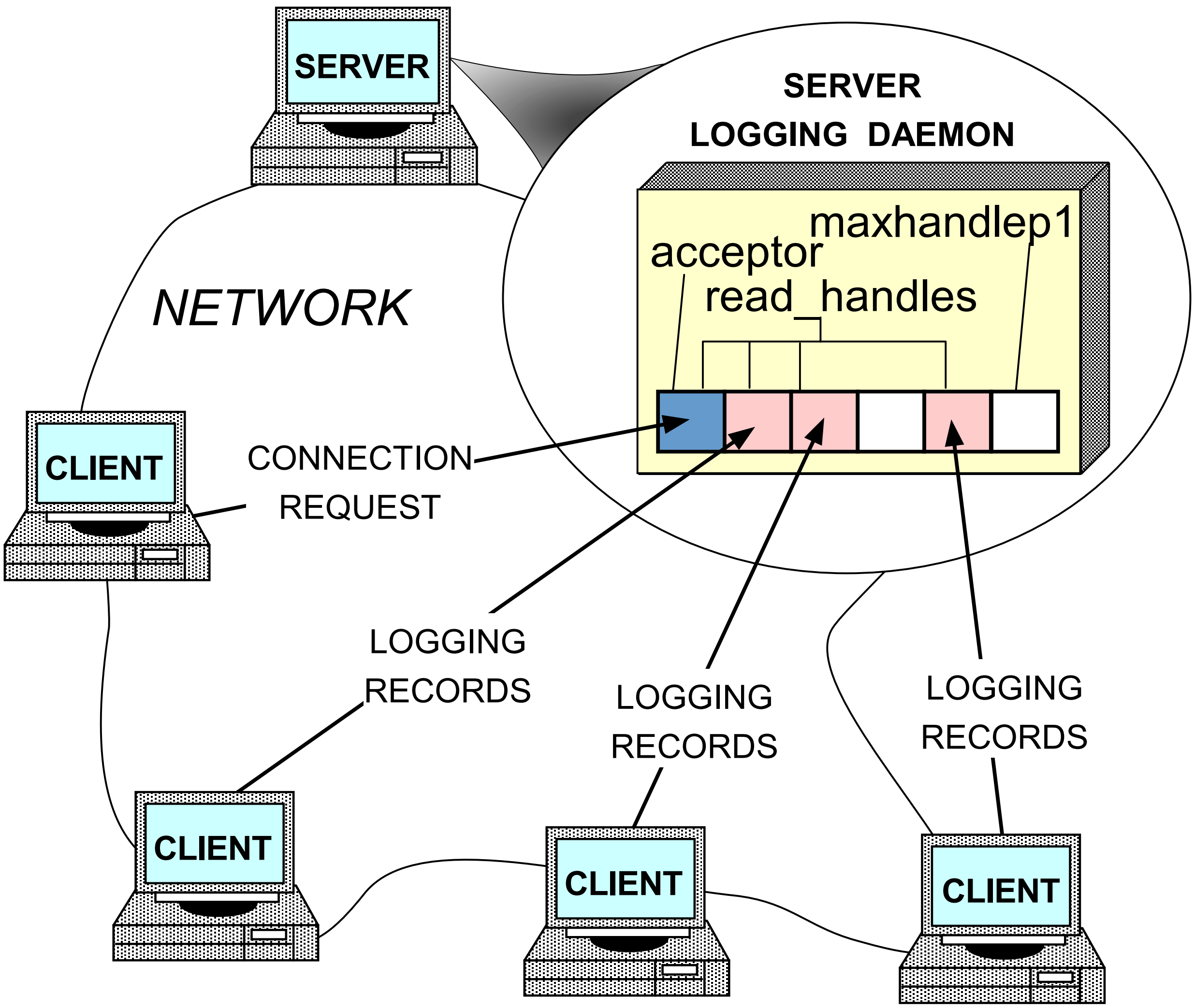
Typical algorithmic pseudo-code for networked logging server:

```
void logging_server (void) {
  initialize acceptor endpoint

  loop forever {
    wait for events
    handle data events
    handle connection events
  }
}
```

The “grand mistake:”

- Avoid the temptation to “step-wise refine” this algorithmically decomposed pseudo-code directly into the detailed design and implementation of the logging server!

The `select()`-based Logging Server Implementation



Serializes server processing at `select()` demuxing level

Conventional Logging Server Implementation

Note the excessive amount of detail required to program at the socket level...

```
// Main program
static const int PORT = 10000;

typedef u_long COUNTER;
typedef int HANDLE;

// Counts the # of logging records processed
static COUNTER request_count;

// Acceptor-mode socket handle
static HANDLE acceptor;

// Highest active handle number, plus 1
static HANDLE maxhp1;

// Set of currently active handles
static fd_set activity_handles;

// Scratch copy of activity_handles
static fd_set ready_handles;
```

Main Event Loop of Logging Server

```
int main (int argc, char *argv[])
{
  initialize_acceptor
    (argc > 1 ? atoi (argv[1]) : PORT);

  // Loop forever performing logging
  // server processing.

  for (;;) {
    // struct assignment.
    ready_handles = activity_handles;

    // Wait for client I/O events.
    select (maxhp1, &ready_handles, 0, 0, 0);

    // First receive pending logging records.
    handle_data ();

    // Then accept pending connections.
    handle_connections ();
  }
}
```

Initialize Acceptor Socket

```
static void initialize_acceptor (u_short port)
{
  struct sockaddr_in saddr;

  // Create a local endpoint of communication.
  acceptor = socket (PF_INET, SOCK_STREAM, 0);

  // Set up the address info. to become server.
  memset ((void *) &saddr, 0, sizeof saddr);
  saddr.sin_family = AF_INET;
  saddr.sin_port = htons (port);
  saddr.sin_addr.s_addr = htonl (INADDR_ANY);

  // Associate address with endpoint
  bind (acceptor,
       (struct sockaddr *) &saddr,
        sizeof saddr);

  // Make endpoint listen for connection requests.
  listen (acceptor, 5);

  // Initialize handle sets.
  FD_ZERO (&ready_handles);
  FD_ZERO (&activity_handles);
  FD_SET (acceptor, &activity_handles);
  maxhp1 = acceptor + 1;
}
```

Handle Data Processing

```
static void handle_data (void) {
  // acceptor + 1 is the lowest client handle

  for (HANDLE h = acceptor + 1; h < maxhp1; h++)
    if (FD_ISSET (h, &ready_handles)) {
      ssize_t n = handle_log_record (h, 1);

      // Guaranteed not to block in this case!
      if (n > 0)
        ++request_count;
        // Count the # of logging records
      else if (n == 0) {
        // Handle connection shutdown.
        FD_CLR (h, &activity_handles);
        close (h);
        if (h + 1 == maxhp1) {
          // Skip past unused handles
          while (!FD_ISSET (--h,
                            &activity_handles))
            continue;
          maxhp1 = h + 1;
        }
      }
    }
}
```

Receive and Process Logging Records

```
static ssize_t handle_log_record (HANDLE in_h,
                                  HANDLE out_h) {
  ssize_t n;
  size_t len;
  Log_Record lr;

  // The first recv reads the length (stored as a
  // fixed-size integer) of adjacent logging record.

  n = recv (in_h, (char *) &len, sizeof len, 0);
  if (n <= 0) return n;
  len = ntohl (len); // Convert byte-ordering

  // The second recv then reads <len> bytes to
  // obtain the actual record.
  for (size_t nread = 0; nread < len; nread += n
    n = recv (in_h, ((char *) &lr) + nread,
                     len - nread, 0);
  // Decode and print record.
  decode_log_record (&lr);
  if (write (out_h, lr.buf, lr.size) == -1)
    return -1;
  else return 0;
}
```

Handle Connection Acceptance

```
static void handle_connections (void)
{
  if (FD_ISSET (acceptor, &ready_handles)) {
    static struct timeval poll_tv = {0, 0};
    HANDLE h;

    // Handle all pending connection requests
    // (note use of select's polling feature)

    do {
      // Beware of subtle bug(s) here...
      h = accept (acceptor, 0, 0);
      FD_SET (h, &activity_handles);

      // Grow max. socket handle if necessary.
      if (h >= maxhp1)
        maxhp1 = h + 1;
    } while (select (acceptor + 1, &ready_handles,
                     0, 0, &poll_tv) == 1);
}
```

Conventional Client Logging Daemon Implementation

The `main()` method receives logging records from client applications and forwards them on to the logging server

```
int main (int argc, char *argv[])
{
  HANDLE stream = initialize_stream_endpoint
                    (argc > 1
                     ? atoi (argv[1])
                     : PORT);
  Log_Record lr;

  // Loop forever performing client
  // logging daemon processing.

  for (;;) {
    // ... get logging records from client
    //     application processes ...

    size_t size = htonl (lr.size);
    send (stream, &size, sizeof size);
    encode_log_record (&lr);
    send (stream, ((char *) &lr), sizeof lr);
  }
}
```

Client Connection Establishment

```
static HANDLE initialize_stream_endpoint
  (const char *host, u_short port)
{
  struct sockaddr_in saddr;

  // Create a local endpoint of communication.
  HANDLE stream = socket (PF_INET, SOCK_STREAM, 0);

  // Set up the address info. to become client.
  memset ((void *) &saddr, 0, sizeof saddr);
  saddr.sin_family = AF_INET;
  saddr.sin_port = htons (port);
  hostent *hp = gethostbyname (host);
  memcpy ((void *) &saddr,
          htonl (hp->h_addr),
          hp->h_length);

  // Associate address with endpoint
  connect (stream,
           (struct sockaddr *) &saddr,
           sizeof saddr);
  return stream;
}
```

Limitations with Algorithmic Decomposition

Algorithmic decomposition tightly couples application-specific *functionality* and the following configuration-related characteristics:

- **Application Structure**
  - The number of services per process
  - Time when services are configured into a process
- **Communication and Demultiplexing Mechanisms**
  - The underlying IPC mechanisms that communicate with other participating clients and servers
  - Event demultiplexing and event handler dispatching mechanisms
- **Concurrency and Synchronization Model**
  - The process and/or thread architecture that executes service(s) at run-time

Overcoming Limitations via OO

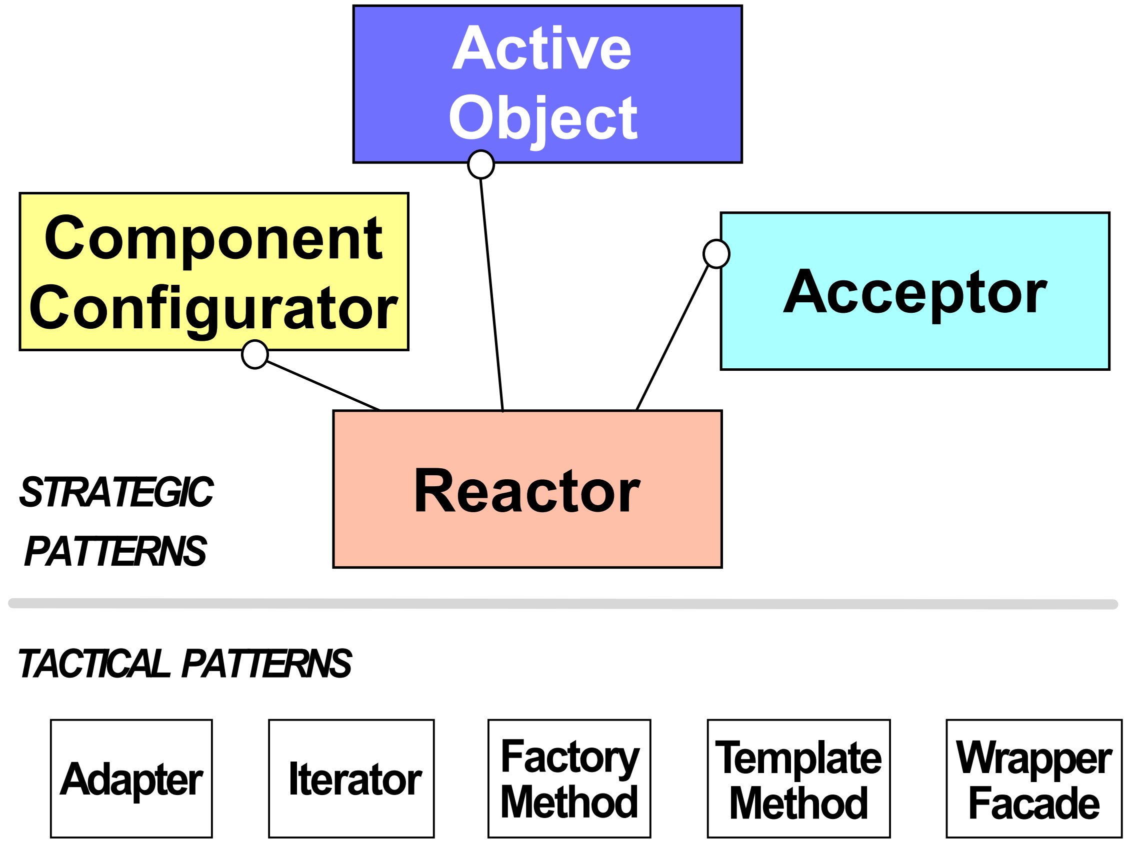
- The algorithmic decomposition illustrated above specifies *many* low-level details
  - Moreover, the excessive coupling impedes reusability, extensibility, and portability...
- In contrast, OO focuses on *application-specific* behavior, *e.g.*,

```
int Logging_Handler::handle_input (void)
{
  ssize_t n = handle_log_record (peer ().get_handle (),
                                 ACE_STDOUT);
  if (n > 0)
    ++request_count; // Count the # of logging records

  return n <= 0 ? -1 : 0;
}
```

OO Contributions to Software

- *Patterns* facilitate the large-scale reuse of software architecture
  - Even when reuse of algorithms, detailed designs, and implementations is not feasible
- *Frameworks* achieve large-scale design and code reuse
  - In contrast, traditional techniques focus on the *functions* and *algorithms* that solve particular requirements
- Note that patterns and frameworks are not unique to OO!
  - However, objects and classes are useful abstraction mechanisms

Patterns in the Networked Logging Server



- *Strategic* and *tactical* are relative to the *context* and *abstraction level*

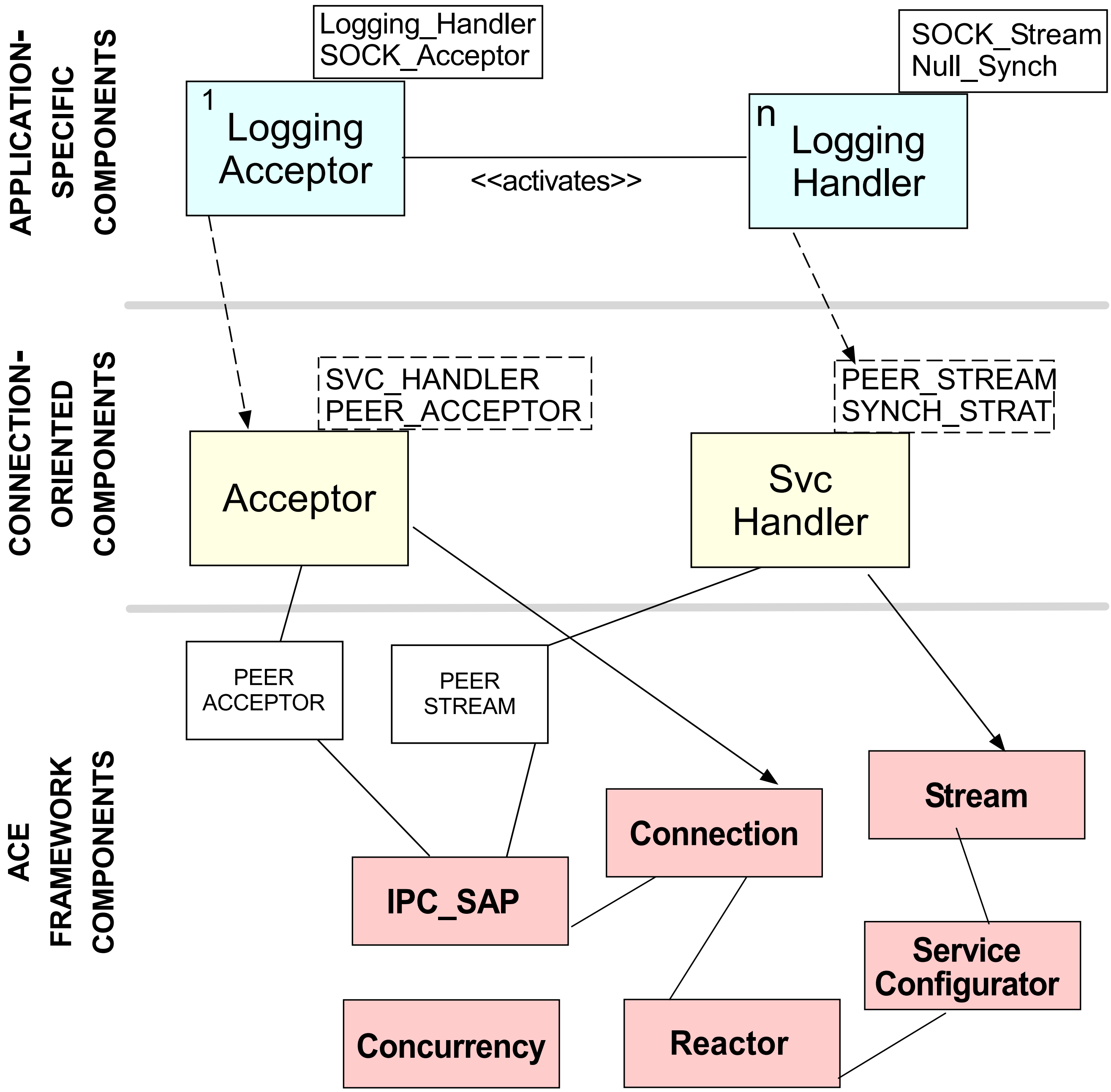
Summary of Pattern Intents

- *Wrapper Facade* $\rightarrow$ "Encapsulates the functions and data provided by existing non-OO APIs within more concise, robust, portable, maintainable, and cohesive OO class interfaces"
- *Reactor* $\rightarrow$ "Demultiplexes and dispatches requests that are delivered concurrently to an application by one or more clients"
- *Acceptor* $\rightarrow$ "Decouple the passive connection and initialization of a peer service in a distributed system from the processing performed once the peer service is connected and initialized"
- *Component Configurator* $\rightarrow$ "Decouples the implementation of services from the time when they are configured"
- *Active Object* $\rightarrow$ "Decouples method execution from method invocation to enhance concurrency and simplify synchronized access to an object that resides in its own thread of control"

Components in the OO Logging Server

- *Application-specific components*
  - Process logging records received from clients
- *Connection-oriented application components*
  - `ACE_Svc_Handler` (service handler)
    - Performs I/O-related tasks with clients
  - `ACE_Acceptor` factory
    - Passively accepts connection requests
    - Dynamically creates a service handler for each client and “activates” it
- *Application-independent ACE framework components*
  - Perform IPC, explicit dynamic linking, event demultiplexing, event handler dispatching, multi-threading, etc.

Class Diagram for OO Logging Server



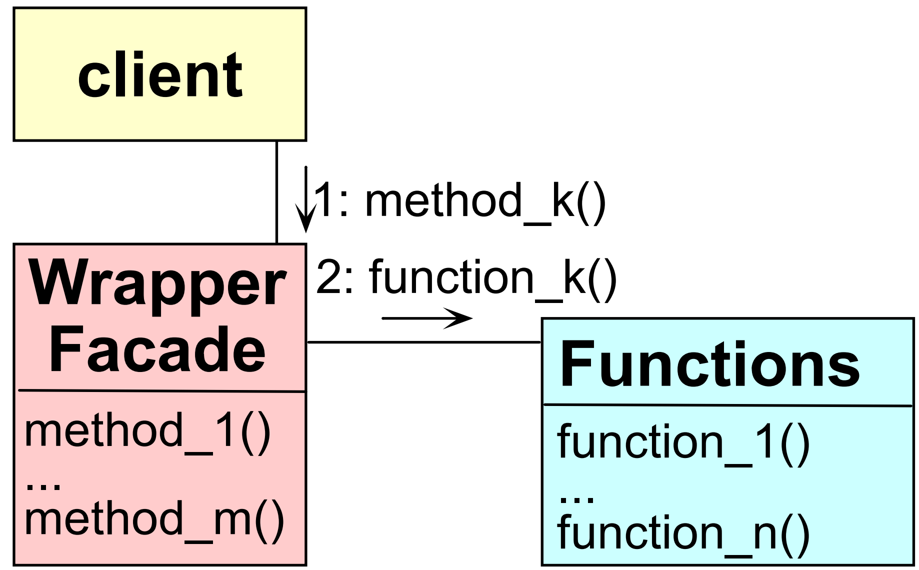
Addressing Robustness, Portability, and Maintainability Challenges

- Problem
  - Building distributed applications using low-level APIs is hard
- Forces
  - Low-level APIs are verbose, tedious, and error-prone to program
  - Low-level APIs are non-portable and non-maintainable
- Solution
  - Apply the *Wrapper Facade* pattern to encapsulate low-level functions and data structures

The Wrapper Facade Pattern

Intent

- *Encapsulates the functions and data provided by existing lower-level, non-OO APIs within more concise, robust, portable, maintainable, and cohesive higher-level OO class interfaces*

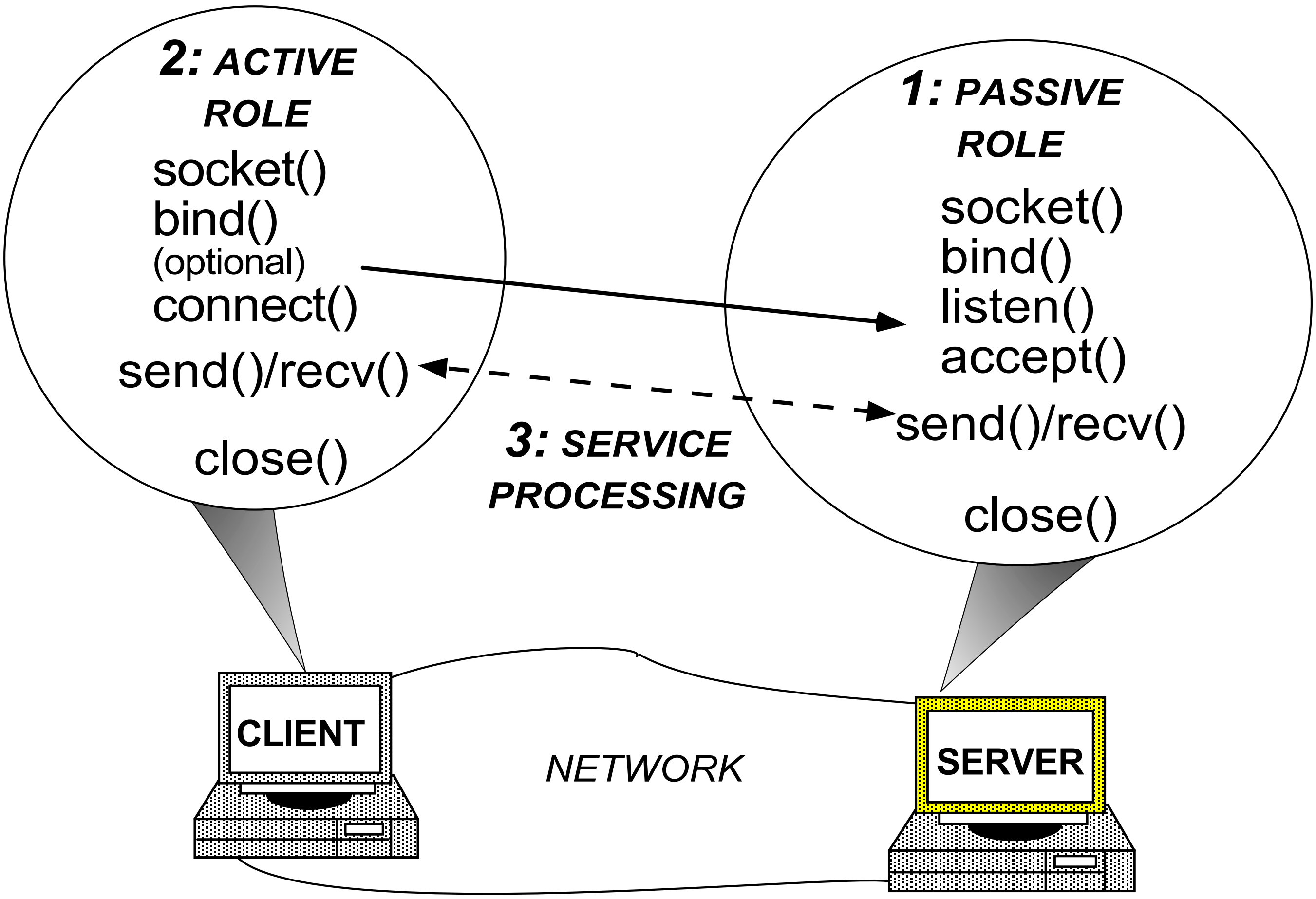


POSA2 (`www.cs.wustl.edu/~schmidt/POSA/`)

Forces Resolved

- Avoid tedious, error-prone, and non-portable system APIs
- Create cohesive abstractions

Motivating the Wrapper Facade Pattern: the Socket API



Sockets are the most common network programming API and are available on most OS platforms

Problem with Sockets: Lack of Type-safety

```
int buggy_echo_server (u_short port_num)
{ // Error checking omitted.
  sockaddr_in s_addr;
  int acceptor =
    socket (PF_UNIX, SOCK_DGRAM, 0);
  s_addr.sin_family = AF_INET;
  s_addr.sin_port = port_num;
  s_addr.sin_addr.s_addr = INADDR_ANY;
  bind (acceptor, (sockaddr *) &s_addr,
        sizeof s_addr);
  int handle = accept (acceptor, 0, 0);
  for (;;) {
    char buf[BUFSIZ];
    ssize_t n = read (acceptor, buf, sizeof buf);
    if (n <= 0) break;
    write (handle, buf, n);
  }
}
```

- I/O handles are not amenable to strong type checking at compile-time
- The adjacent code contains many subtle, common bugs

Problem with Sockets: Steep Learning Curve

Many socket/TLI API functions have complex semantics, *e.g.*:

- Multiple protocol families and address families
  - *e.g.*, TCP, UNIX domain, OSI, XNS, etc.
- Infrequently used features, *e.g.*:
  - Broadcasting/multicasting
  - Passing open file handles
  - Urgent data delivery and reception
  - Asynch I/O, non-blocking I/O, I/O-based and timer-based event multiplexing

Problem with Sockets: Portability

- Having multiple "standards," *i.e.*, sockets and TLI, makes portability difficult, *e.g.*,
  - May require conditional compilation
  - In addition, related functions are not included in POSIX standards
    - *e.g.*, `select()`, `WaitForMultipleObjects()`, and `poll()`
- Portability between UNIX and Windows Sockets is problematic, *e.g.*:
  - Header files
  - Error numbers
  - Handle vs. descriptor types
  - Shutdown semantics
  - I/O controls and socket options

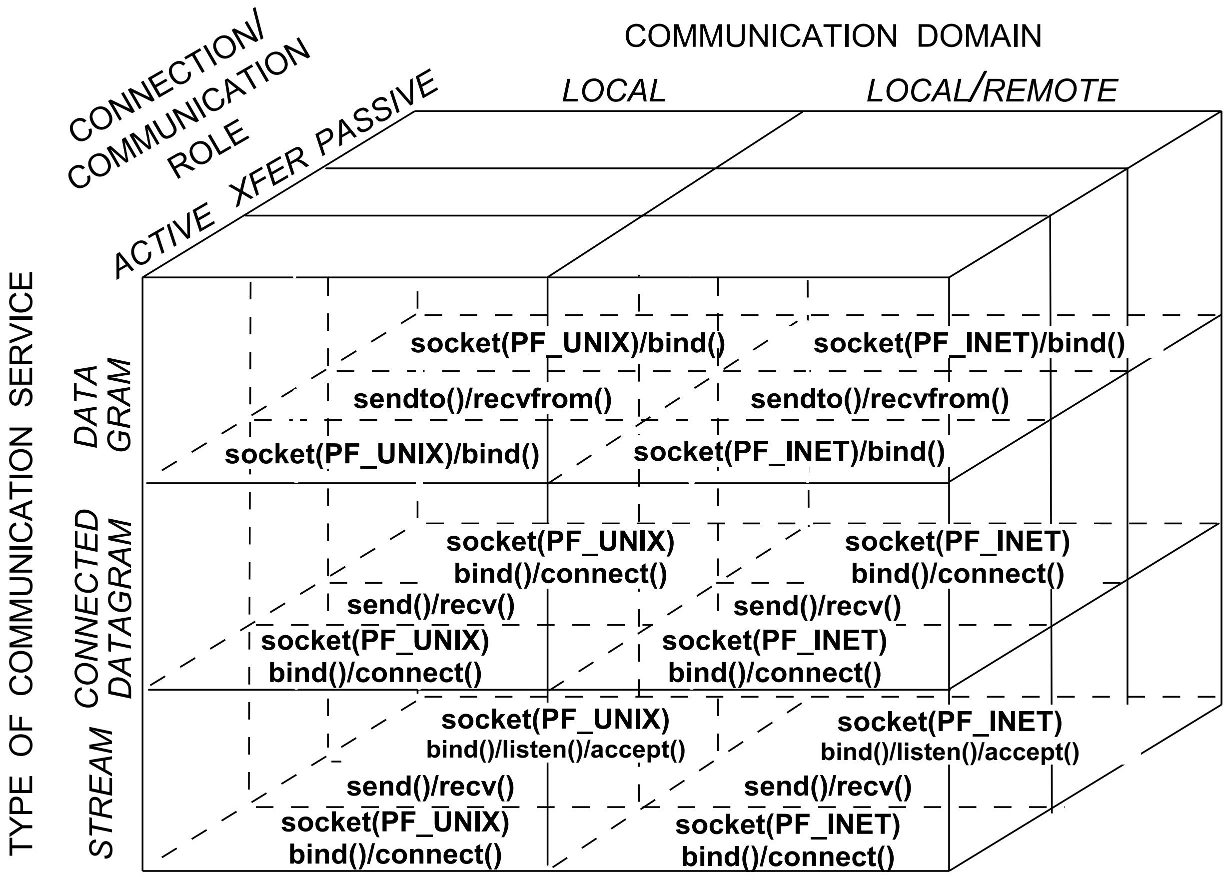
Problem with Sockets: Poorly Structured

socket() bind() connect() listen() accept() read() write() readv() writev() recv() send() recvfrom() sendto() recvmsg() sendmsg() setsockopt() getsockopt() getpeername() getsockname() gethostbyname() getservbyname()

Limitations

- Socket API is *linear* rather than *hierarchical*
- There is no consistency among names...
- Non-portable

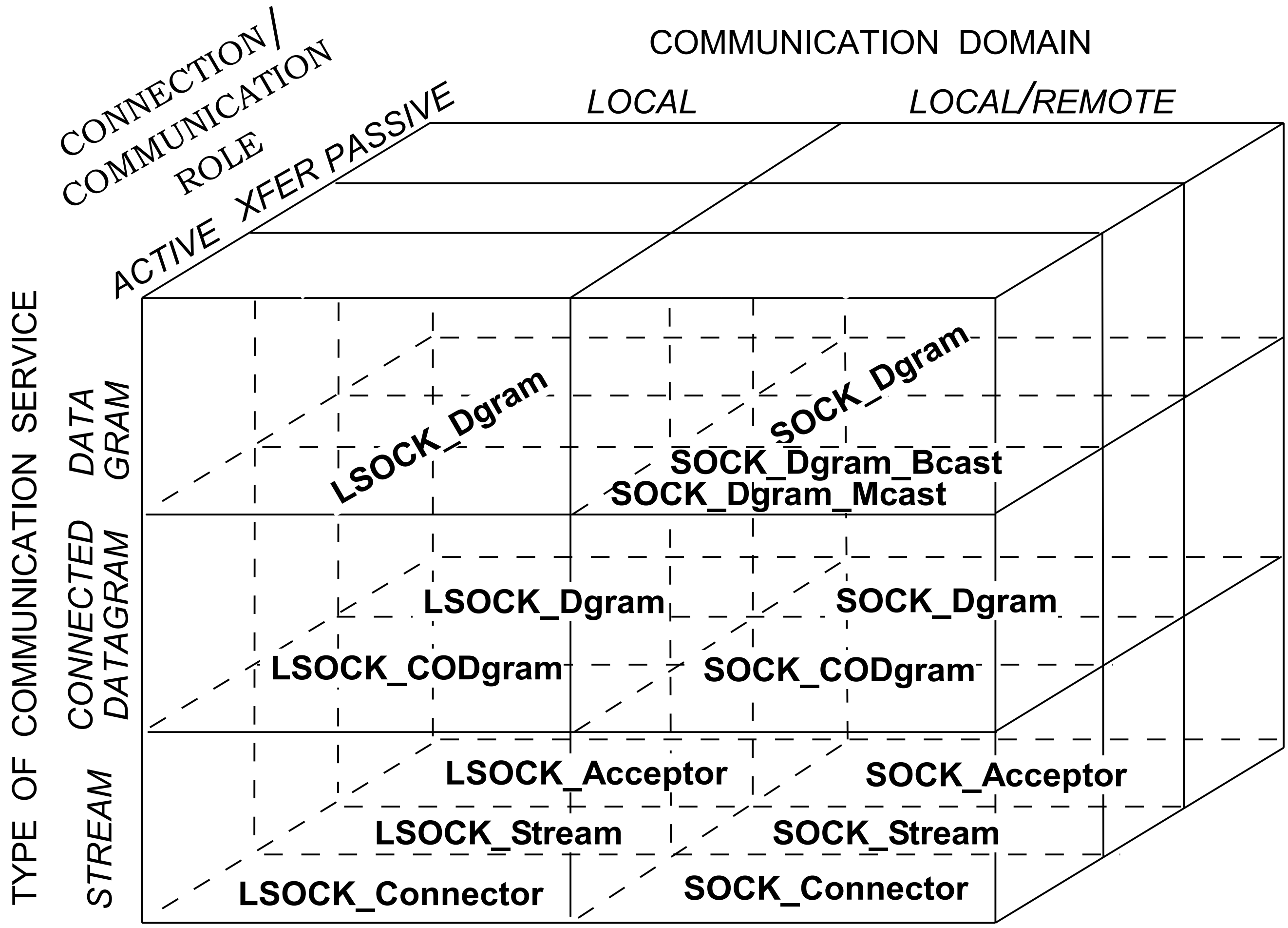
Socket Taxonomy



The Socket API can be classified along three dimensions

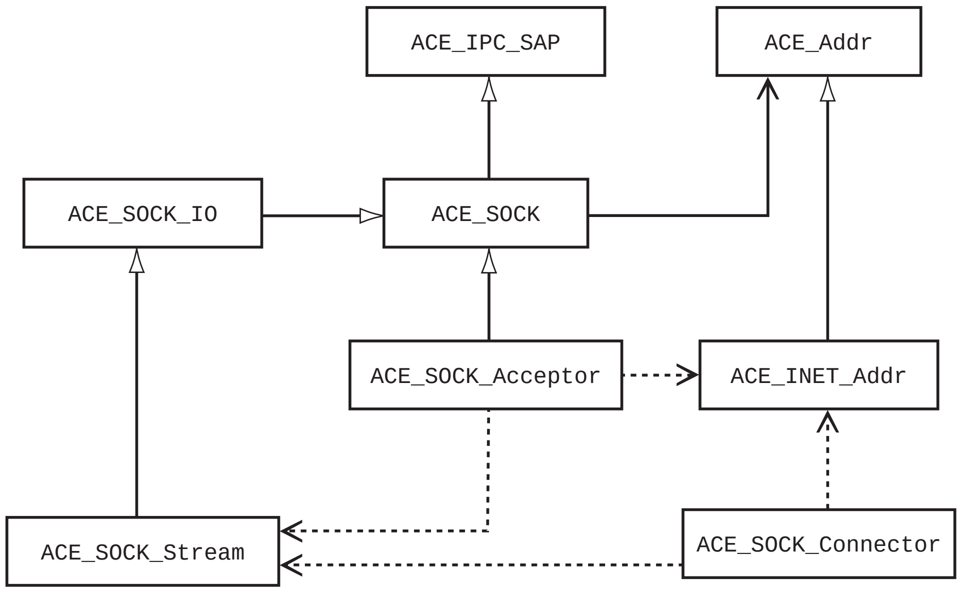
1. Connection role
2. Communication domain
3. Type of service

Solution: ACE Socket Wrapper Facades



The ACE C++ wrapper facades more explicitly model the key socket components using OO classes

The ACE Connection-Oriented Socket Wrapper Facades



Participants

- Passive and active connection factories
  - `ACE_SOCK_Acceptor` and `ACE_SOCK_Connector`
- Streaming classes
  - `ACE_SOCK_Stream` and `ACE_SOCK_IO`
- Addressing classes
  - `ACE_Addr` and `ACE_INET_Addr`

The ACE Connection-Oriented Socket Wrapper Facade Factories

```
class ACE_SOCK_Connector
{
public:
  // Traits
  typedef ACE_INET_Addr PEER_ADDR;
  typedef ACE_SOCK_Stream PEER_STREAM;

  int connect
    (ACE_SOCK_Stream &new_sap,
     const ACE_INET_Addr &raddr,
     ACE_Time_Value *timeout,
     const ACE_INET_Addr &laddr);
  // ...
};
```

```
class ACE_SOCK_Acceptor
  : public ACE_SOCK
{
public:
  // Traits
  typedef ACE_INET_Addr PEER_ADDR;
  typedef ACE_SOCK_Stream PEER_STREAM;

  ACE_SOCK_Acceptor (const ACE_INET_Addr &);
  int open (const ACE_INET_Addr &addr);
  int accept
    (ACE_SOCK_Stream &new_sap,
     ACE_INET_Addr *,
     ACE_Time_Value *);
  //...
};
```

ACE Connection-Oriented Socket Wrapper Facade Streaming and Addressing Classes

```
class ACE_SOCK_Stream
  : public ACE_SOCK {
public:
  // Trait.
  typedef ACE_INET_Addr PEER_ADDR;
  ssize_t send (const void *buf,
                int n);
  ssize_t recv (void *buf,
                int n);
  ssize_t send_n (const void *buf,
                  int n);
  ssize_t sendv_n (const iovec *iov,
                   int n);
  ssize_t recv_n (void *buf, int n);
  int close (void);
  // ...
};
```

```
class ACE_INET_Addr
  : public ACE_Addr
{
public:
  ACE_INET_Addr (u_short port,
                 const char host[]);
  u_short get_port_number (void);
  ACE_UINT_32 get_ip_addr (void);
  // ...
};
```

Design Interlude: Motivating the Socket Wrapper Facade Structure

- Q: *Why decouple the `ACE_SOCK_Acceptor` and the `ACE_SOCK_Connector` from `ACE_SOCK_Stream`?*
- A: For the same reasons that `ACE_Acceptor` and `ACE_Connector` are decoupled from `ACE_Svc_Handler`, *e.g.*,
  - An `ACE_SOCK_Stream` is only responsible for data transfer
    - Regardless of whether the connection is established passively or actively
  - This ensures that the `ACE_SOCK*` components aren't used incorrectly...
    - *e.g.*, you can't accidentally `read()` or `write()` on `ACE_SOCK_Connectors` or `ACE_SOCK_Acceptors`, etc.

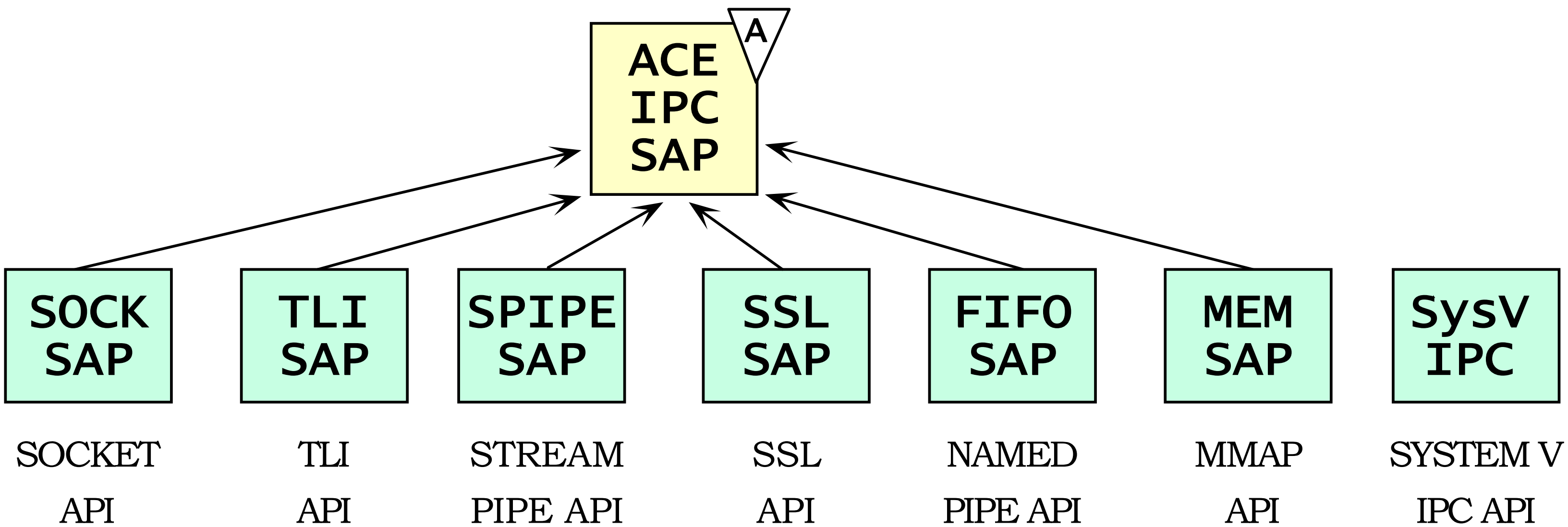
An Echo Server Written using ACE C++ Socket Wrapper Facades

```
int echo_server (u_short port_num)
{
  // Local server address.
  ACE_INET_Addr my_addr (port_num);

  // Initialize the acceptor mode server.
  ACE_SOCK_Acceptor acceptor (my_addr);

  // Data transfer object.
  ACE_SOCK_Stream new_stream;

  // Accept a new connection.
  acceptor.accept (new_stream);

  for (;;) {
    char buf[BUFSIZ];
    // Error caught at compile time!
    ssize_t n =
      acceptor.recv (buf, sizeof buf);
    new_stream.send_n (buf, n);
  }
}
```

A Generic Version of the Echo Server

```
template <class ACCEPTOR>
int echo_server (u_short port)
{
  // Local server address (note traits).
  typename
  ACCEPTOR::PEER_ADDR my_addr (port);

  // Initialize the acceptor mode server.
  ACCEPTOR acceptor (my_addr);

  // Data transfer object (note traits).
  typename ACCEPTOR::PEER_STREAM stream;

  // Accept a new connection.
  acceptor.accept (stream);

  for (;;) {
    char buf[BUFSIZ];
    ssize_t n =
      stream.recv (buf, sizeof buf);
    stream.send_n (buf, n);
  }
}
```

Scope of the ACE IPC Wrapper Facades



C++NPv1 (`www.cs.wustl.edu/~schmidt/ACE/book1/`)

Using the Wrapper Facade Pattern for the Logging Server

Note we haven’t improved the overall design (yet)

```
// ... Same as before ...

// Acceptor-mode socket handle.
static ACE_SOCK_Acceptor acceptor;

// Set of currently active handles
static ACE_Handle_Set activity_handles;

// Scratch copy of activity_handles
static ACE_Handle_Set ready_handles;

static void initialize_acceptor (u_short port)
{
  // Set up address info. to become server.
  ACE_INET_Addr saddr (port);

  // Create a local endpoint of communication.
  acceptor.open (saddr);

  // Set the <SOCK_Acceptor> into non-blocking mode.
  acceptor.enable (ACE_NONBLOCK);

  activity_handles.set_bit (acceptor.get_handle ());
}
```

Main Event Loop of Logging Server

```
int main (int argc, char *argv[])
{
  initialize_acceptor
    (argc > 1 ? atoi (argv[1]) : PORT);

  // Loop forever performing logging
  // server processing.

  for (;;) {
    // object assignment.
    ready_handles = activity_handles;

    // Wait for client I/O events.
    ACE::select (int (maxhp1),
                 // calls operator fd_set *().
                 ready_handles);

    // First receive pending logging records.
    handle_data ();

    // Then accept pending connections.
    handle_connections ();
  }
}
```

Handling Connections and Data Processing

```
static void handle_connections (void) {
  if (ready_handles.is_set (acceptor.get_handle ())) {
    ACE_SOCK_Stream str;

    // Handle all pending connection requests.
    while (acceptor.accept (str) != -1)
      activity_handles.set_bit (str.get_handle ());
  }
}

static void handle_data (void) {
  ACE_HANDLE h;
  ACE_Handle_Set_Iterator iter (ready_handles);

  while ((h = iter ()) != ACE_INVALID_HANDLE) {
    ACE_SOCK_Stream str (h);
    ssize_t n = handle_log_record (str, ACE_STDOUT);
    if (n > 0) // Count # of logging records.
      ++request_count;
    else if (n == 0) {
      // Handle connection shutdown.
      activity_handles.clr_bit (h);
      s.close ();
    }
}
```

Receive and Process Logging Records

```
static ssize_t handle_log_record (ACE_SOCK_Stream s,
                                  ACE_HANDLE out_h)
  ACE_UINT_32 len;
  ACE_Log_Record lr;

  // The first recv reads the length (stored as a
  // fixed-size integer) of adjacent logging record.

  ssize_t n = s.recv_n ((char *) &len, sizeof len);
  if (n <= 0) return n;

  len = ntohl (len); // Convert byte-ordering
  // Perform sanity check!
  if (len > sizeof (lr)) return -1;

  // The second recv then reads <len> bytes to
  // obtain the actual record.
  s.recv_n ((char *) &lr, sizeof lr);

  // Decode and print record.
  decode_log_record (&lr);
  if (ACE_OS::write (out_h, lr.buf, lr.size) == -1)
    return -1;
  else return 0;
}
```

OO Client Logging Daemon Implementation

```
int main (int argc, char *argv[])
{
  ACE_SOCK_Stream stream;
  ACE_SOCK_Connector con;   // Establish connection.
  con.connect (stream, ACE_INET_Addr (argc > 1
                    ? atoi (argv[1]) : PORT));
  ACE_Log_Record lr;

  // Loop forever performing client
  // logging daemon processing.
  for (;;) {
    // ... get logging records from client
    //     application processes ...
    ACE_UINT_32 size = lr.size;
    lr.size = htonl (lr.size);
    encode_log_record (&lr);
    iovec iov[2];
    iov[0].iov_len = sizeof (ACE_UINT_32);
    iov[0].iov_base = &lr.size;
    iov[1].iov_len = size;
    iov[1].iov_base = &lr;
    // Uses writev(2);
    stream.sendv_n (iov, 2);
  }
}
```

Evaluating the Wrapper Facade Solution

Benefits

- More concise
- More robust
- More portable
- More maintainable
- More efficient

Liabilities

- Potentially more indirection
- Additional learning curve
- Still haven't solved the overall design problem
  - *i.e.*, the overall design is still based on step-wise refinement of functions

ACE C++ Wrapper Facade Design Refactoring Principles

- Enforce typesafety at compile-time
- Allow controlled violations of typesafety
- Simplify for the common case
- Replace one-dimensional interfaces with hierarchical class categories
- Enhance portability with parameterized types
- Inline performance critical methods
- Define auxiliary classes to hide error-prone details

Enforce Typesafety at Compile-Time

Sockets cannot detect certain errors at compile-time, *e.g.*,

```
int acceptor = socket (PF_INET, SOCK_STREAM, 0);
// ...
bind (acceptor, ...); // Bind address.
listen (acceptor); // Make a acceptor-mode socket.
HANDLE n_sd = accept (acceptor, 0, 0);
// Error not detected until run-time.
read (acceptor, buf, sizeof buf);
```

ACE enforces type-safety at compile-time via *factories*, *e.g.*:

```
ACE_SOCK_Acceptor acceptor (port);

// Error: recv() not a method of <ACE_SOCK_Acceptor>.
acceptor.recv (buf, sizeof buf);
```

Allow Controlled Violations of Typesafety

Make it easy to use the C++ Socket wrapper facades correctly, hard to use it incorrectly, but not impossible to use it in ways the class designers did not anticipate

- *e.g.*, it may be necessary to retrieve the underlying socket handle:

```
ACE_SOCK_Acceptor acceptor;

// ...

ACE_Handle_Set ready_handles;

// ...

if (ready_handles.is_set (acceptor.get_handle ())
  ACE::select (acceptor.get_handle () + 1, ready_handles);
```

Supply Default Parameters

```
ACE_SOCK_Connector (ACE_SOCK_Stream &new_stream,
                    const ACE_Addr &remote_sap,
                    ACE_Time_Value *timeout = 0,
                    const ACE_Addr &local_sap = ACE_Addr::sap_any,
                    int protocol_family = PF_INET,
                    int protocol = 0);
```

The result is extremely concise for the common case:

```
ACE_SOCK_Stream stream;

// Compiler supplies default values.
ACE_SOCK_Connector con (stream, ACE_INET_Addr (port, host));
```

Define Parsimonious Interfaces

e.g., use LSOCK to pass socket handles:

```
ACE_LSOCK_Stream stream;
ACE_LSOCK_Acceptor acceptor ("/tmp/foo");

acceptor.accept (stream);
stream.send_handle (stream.get_handle ());
```

versus the less parsimonious BSD 4.3 socket code

```
ACE_LSOCK::send_handle
    (const ACE_HANDLE sd) const {
  u_char a[2]; iovec iov; msghdr send_msg;

  a[0] = 0xab, a[1] = 0xcd;
  iov.iov_base = (char *) a;
  iov.iov_len = sizeof a;
  send_msg.msg_iov = &iov;
  send_msg.msg_iovlen = 1;
  send_msg.msg_name = (char *) 0;
  send_msg.msg_namelen = 0;
  send_msg.msg_accrights = (char *) &sd;
  send_msg.msg_accrightslen = sizeof sd;
  return sendmsg (this->get_handle (),
                  &send_msg, 0);
```

Note that SVR4 and BSD 4.4 APIs are different than BSD 4.3!

Combine Multiple Operations into One Operation

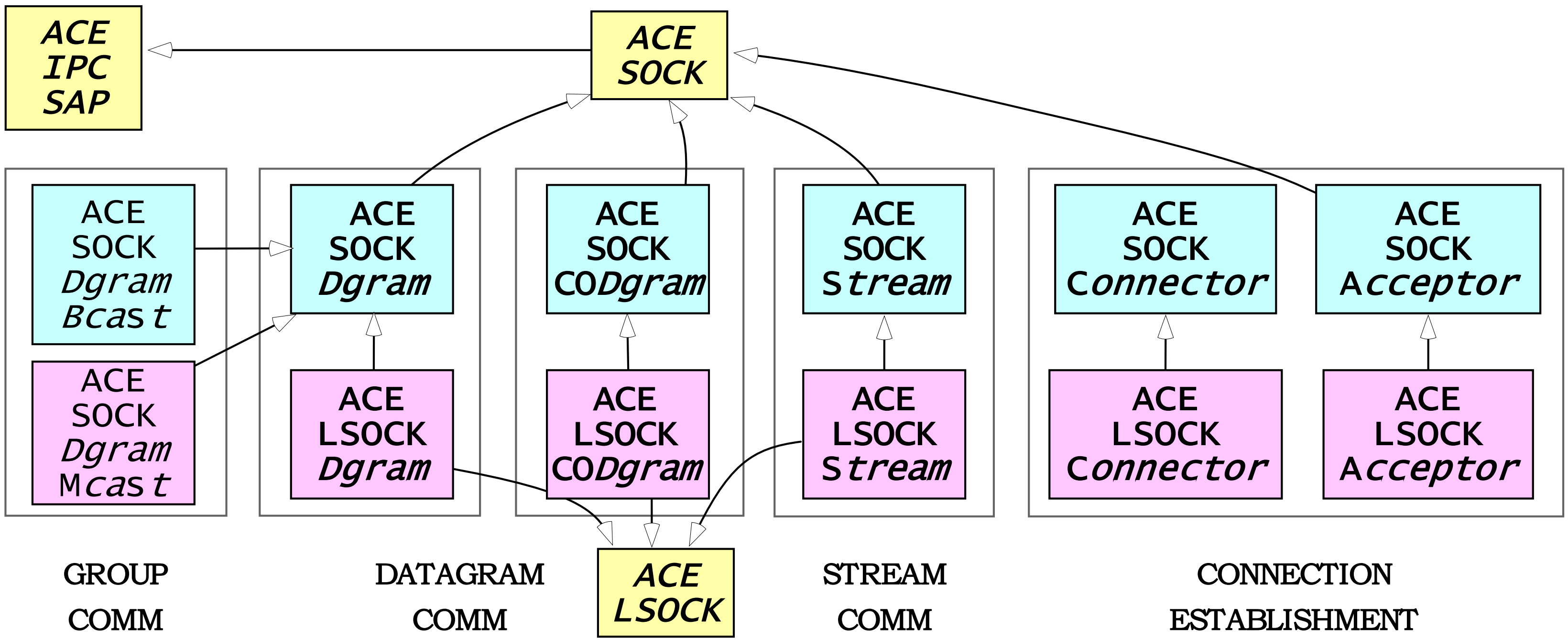
Creating a conventional acceptor-mode socket requires multiple calls:

```
int acceptor = socket (PF_INET, SOCK_STREAM, 0);
sockaddr_in addr;
memset (&addr, 0, sizeof addr);
addr.sin_family = AF_INET;
addr.sin_port = htons (port);
addr.sin_addr.s_addr = INADDR_ANY;
bind (acceptor, &addr, addr_len);
listen (acceptor);
// ...
```

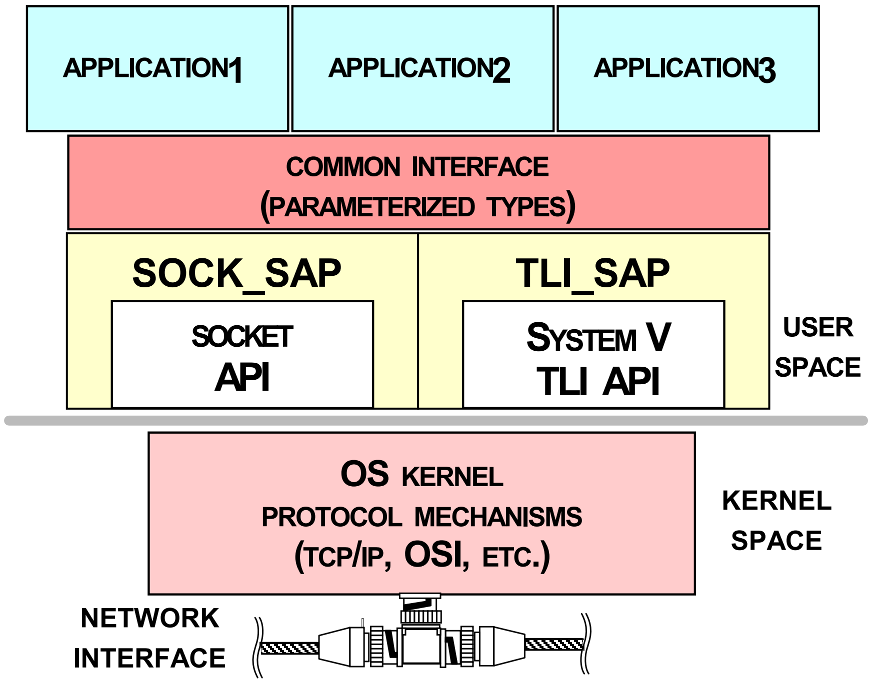
`ACE_SOCK_Acceptor` combines this into a single operation:

```
ACE_SOCK_Acceptor acceptor ((ACE_INET_Addr) port);
```

Create Hierarchical Class Categories



Enhance Portability with Parameterized Types




```
// Conditionally select IPC mechanism.
#if defined (USE_SOCKETS)
typedef ACE_SOCK_Acceptor PEER_ACCEPTOR;
#elif defined (USE_TLI)
typedef ACE_TLI_Acceptor PEER_ACCEPTOR;
#endif // USE_SOCKETS.

int main (void)
{
  // ...
  // Invoke with appropriate
  // network programming interface.
  echo_server<PEER_ACCEPTOR> (port);
}
```

Switching wholesale between sockets and TLI simply requires instantiating a different ACE C++ wrapper facade

Inline Performance Critical Methods

Inlining is time and space efficient since key methods are very short:

```
class ACE_SOCK_Stream : public ACE_SOCK
{
public:
  ssize_t send (const void *buf, size_t n)
  {
    return ACE_OS::send (this->get_handle (), buf, n);
  }

  ssize_t recv (void *buf, size_t n)
  {
    return ACE_OS::recv (this->get_handle (), buf, n);
  }
};
```

Define Auxiliary Classes to Hide Error-Prone Details

Standard C socket addressing is awkward and error-prone

- *e.g.*, easy to neglect to zero-out a `sockaddr_in` or convert port numbers to network byte-order, etc.

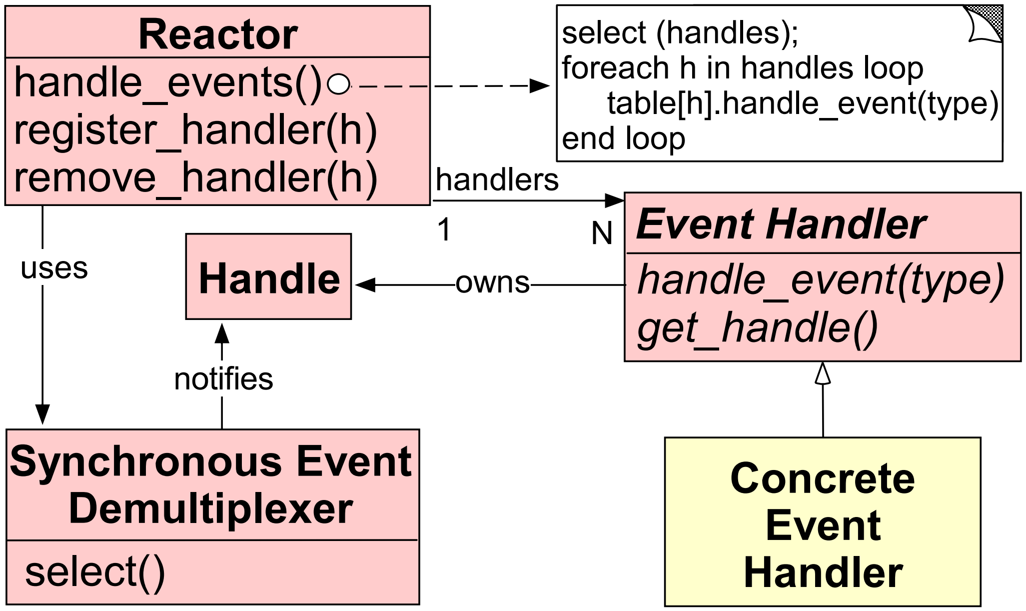
ACE C++ Socket wrapper facades define classes to handle details

```
class ACE_INET_Addr : public ACE_Addr { public:
  ACE_INET_Addr (u_short port, long ip_addr = 0) {
    memset (&this->inet_addr_, 0, sizeof this->inet_addr_);
    this->inet_addr_.sin_family = AF_INET;
    this->inet_addr_.sin_port = htons (port);
    memcpy (&this->inet_addr_.sin_addr, &ip_addr, sizeof ip_addr);
  }
  // ...
private:
  sockaddr_in inet_addr_;
};
```

Demultiplexing and Dispatching Events

- Problem
  - The logging server must process several different types of events simultaneously from different sources of events
- Forces
  - Multi-threading is not always available
  - Multi-threading is not always efficient
  - Multi-threading can be error-prone
  - Tightly coupling event demuxing with server-specific logic is inflexible
- Solution
  - Use the *Reactor* pattern to decouple event demuxing/dispatching from server-specific processing

The Reactor Pattern



`www.cs.wustl.edu/~schmidt/POSA/`

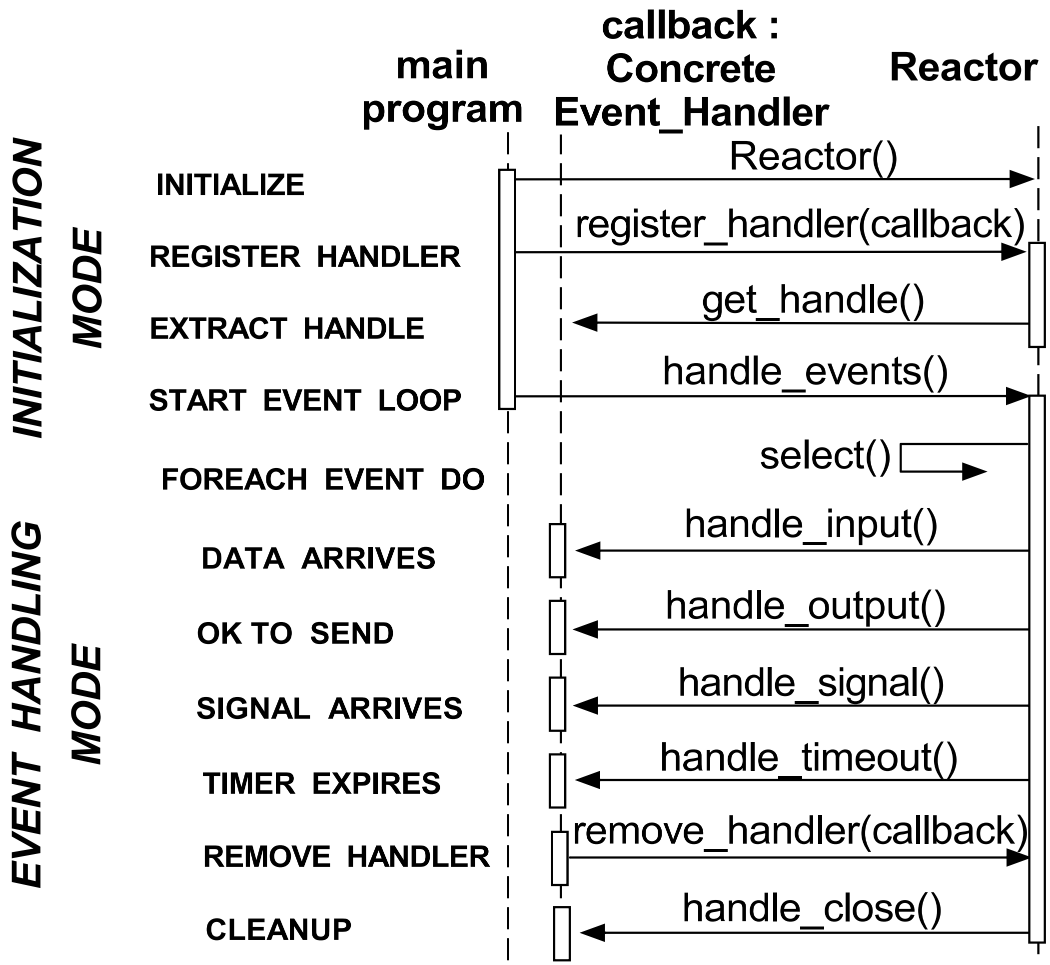
Intent

- *Demuxes & dispatches requests that are delievered concurrency to an application by one or more clients*

Forces Resolved

- Serially demux events *synchronously* & efficiently
- Extend applications without changing demuxing code

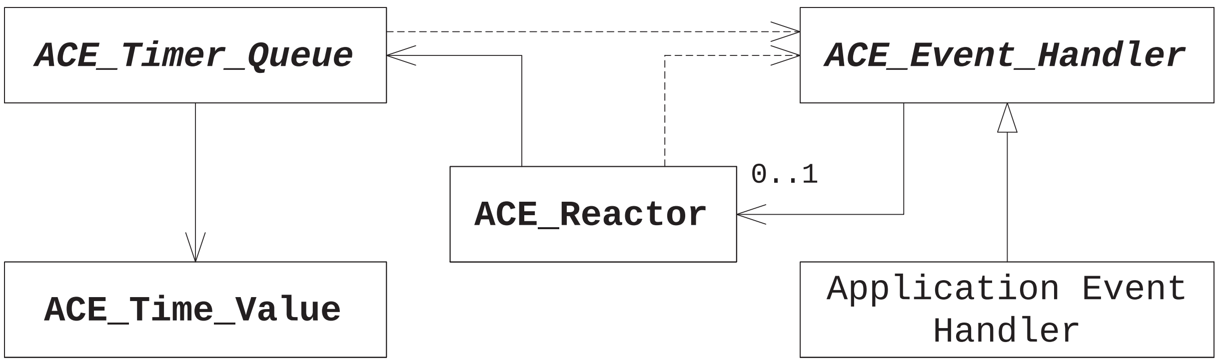
Collaboration in the Reactor Pattern



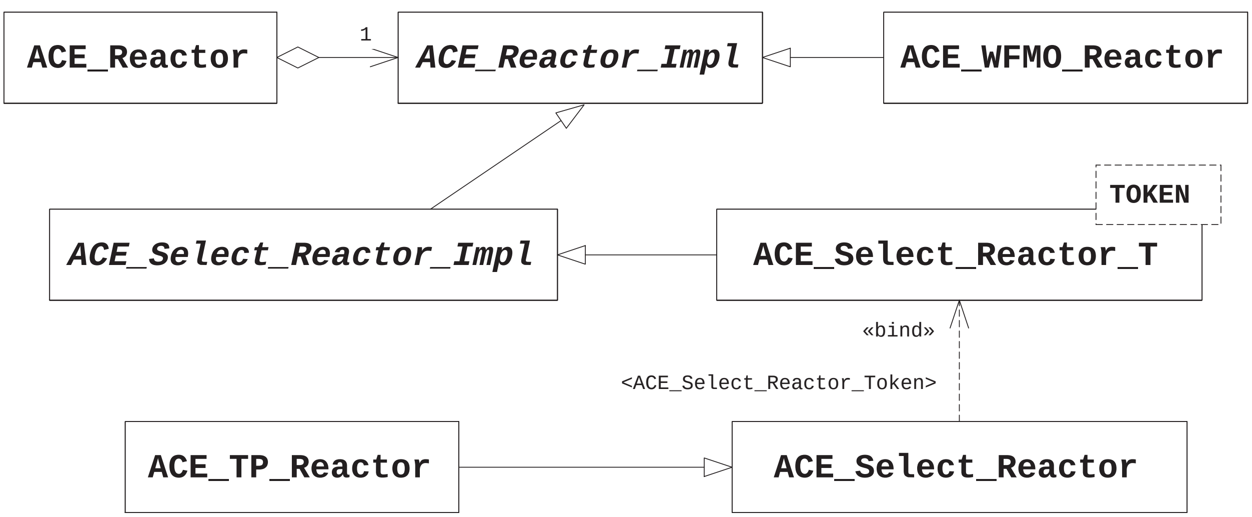
- Note *inversion of control*
- Also note how long-running event handlers can degrade quality of service since callbacks "steal" Reactor's thread of control...

Structure and Implementations of the ACE Reactor Framework

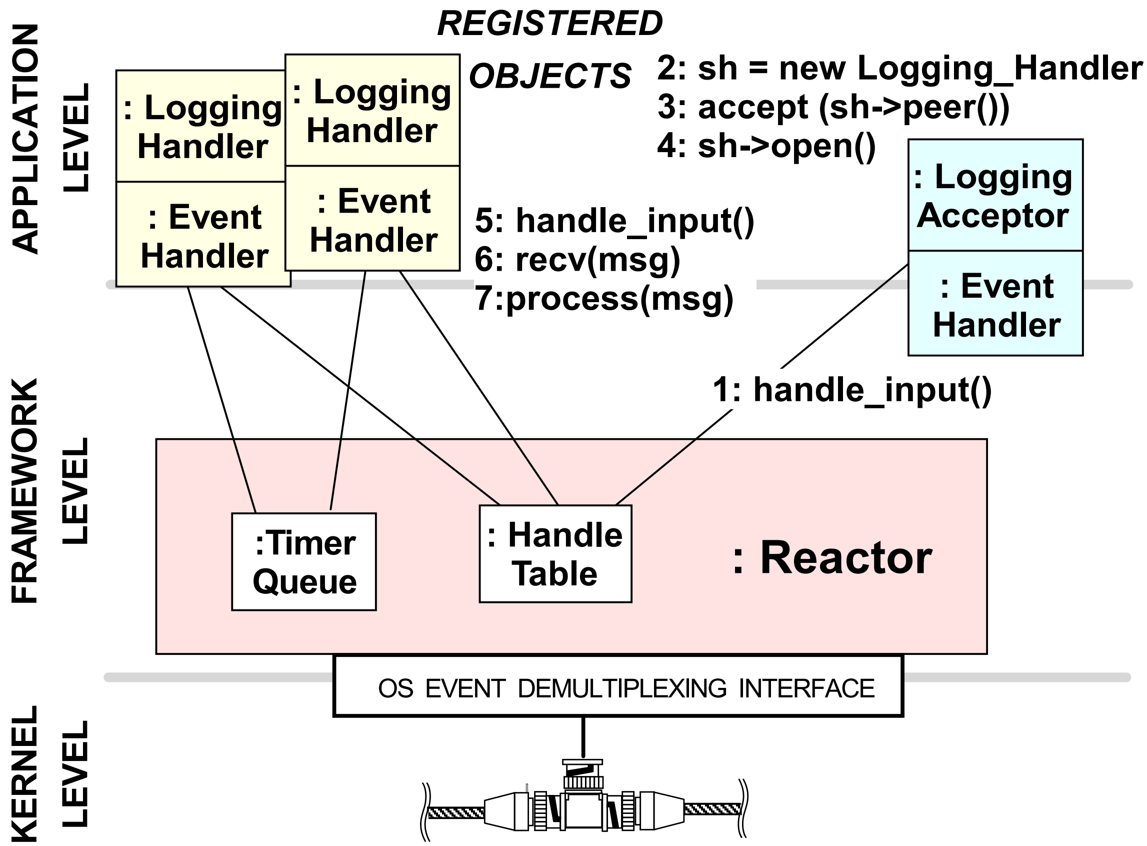
Reactor framework participants



Common Reactor implementations in ACE



Using the ACE Reactor Framework in the Logging Server



Benefits

- Straightforward to program
- Concurrency control is easy

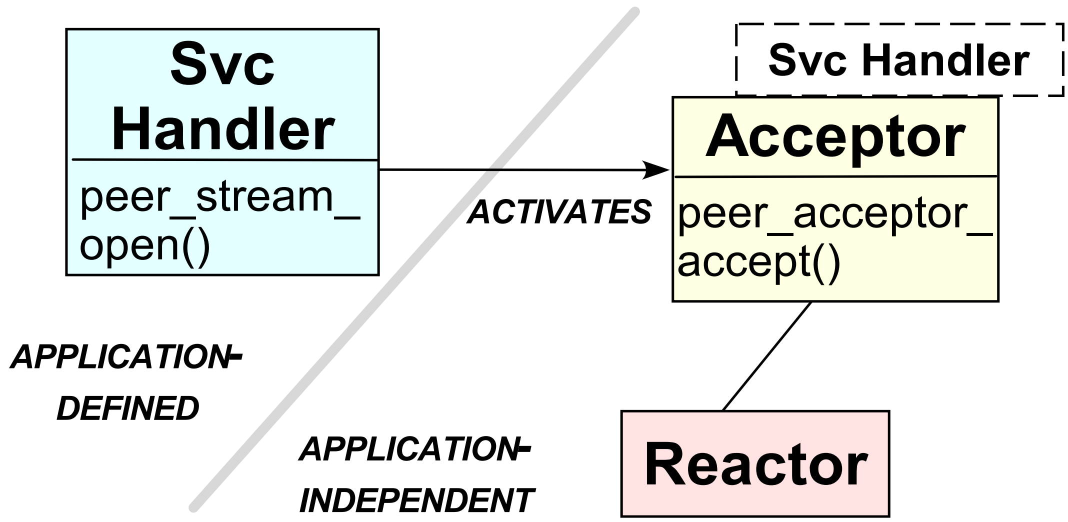
Liabilities

- Callbacks are “brittle”
- Can’t leverage multi-processors

Addressing Acceptor Endpoint Connection and Initialization Challenges

- Problem
  - The *communication* protocol used between applications is often orthogonal to its *connection establishment* and *service handler initialization* protocols
- Forces
  - Low-level connection APIs are error-prone and non-portable
  - Separating *initialization* from *processing* increases software reuse
- Solution
  - Use the *Acceptor* pattern to decouple passive connection establishment and connection handler initialization from the subsequent logging protocol

The Acceptor-Connector Pattern (Acceptor Role)



www.cs.wustl.edu/˜schmidt/POSA/

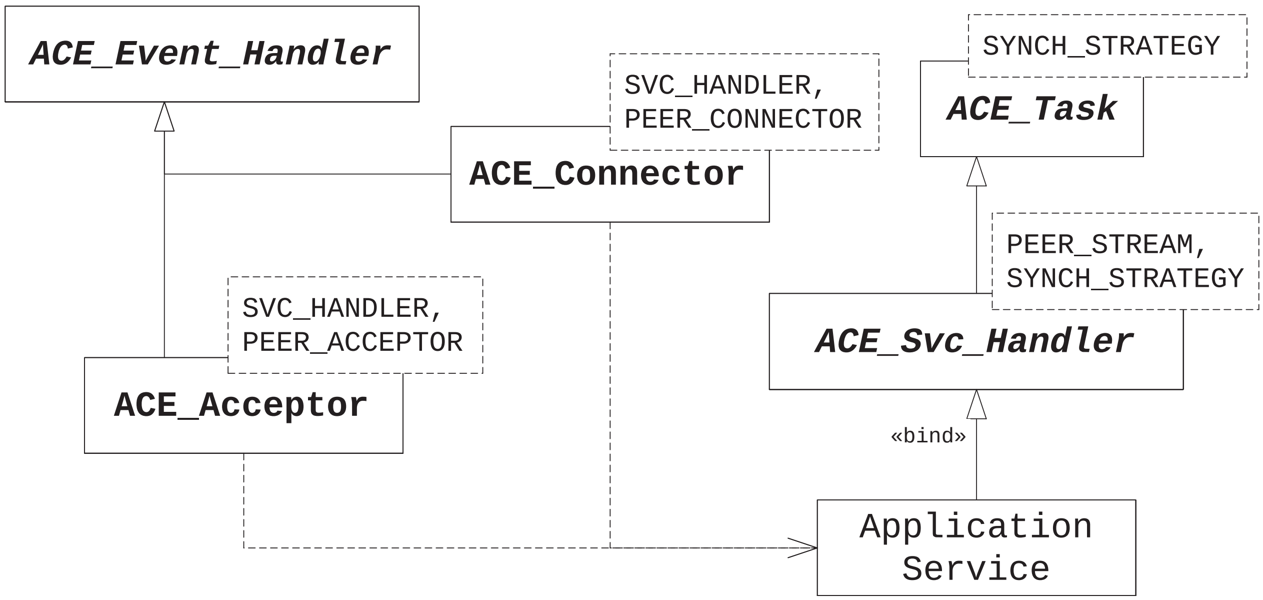
Intent of Acceptor Role

- *Decouple the passive connection and initialization of a peer service in a distributed system from the processing performed once the peer service is connected and initialized*

Forces resolved

- Reuse passive connection setup and service initialization code
- Ensure that acceptor-mode handles aren't used to read/write data

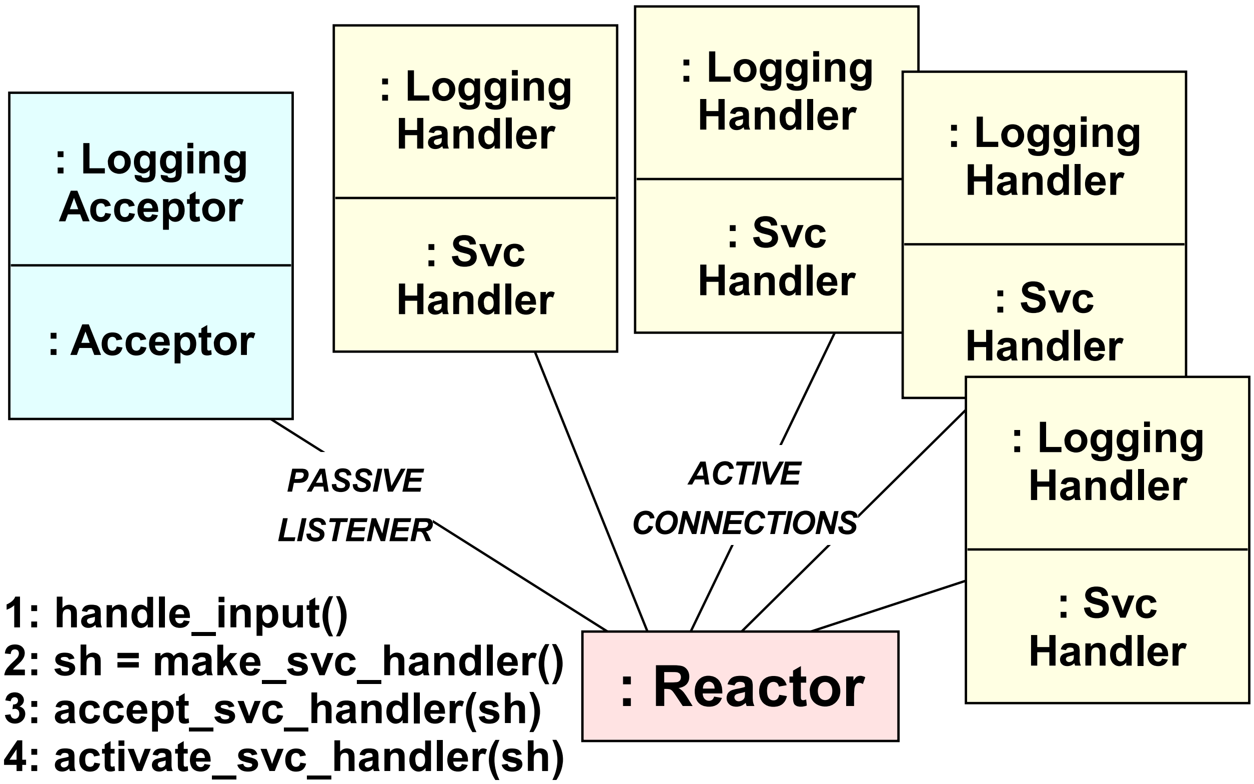
Structure of the ACE Acceptor-Connector Framework



Framework characteristics

- Uses C++ parameterized types to *strategize* IPC and service *aspects*
- Uses Template Method pattern to strategize creation, connection establishment, and concurrency policies

Using the ACE_Acceptor in the Logging Server



- The `ACE_Acceptor` is a *factory*
  - *i.e.*, it *creates*, *connects*, and *activates* an `ACE_Svc_Handler`
- There's often one `ACE_Acceptor` per-service/per-port

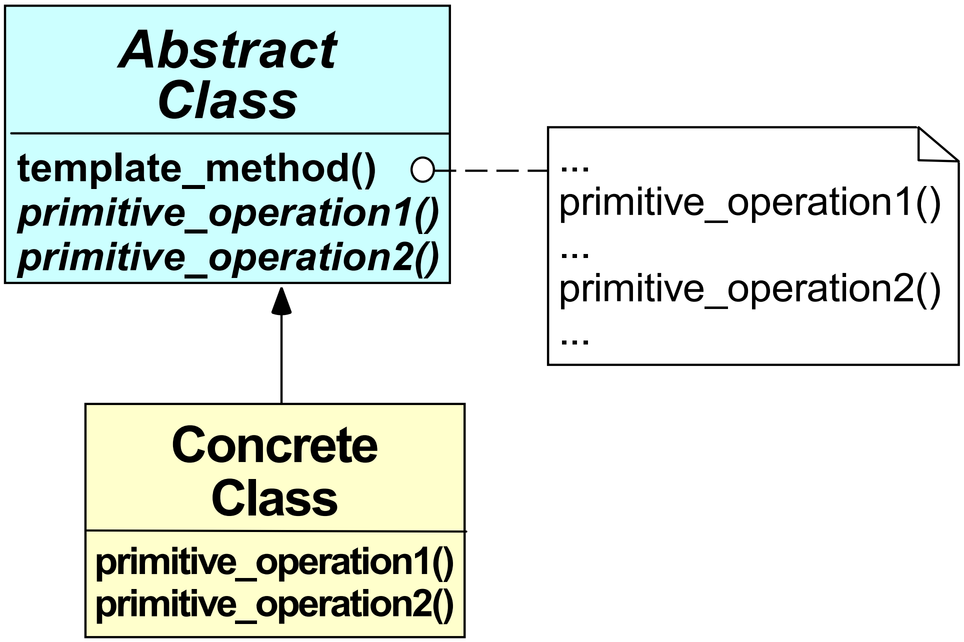
ACE_Acceptor Class Public Interface

```
template <class SVC_HANDLER, // Service aspect
          class PEER_ACCEPTOR> // IPC aspect
class ACE_Acceptor : public ACE_Service_Object
{
  // Inherits indirectly from <ACE_Event_Handler>
public:
    // Initialization.
  virtual int open
    (typename const PEER_ACCEPTOR::PEER_ADDR &,
     ACE_Reactor * = ACE_Reactor::instance ());
    // Template Method.
  virtual int handle_input (ACE_HANDLE);

protected:
    // Factory method creates a service handler.
  virtual SVC_HANDLER *make_svc_handler (void);
    // Accept a new connection.
  virtual int accept_svc_handler (SVC_HANDLER *);
    // Activate a service handler.
  virtual int activate_svc_handler (SVC_HANDLER *);

private:
    // Acceptor IPC connection strategy.
  PEER_ACCEPTOR peer_acceptor_;
};
```

ACE_Acceptor Class Implementation

```
// Shorthand names.
#define SH SVC_HANDLER
#define PA PEER_ACCEPTOR

// Template Method that creates, connects,
// and activates service handlers.

template <class SH, class PA> int
ACE_Acceptor<SH, PA>::handle_input (ACE_HANDLE)
{
  // Factory method that makes a service handler.

  SH *svc_handler = make_svc_handler ();

  // Accept the connection.

  accept_svc_handler (svc_handler);

  // Delegate control to the service handler.

  activate_svc_handler (svc_handler);
}
```

The Template Method Pattern

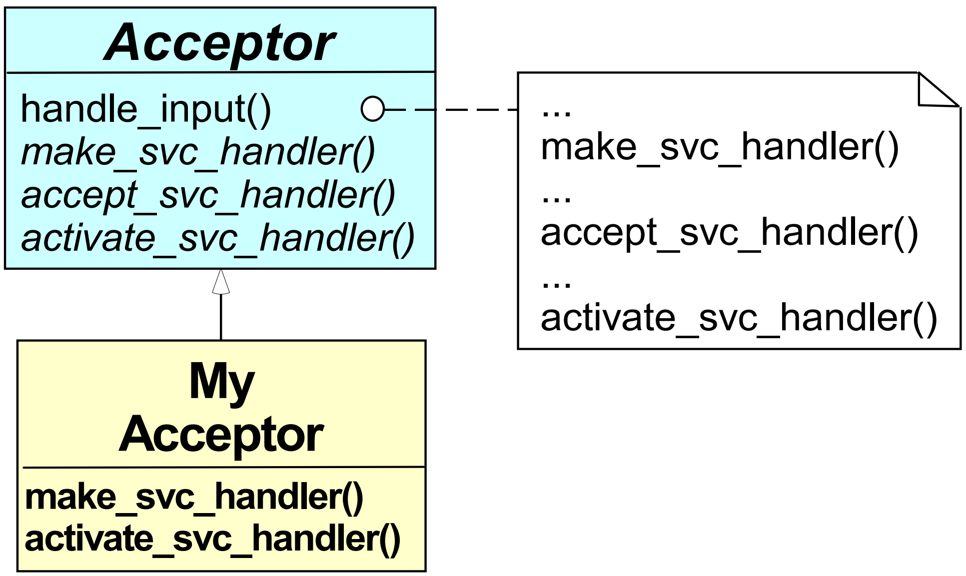


Intent

- *Define the skeleton of an algorithm in an operation, deferring some steps to subclasses*

Gamma et al., *Design Patterns: Elements of Reusable Object-Oriented Software* AW, ’94

Using the Template Method Pattern in the ACE Acceptor Implementation



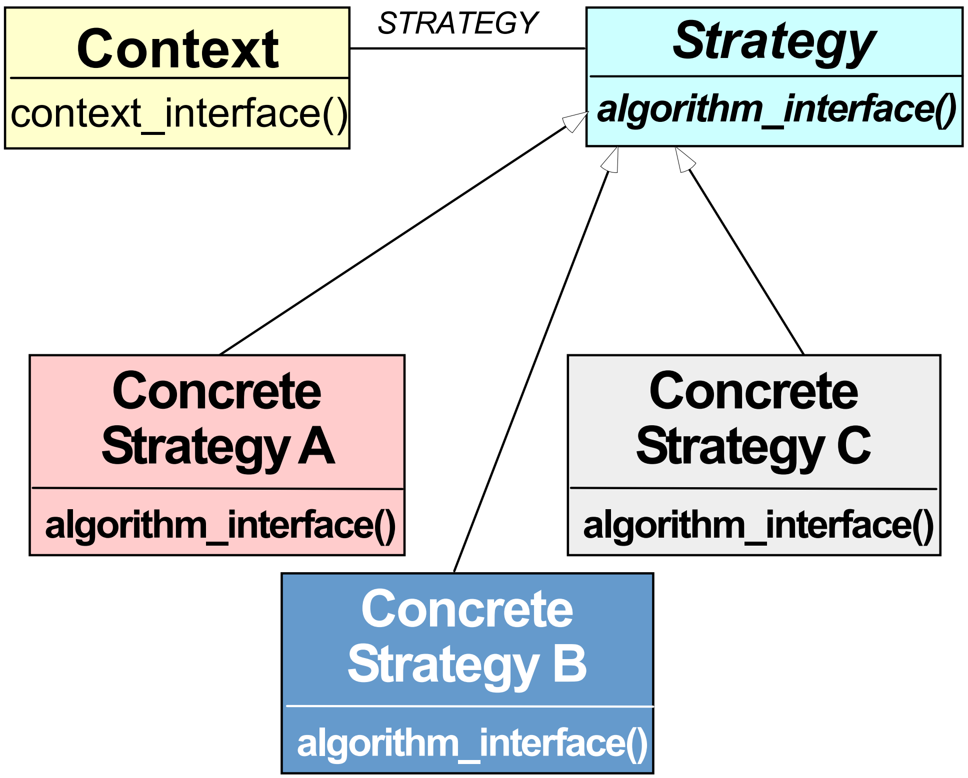
Benefits

- Straightforward to program via inheritance and dynamic binding

Liabilities

- Design is “brittle” and can cause “explosion” of subclasses due to “whitebox” design

The Strategy Pattern

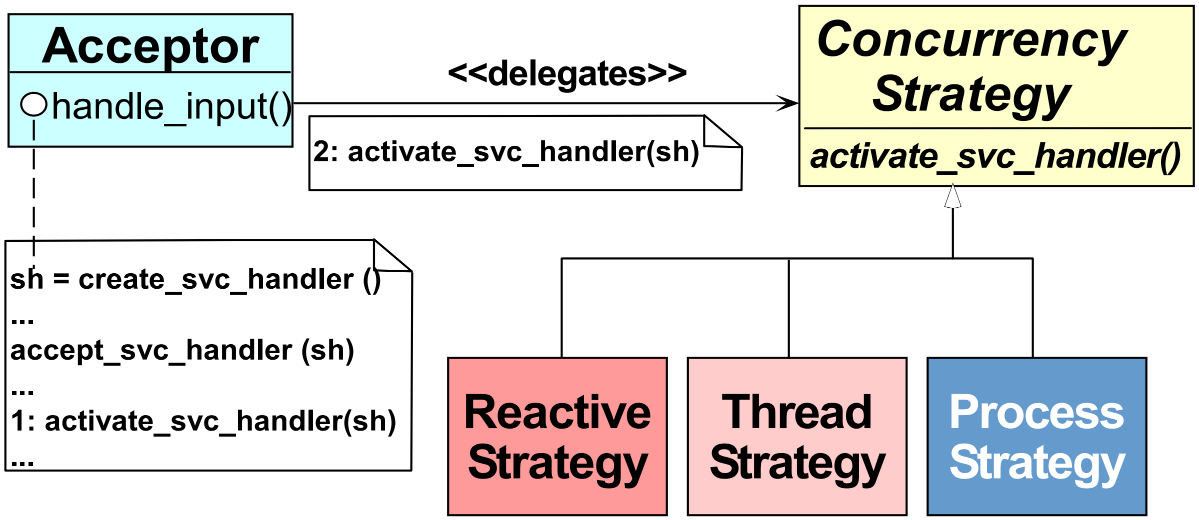


Intent

- *Define a family of algorithms, encapsulate each one, and make them interchangeable*

Gamma et al., *Design Patterns: Elements of Reusable Object-Oriented Software* AW, '94

Using the Strategy Pattern in the ACE Acceptor Implementation



Benefits

- More extensible due to “blackbox” design

Liabilities

- More complex and harder to develop initially

ACE_Acceptor Template Method Hook Implementations

Template method hooks can be overridden

```
// Factory method for creating a service handler.
template <class SH, class PA> SH *
ACE_Acceptor<SH, PA>::make_svc_handler (ACE_HANDLE)
  return new SH; // Default behavior.
}

// Accept connections from clients.
template <class SH, class PA> int
ACE_Acceptor<SH, PA>::accept_svc_handler (SH *sh)
{
  peer_acceptor_.accept (sh->peer ());
}

// Activate the service handler.
template <class SH, class PA> int
ACE_Acceptor<SH, PA>::activate_svc_handler (SH *sh)
{
  if (sh->open () == -1)
    sh->close ();
}
```

ACE_Acceptor Initialization Implementation

Note how the PEER_ACCEPTOR's open() method hides all the details associated with passively initializing communication endpoints

```
// Initialization.

template <class SH, class PA> int
ACE_Acceptor<SH, PA>::open
  (typename const PA::PEER_ADDR &addr,
   ACE_Reactor *reactor)
{
  // Forward initialization to the concrete
  // peer acceptor.
  peer_acceptor_.open (addr);

  // Register with Reactor.
  reactor->register_handler
           (this, ACE_Event_Handler::ACCEPT_MASK);
}
```

ACE_Svc_Handler Class Public Interface

Note how IPC and synchronization *aspects* are strategized

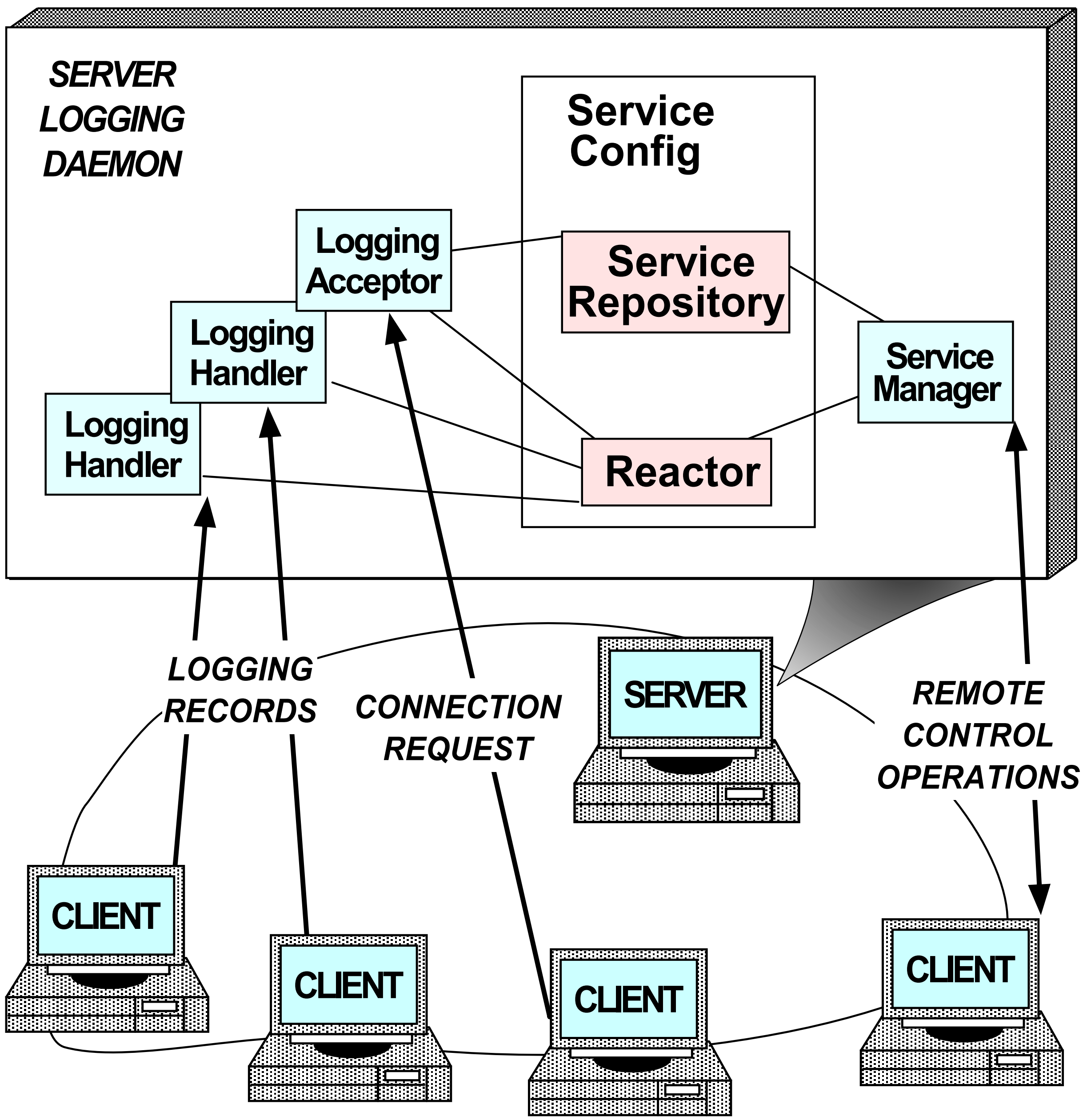
```
template <class PEER_STREAM, // IPC aspect
          class SYNCH_STRAT> // Synch aspect
class ACE_Svc_Handler
  : public ACE_Task<SYNCH_STRAT>
// Task is-a Service_Object,
// which is-an Event_Handler
{
public:
    // Constructor.
  ACE_Svc_Handler (Reactor * =
                     ACE_Reactor::instance ());
    // Activate the handler (called by the
.   // <ACE_Acceptor> or <ACE_Connector>).
  virtual int open (void *);

    // Return underlying IPC mechanism.
  PEER_STREAM &peer (void);

  // ...
private:
  PEER_STREAM peer_; // IPC mechanism.
  virtual ~ACE_Svc_Handler (void);
};
```

ACE_Svc_Handler Implementation

```
#define PS PEER_STREAM
#define SS SYNCH_STRAT

template <class PS, class SS>
ACE_Svc_Handler<PS, SS>::ACE_Svc_Handler
  (ACE_Reactor *r): ACE_Service_Object (r)
  {}
template <class PS, class SS>
int ACE_Svc_Handler<PS, SS>::open
  (void *) {
  // Enable non-blocking I/O.
  peer ().enable (ACE_NONBLOCK);

  // Register handler with the Reactor.
  reactor ()->register_handler
    (this, ACE_Event_Handler::READ_MASK);
}
```

- By default, a `ACE_Svc_Handler` object is registered with the singleton `ACE_Reactor`
  - This makes the service “reactive” so that no other synchronization mechanisms are necessary

Object Diagram for OO Logging Server



The Logging_Handler and Logging_Acceptor Classes

```
// Performs I/O with client logging daemons.

class Logging_Handler : public
  ACE_Svc_Handler<ACE_SOCK_Acceptor::PEER_STREAM,
                  // Trait!
                  ACE_NULL_SYNCH>
{
public:
    // Recv and process remote logging records.
  virtual int handle_input (ACE_HANDLE);
};

// Logging_Handler factory.

class Logging_Acceptor : public
  ACE_Acceptor<Logging_Handler, ACE_SOCK_Acceptor>
{
public:
    // Dynamic linking hooks.
  virtual int init (int argc, char *argv[]);
  virtual int fini (void);
};
```

Design Interlude: Parameterizing IPC Mechanisms

- Q: *How can you switch between different IPC mechanisms?*
- A: By parameterizing IPC Mechanisms with C++ Templates, *e.g.*:

```
#if defined (ACE_USE_SOCKETS)
typedef ACE_SOCK_Acceptor PEER_ACCEPTOR;
#elif defined (ACE_USE_TLI)
typedef ACE_TLI_Acceptor PEER_ACCEPTOR;
#endif /* ACE_USE_SOCKETS */

class Logging_Handler : public
  ACE_Svc_Handler<PEER_ACCEPTOR::PEER_STREAM, // Trait!
                  ACE_NULL_SYNCH>
    { /* ... /* };

class Logging_Acceptor : public
  ACE_Acceptor <Logging_Handler, PEER_ACCEPTOR>
    { /* ... */ };
```

Logging_Handler Input Method

Callback routine that receives logging records

```
int
Logging_Handler::handle_input (ACE_HANDLE)
{
  // Call existing function to recv
  // logging record and print to stdout.
  ssize_t n =
    handle_log_record (peer ().get_handle (),
                       ACE_STDOUT);
  if (n > 0)
    // Count the # of logging records
    ++request_count;
  return n <= 0 ? -1 : 0;
}
```

- Implementation of application-specific logging method
- This is the main code supplied by a developer!

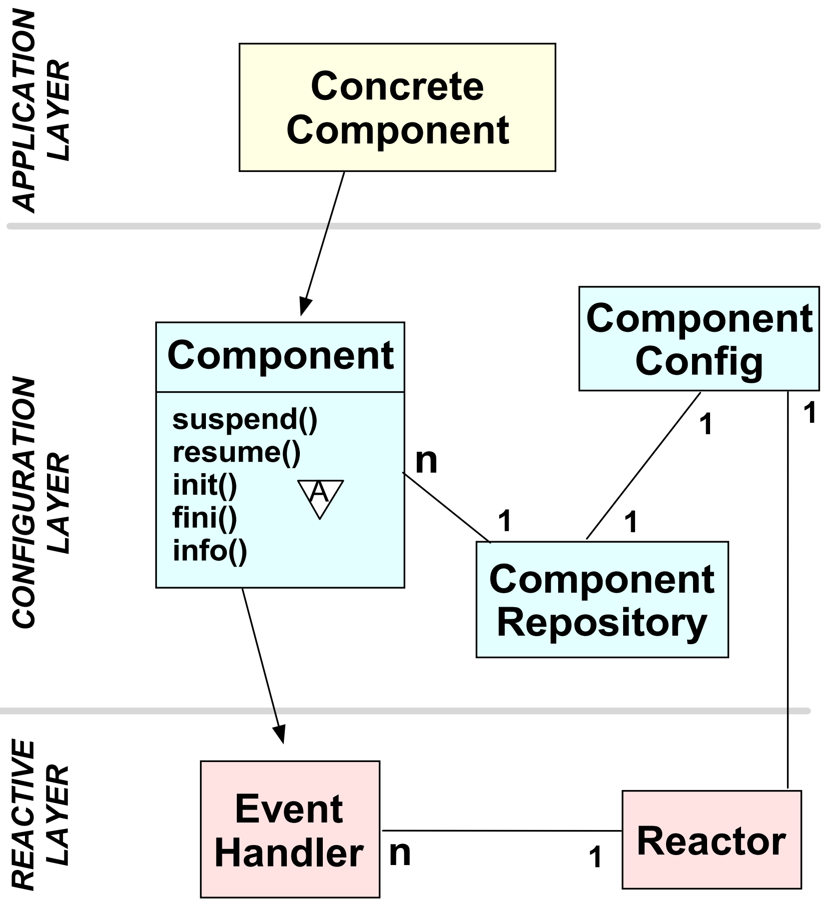
Logging_Acceptor Initialization and Termination

```
// Automatically called when a Logging_Acceptor
// object is linked dynamically.

Logging_Acceptor::init (int argc, char *argv[])
{
  ACE_Get_Opt get_opt (argc, argv, "p:", 0);
  ACE_INET_Addr addr (DEFAULT_PORT);

  for (int c; (c = get_opt ()) != -1; )
    switch (c) {
      case 'p':
        addr.set (atoi (getopt.optarg));
        break;
      default:
        break;
    }
  // Initialize endpoint and register
  // with the <ACE_Reactor>.
  open (addr, ACE_Reactor::instance ());
}

// Automatically called when object is unlinked.

Logging_Acceptor::fini (void) { handle_close (); }
```

Putting the Pieces Together at Run-time

- Problem
  - Prematurely committing ourselves to a particular logging server configuration is inflexible and inefficient
- Forces
  - It is useful to build systems by “scripting” components
  - Certain design decisions can’t be made efficiently until run-time
  - It is a bad idea to force users to “pay” for components they do not use
- Solution
  - Use the *Component Configurator* pattern to assemble the desired logging server components dynamically

The Component Configurator Pattern



Intent

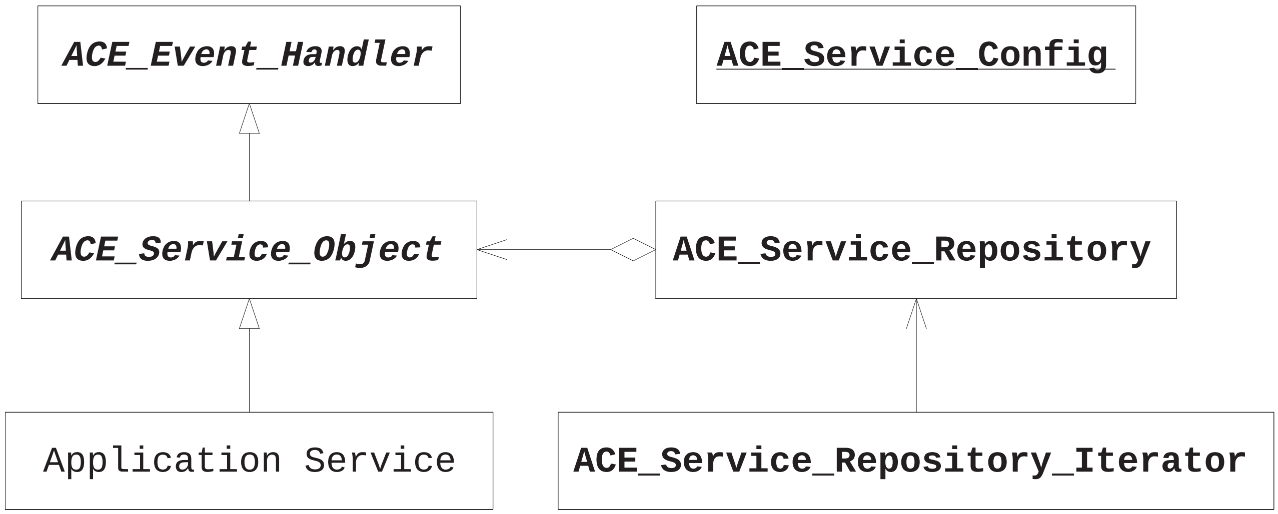
- *Decouples the implementation of services from the time when they are configured*

Forces Resolved

- Reduce resource utilization
- Support dynamic (re)configuration

`www.cs.wustl.edu/~schmidt/POSA/`

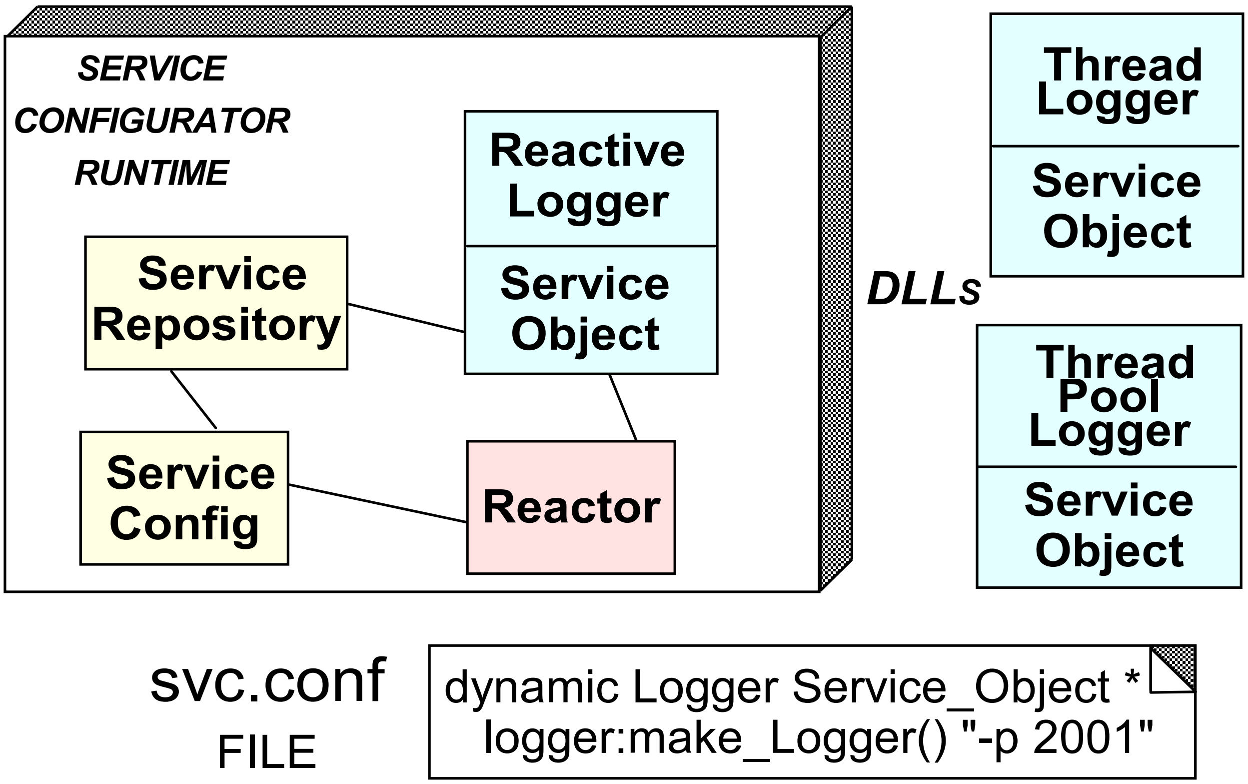
Structure of the ACE Service Configurator Framework



Framework characteristics

- `ACE_Service_Config` uses a variant of the Monostate pattern
- Can be accessed either via a script or programmatically

Using the ACE Service Configurator Framework for the Logging Server



- The existing Logging Server service is single-threaded
- Other versions could be multi-threaded
- Note how we can script this via the `svc.conf` file

Dynamically Linking a Service

Dynamically linked factory function that allocates a new `Logging_Acceptor`

```
extern "C"
ACE_Service_Object *
make_Logger (void);

ACE_Service_Object *
make_Logger (void)
{
  return new Logging_Acceptor;
  // Framework automatically
  // deletes memory.
}
```

- Application-specific factory function used to dynamically create a service
- The `make_Logger()` function provides a *hook* between an *application-specific* service and the *application-independent* ACE mechanisms
  - ACE handles all memory allocation and deallocation

Service Configuration

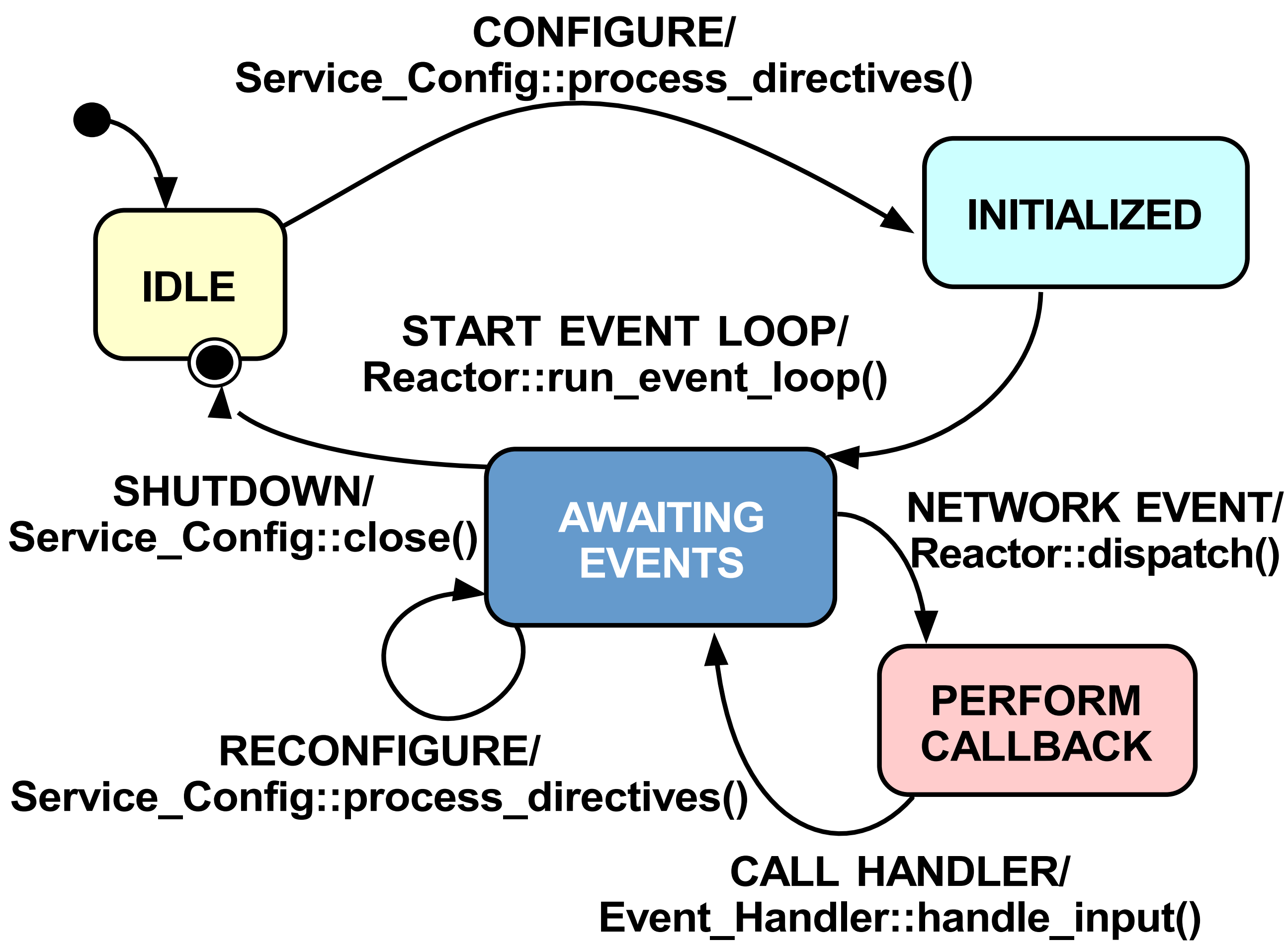
The logging service is configured via scripting in a `svc.conf` file:

```
% cat ./svc.conf
# Dynamically configure
# the logging service
dynamic Logger
Service_Object *
logger:_make_Logger() "-p 2001"
# Note, .dll or .so suffix
# added to the logger
# automatically
```

Generic event-loop to dynamically configure service daemons

```
int main (int argc, char *argv[])
{
  // Initialize the daemon and
  // configure services
  ACE_Service_Config::open (argc,
                            argv);
  // Run forever, performing the
  // configured services
  ACE_Reactor::instance ()->
    run_reactor_event_loop ();
  /* NOTREACHED */
}
```

State Chart for the Service Configurator Framework



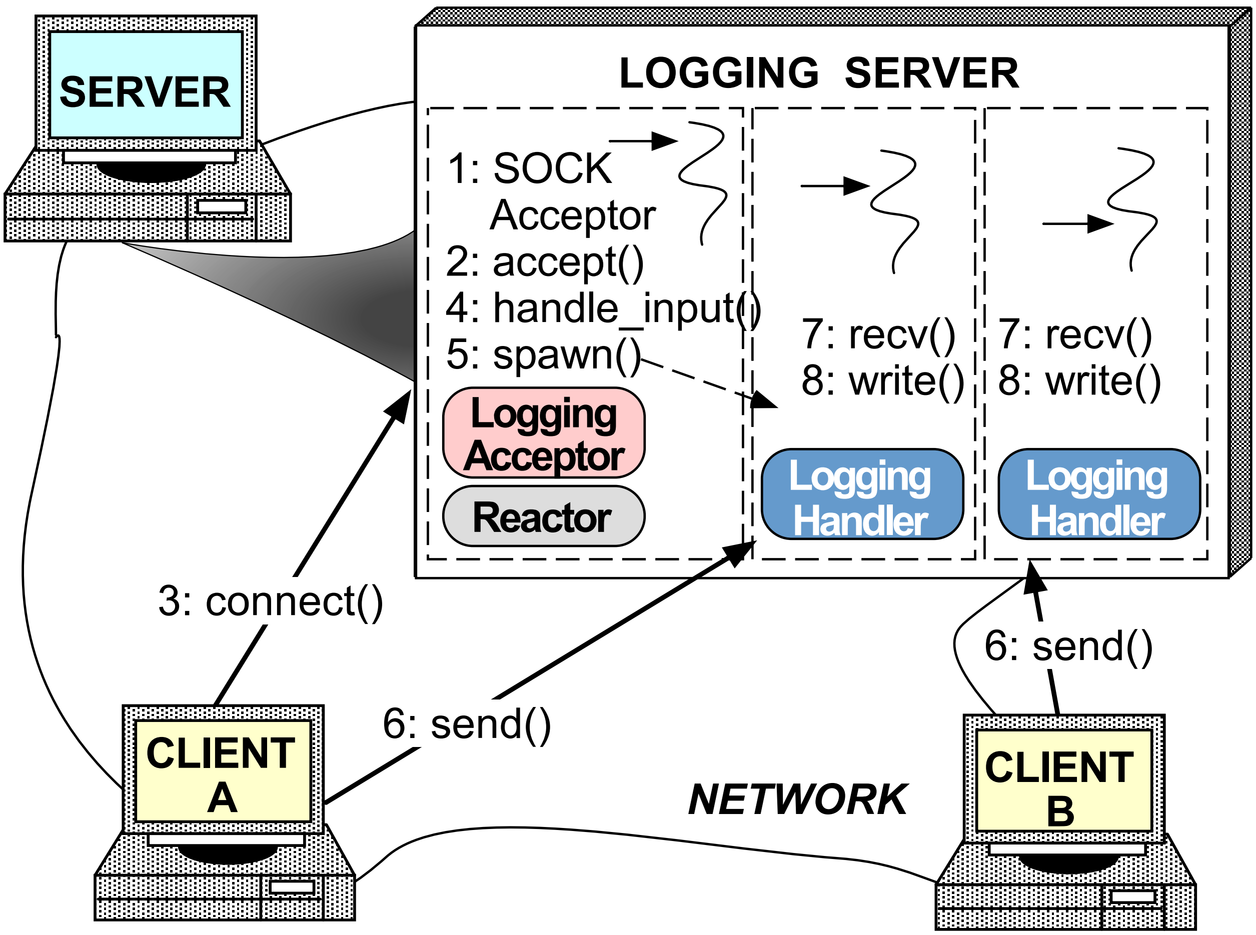
Advantages of OO Logging Server

- The OO architecture illustrated thus far decouples application-specific service functionality from:
  - Time when a service is configured into a process
  - The number of services per-process
  - The type of IPC mechanism used
  - The type of event demultiplexing mechanism used
- We can use the techniques discussed thus far to extend applications *without*:
  - *Modifying*, *recompiling*, and *relinking* existing code
  - *Terminating* and *restarting* executing daemons
- The remainder of the Logging Server slides examine a set of techniques for decoupling functionality from *concurrency* mechanisms, as well

Concurrent OO Logging Server

- The structure of the Logging Server can benefit from concurrent execution on a multi-processor platform
- This section examines ACE C++ classes and patterns that extend the logging server to incorporate concurrency
  - Note how most extensions require minimal changes to the existing OO architecture...
- This example also illustrates additional ACE components involving synchronization and multi-threading

Concurrent OO Logging Server Architecture



Runs each client connection in a separate thread

Pseudo-code for Concurrent Server

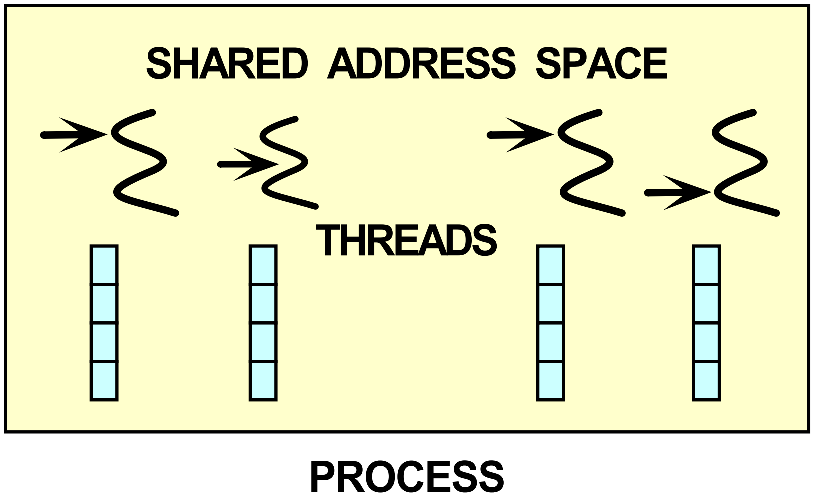
- Pseudo-code for multi-threaded `Logging_Handler` factory Logging Server

```
void handler_factory (void) {
  initialize acceptor endpoint
  foreach (pending connection event) {
          accept connection
          spawn a thread to handle connection and
          run logging_handler() entry point
  }
}
```

- Pseudo-code for `logging_handler()` function

```
void logging_handler (void) {
  foreach (incoming logging records from client)
         call handle_log_record()
  exit thread
}
```

Concurrency Overview



- A thread is a sequence of instructions executed in one or more processes
  - *One process* $\rightarrow$ stand-alone systems
  - *More than one process* $\rightarrow$ distributed systems

Traditional OS processes contain a single thread of control

- This simplifies programming since a sequence of execution steps is protected from unwanted interference by other execution sequences...

Traditional Approaches to OS Concurrency

1. Device drivers and programs with signal handlers utilize a limited form of *concurrency*
   - *e.g.*, asynchronous I/O
   - Note that *concurrency* encompasses more than *multi-threading*...
2. Many existing programs utilize OS processes to provide "coarse-grained" concurrency
   - *e.g.*,
     - Client/server database applications
     - Standard network daemons like UNIX INETD
   - Multiple OS processes may share memory via memory mapping or shared memory and use semaphores to coordinate execution
   - The OS kernel scheduler dictates process behavior

Evaluating Traditional OS Process-based Concurrency

- Advantages
  - *Easy to keep processes from interfering*
    - A process combines *security*, *protection*, and *robustness*
- Disadvantages
  - *Complicated to program*, *e.g.*,
  - Signal handling may be tricky
  - Shared memory may be inconvenient
- *Inefficient*
  - The OS kernel is involved in synchronization and process management
  - Difficult to exert fine-grained control over scheduling and priorities

Modern OS Concurrency

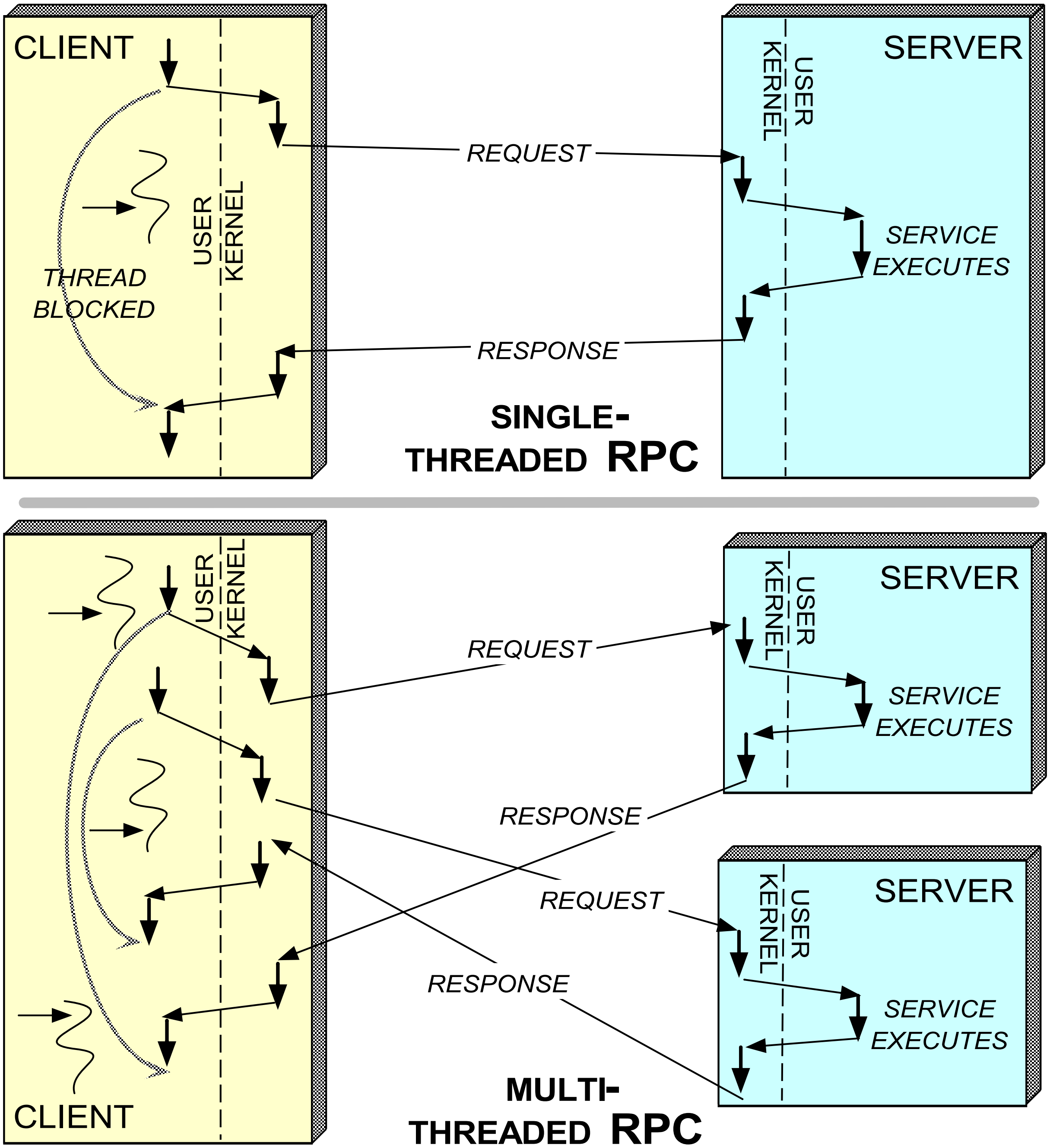
- Modern OS platforms typically provide a standard set of APIs that handle
  - Process/thread creation and destruction
  - Various types of process/thread synchronization and mutual exclusion
  - Asynchronous facilities for interrupting long-running processes/threads to report errors and control program behavior
- Once the underlying concepts are mastered, it's relatively easy to learn different concurrency APIs
  - *e.g.*, traditional UNIX process operations, Solaris threads, POSIX pthreads, WIN32 threads, Java threads, etc.

Lightweight Concurrency

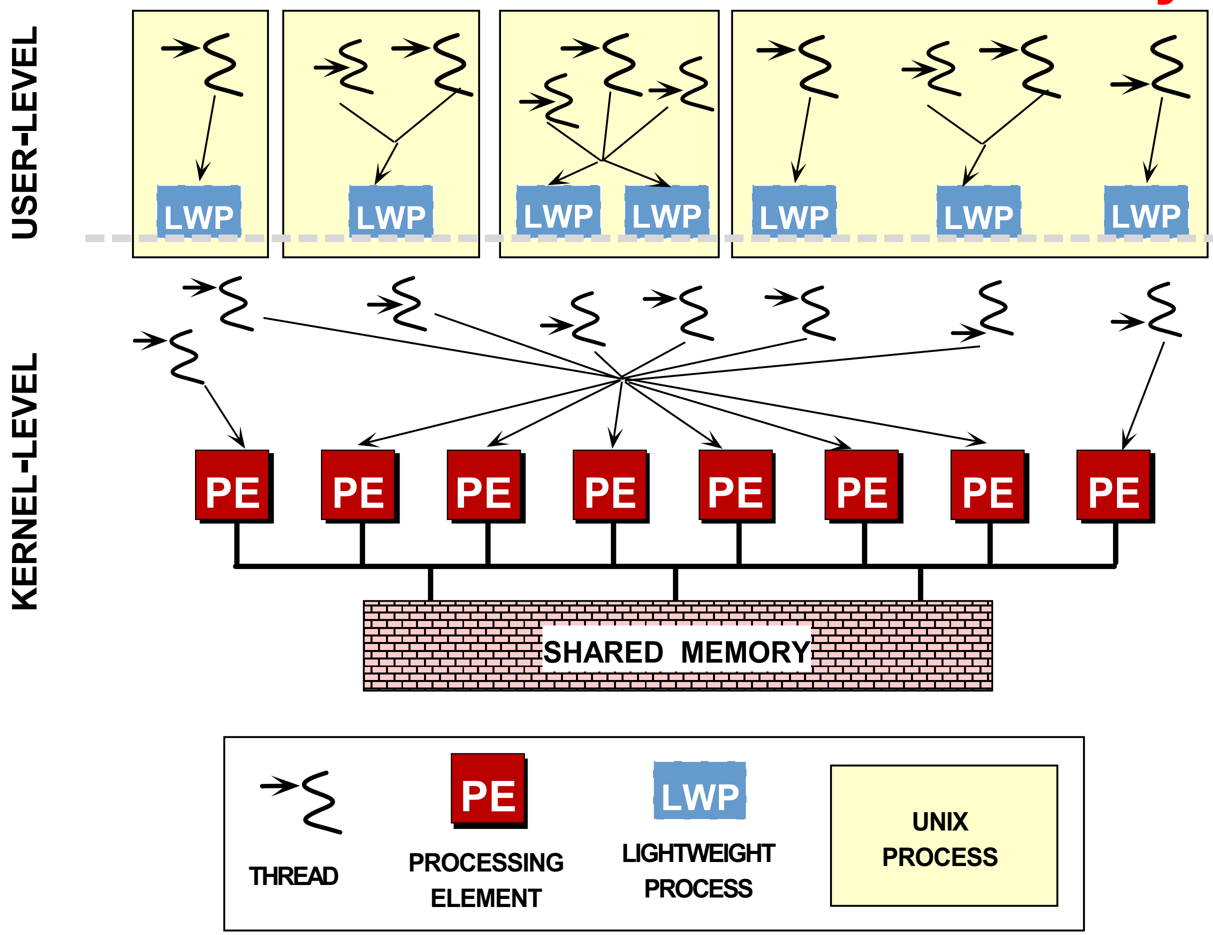
- Modern operating systems provide lightweight mechanisms that manage and synchronize multiple threads *within* a process
  - Some systems also allow threads to synchronize *across* multiple processes
- Benefits of threads

1. *Relatively simple and efficient to create, control, synchronize, and collaborate*
   - Threads share many process resources by default
2. *Improve performance by overlapping computation and communication*
   - Threads may also consume less resources than processes
3. *Improve program structure*
   - *e.g.*, compared with using asynchronous I/O

Example: Single-threaded vs. Multi-threaded Applications



Hardware and OS Concurrency Support



Four typical abstractions

1. *Application threads*
2. *Lightweight processes*
3. *Kernel threads*
4. *Processing elements*

Application Threads

Most process resources are equally accessible to all threads in a process, *e.g.*,

- *Virtual memory*
- *User permissions and access control privileges*
- *Open files*
- *Signal handlers*

Each thread also contains unique information, *e.g.*,

- *Identifier*
- *Register set* (*e.g.*, PC and SP)
- *Run-time stack*
- *Signal mask*
- *Priority*
- *Thread-specific data* (*e.g.*, `errno`)

Note, there is no MMU protection for threads in a single process

Kernel-level vs. User-level Threads

- Application and system characteristics influence the choice of *user-level* vs. *kernel-level* threading
- A high degree of “virtual” application concurrency implies user-level threads (*i.e.*, unbound threads)
  – *e.g.*, desktop windowing system on a uni-processor
- A high degree of “real” application parallelism implies lightweight processes (LWPs) (*i.e.*, bound threads)
  – *e.g.*, video-on-demand server or matrix multiplication on a multi-processor

Overview of OS Synchronization Mechanisms

- Threads share resources in a process address space
- Therefore, they must use *synchronization mechanisms* to coordinate their access to shared data
- Traditional OS synchronization mechanisms are very low-level, tedious to program, error-prone, and non-portable
- ACE encapsulates these mechanisms with wrapper facades and higher-level patterns/components

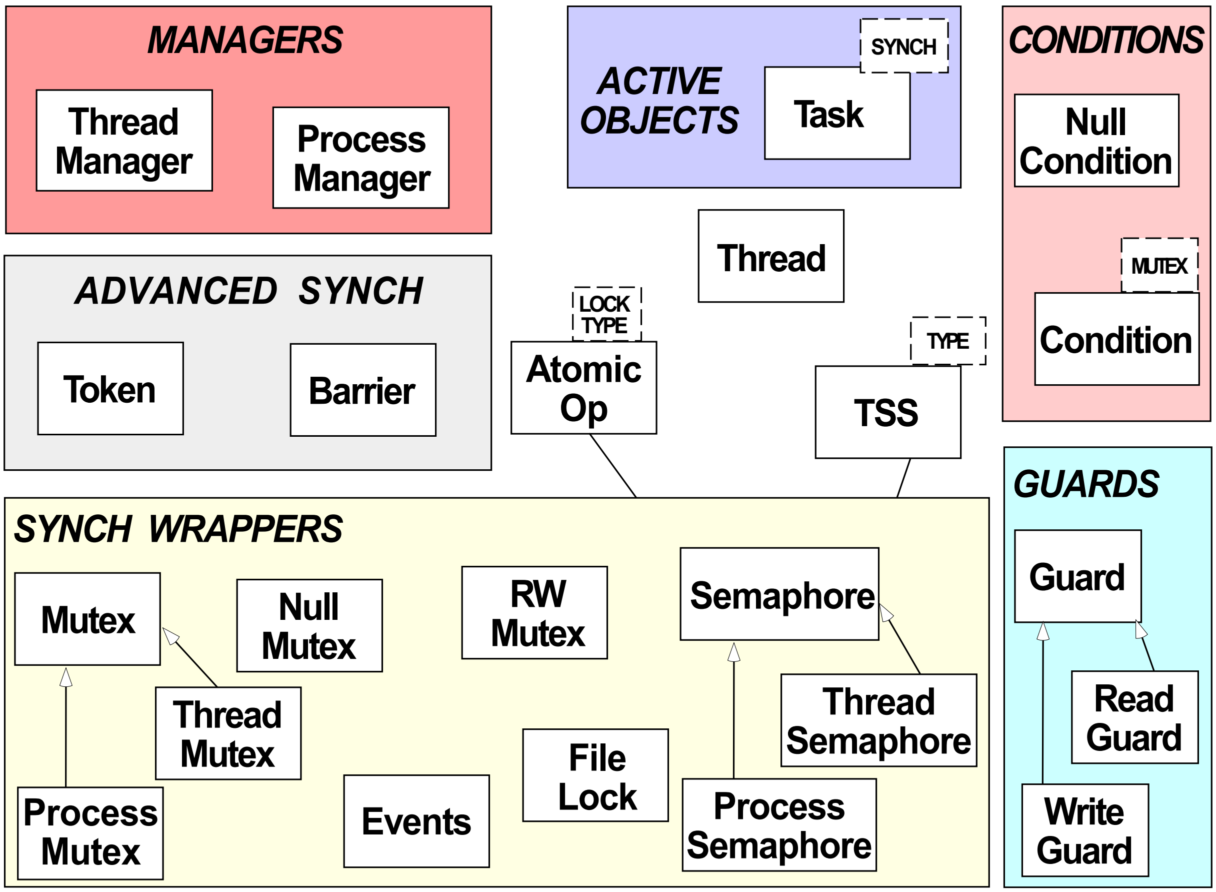
Common OS Synchronization Mechanisms

- Mutual exclusion (mutex) locks
  - Serialize thread access to a shared resource
- Counting semaphores
  - Synchronize thread execution
- Readers/writer (R/W) locks
  - Serialize resources that are searched more than changed
- Condition variables
  - Used to block threads until shared data changes state
- File locks
  - System-wide R/W locks accessed by processes

Additional ACE Synchronization Mechanism

- Events
  - *Gates* and *latches*
- Barriers
  - Allows threads to synchronize their completion
- Token
  - Provides FIFO scheduling order
- Task
  - Provides higher-level “active object” for concurrent applications
- Thread-specific storage
  - Low-overhead, contention-free storage

Concurrency Mechanisms in ACE

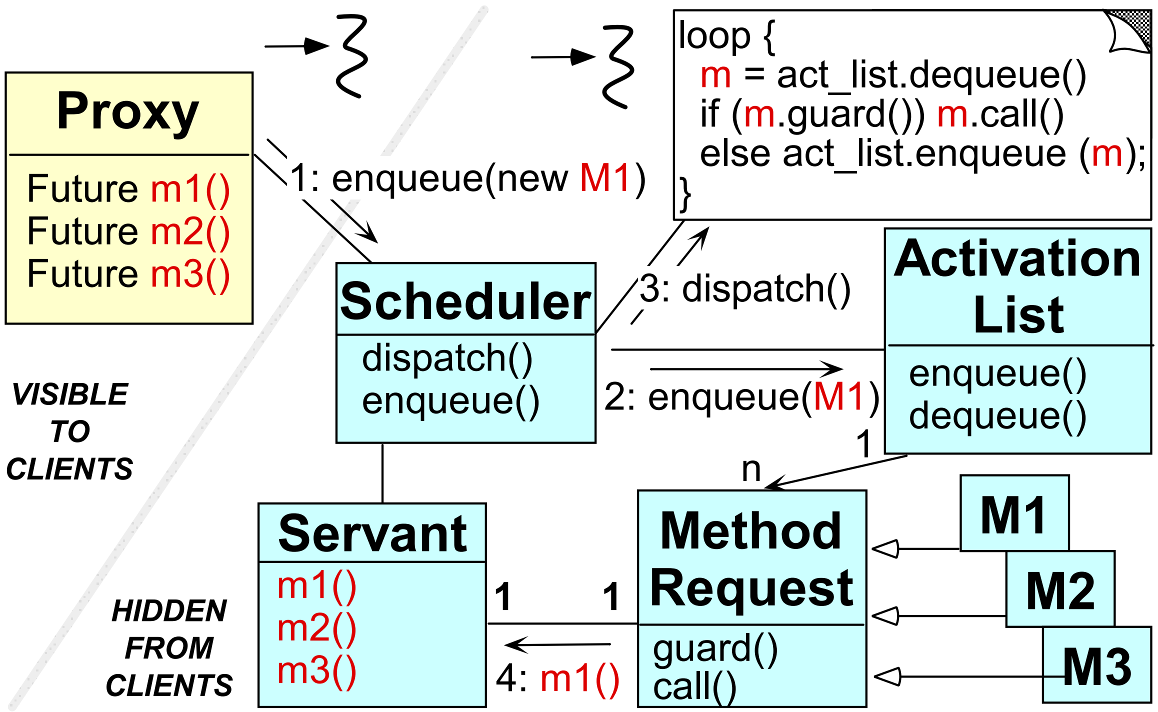


- All ACE Concurrency mechanisms are ported to all OS platforms
- `www.cs.wustl.edu/~schmidt/ACE/book1/`

Addressing Logger Server Concurrency Challenges

- Problem
  - Multi-threaded logging servers may be necessary when single-threaded reactive servers inefficient, non-scalable, or non-robust
- Forces
  - Multi-threading can be very hard to program
  - No single multi-threading model is always optimal
- Solution
  - Use the *Active Object* pattern to allow multiple concurrent logging server operations using an OO programming style

The Active Object Pattern



`www.cs.wustl.edu/˜schmidt/POSA/`

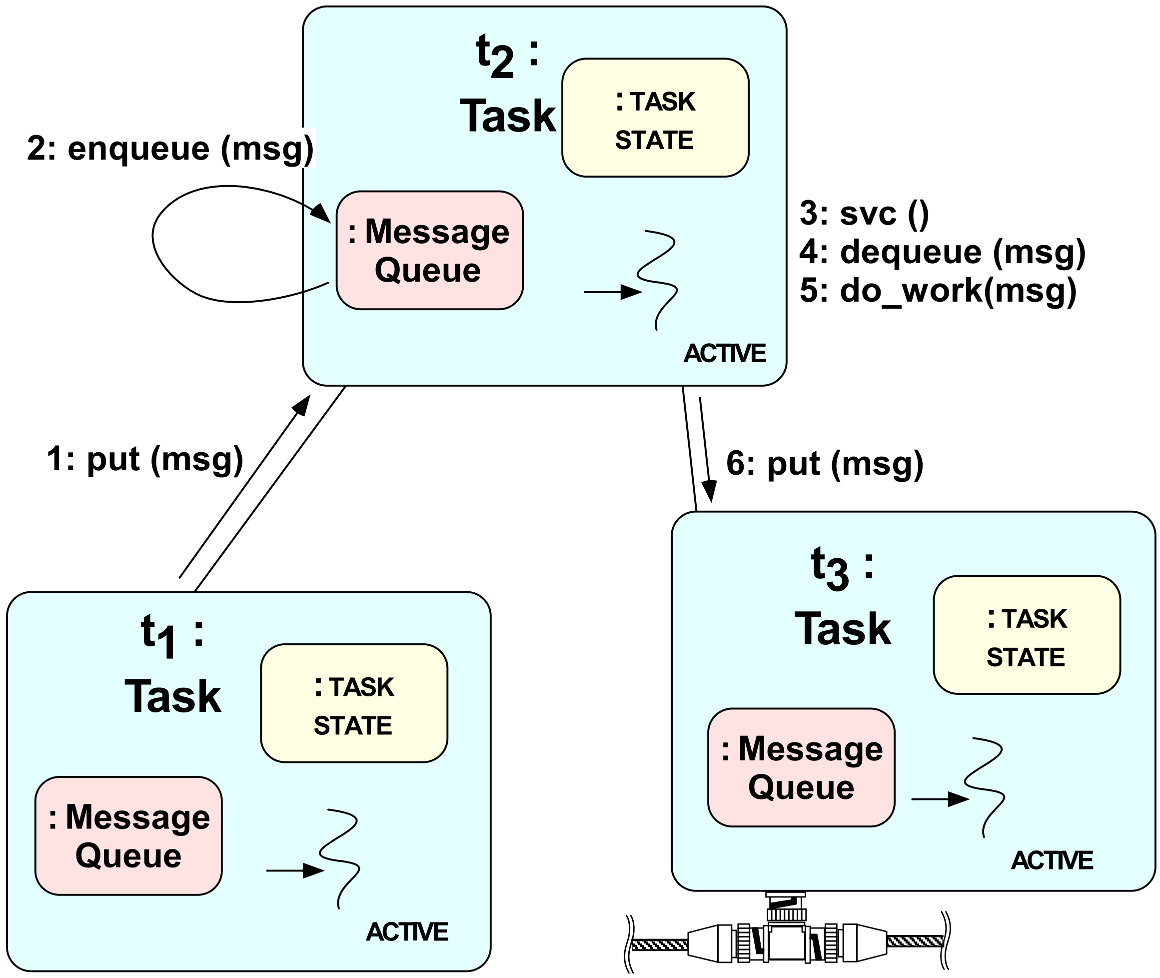
Intent

- *Decouples method execution from method invocation to enhance concurrency and simplify synchronized access to an object that resides in its own thread of control*

Forces Resolved

- Allow blocking operations
- Permit flexible concurrency strategies

ACE Support for Active Objects

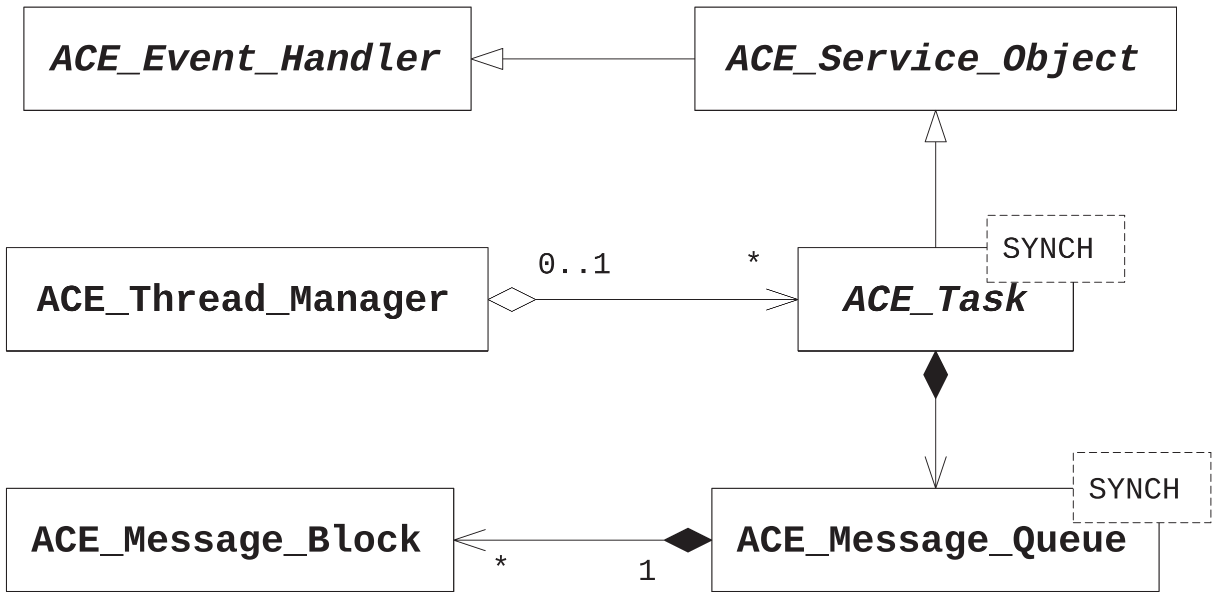


The ACE Task framework can be used to implement the complete Active Object pattern or lighterweight subsets

The ACE Task Framework

- An `ACE_Task` binds a separate thread of control together with an object's data and methods
  - Multiple active objects may execute in parallel in separate lightweight or heavyweight processes
- `ACE_Task` objects communicate by passing typed messages to other `ACE_Task` objects
  - Each `ACE_Task` maintains a queue of pending messages that it processes in *priority order*
- `ACE_Task` is a low-level mechanism to support active objects

Structure of the ACE Task Framework



Framework characteristics

1. ACE_Tasks can register with an ACE_Reactor
2. They can be dynamically linked
3. They can queue data
4. They can run as active objects in 1 or more threads

The ACE_Task Class Public Interface

```
template <class SYNCH_STRAT>
         // Synchronization aspect
class ACE_Task : public ACE_Service_Object {
public:
    // Initialization/termination hooks.
  virtual int open (void *args = 0) = 0;
  virtual int close (u_long = 0) = 0;

    // Transfer msg to queue for immediate processing.
  virtual int put (ACE_Message_Block *, ACE_Time_Value * = 0) = 0;

    // Run by a daemon thread for deferred processing.
  virtual int svc (void) = 0;

    // Turn task into active object.
  int activate (long flags, int threads = 1);
```

ACE_Task Class Protected Interface

Many of the following methods are used by put() and svc()

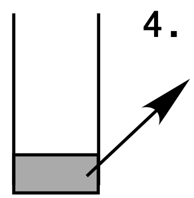
```
  // Accessors to internal queue.
ACE_Message_Queue<SYNCH_STRAT> *msg_queue (void);
void msg_queue (ACE_Message_Queue<SYNCH_STRAT> *);

  // Accessors to thread manager.
ACE_Thread_Manager *thr_mgr (void);
void thr_mgr (ACE_Thread_Manager *);

  // Insert message into the message list.
int putq (ACE_Message_Block *, ACE_Time_Value *tv = 0);

  // Extract the first message from the list (blocking).
int getq (ACE_Message_Block *&mb, ACE_Time_Value *tv = 0);

  // Hook into the underlying thread library.
static void *svc_run (ACE_Task<SYNCH_STRAT> *);
```

Design Interlude: Combining Threads & C++ Objects

- Q: *What is the `svc_run()` function and why is it a static method?*
- A: OS thread APIs require C-style functions as entry point
- The ACE Task framework encapsulates the `svc_run()` function within the `ACE_Task::activate()` method:

```
template <class SYNCH_STRAT> int
ACE_Task<SYNCH_STRAT>::activate (long flags, int n_threads) {
  if (thr_mgr () == NULL) thr_mgr (ACE_Thread_Manager::instance ());
  thr_mgr ()->spawn_n (n_threads, &ACE_Task<SYNCH_STRAT>::svc_run,
                       (void *) this, flags);
}
```

```
1. ACE_Task::activate ()
2. ACE_Thread_Manager::spawn
     (svc_run, this);
3. _beginthreadex
     (0, 0,
      svc_run, this,
      0, &thread_id);
```




```
4. template <SYNCH_STRATEGY> void *
   ACE_Task<SYNCH_STRATEGY>::svc_run
     (ACE_Task<SYNCH_STRATEGY> *t) {
     // ...
     void *status = t->svc ();
     // ...
     return status; // Thread return.
   }
```

The svc_run() Adapter Function

`ACE_Task::svc_run()` is static method used as the entry point to execute an instance of a service concurrently in its own thread

```
template <class SYNCH_STRAT> void *
ACE_Task<SYNCH_STRAT>::svc_run (ACE_Task<SYNCH_STRAT> *t)
{
  // Thread added to thr_mgr() automatically on entry.

  // Run service handler and record return value.
  void *status = (void *) t->svc ();

  t->close (u_long (status));

  // Status becomes "return" value of thread...
  return status;

  // Thread removed from thr_mgr() automatically on return.
}
```

Design Interlude: Motivation for the `ACE_Thread_Manager`

- Q: *How can groups of collaborating threads be managed atomically?*
- A: Develop the `ACE_Thread_Manager` class that:
  - Supports the notion of *thread groups*
    - *i.e.*, operations on all threads in a group
  - Implements *barrier synchronization* on thread exits
  - Shields applications from incompatibilities between different OS thread libraries
    - *e.g.*, detached threads and thread joins

Using ACE Task Framework for Logging Server

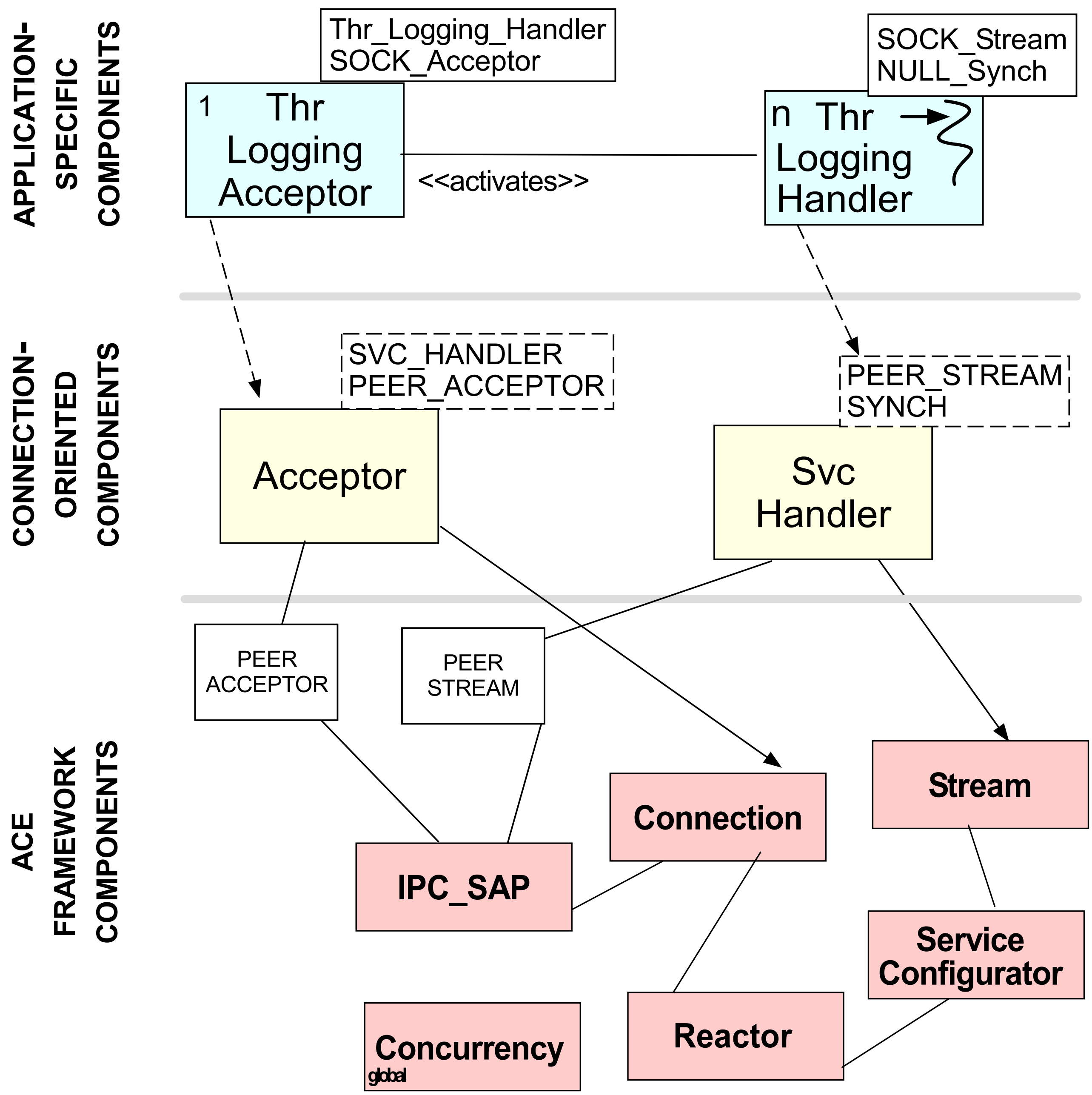
Process remote logging records by looping until the client terminates connection

```
int
Thr_Logging_Handler::svc (void)
{
  while (handle_input () != -1)
    // Call existing function
    //  to recv logging record
    // and print to stdout.
    continue;

  return 0;
}
```

- The OO implementation localizes the application-specific part of the logging service in a single point, while leveraging off reusable ACE components
- Compare with original, which borrow's the Reactor thread

```
int
Logging_Handler::handle_input (void)
{
  handle_log_record
    (peer ().get_handle (),
     ACE_STDOUT);
  // ...
}
```

Class Diagram for Concurrent OO Logging Server



Thr_Logging_Acceptor and Thr_Logging_Handler Interfaces

Template classes that create, connect, and activate a new thread to handle each client

```
class Thr_Logging_Handler
  : public Logging_Handler
  // Inherits <handle_input>
{
public:
    // Override definition in <ACE_Svc_Handler>
    // class to spawn a new thread!  This method
    // is called by the <ACE_Acceptor>.
  virtual int open (void *);

    // Process remote logging records.
  virtual int svc (void);
};

class Thr_Logging_Acceptor : public
  ACE_Acceptor<Thr_Logging_Handler,
               ACE_SOCK_Acceptor>
{
  // Same as <Logging_Acceptor>...
};
```

Thr_Logging_Handler Implementation

Override definition in the ACE_Svc_Handler class to spawn a new thread

```
int
Thr_Logging_Handler::open (void *)
{
  // Spawn a new thread to handle
  // logging records with the client.
  activate (THR_DETACHED);
}
```

Process remote logging records by looping until client terminates connection

```
int
Thr_Logging_Handler::svc (void)
{
  while (handle_input () != -1)
    // Call existing function to recv
    // logging record and print to stdout.
    continue;
}
```

Dynamically Reconfiguring the Logging Server

The logging service is configured via scripting in a `svc.conf` file:

```
% cat ./svc.conf
# Dynamically reconfigure
# the logging service
remove Logger
dynamic Logger
Service_Object *
thr_logger:_make_Logger()
           "-p 2002"
# .dll or .so suffix added to
# "thr_logger" automatically
```

Dynamically linked factory function that allocates a new threaded `Logging_Acceptor`

```
extern "C"
ACE_Service_Object *make_Logger (void);

ACE_Service_Object *
make_Logger (void)
{
  return new Thr_Logging_Acceptor;
}
```

Logging service is reconfigured by changing the `svc.conf` file and sending SIGHUP signal to server

Caveats for the Concurrent Logging Server

- The concurrent Logging Server has several problems
  - Output in the `handle_log_record()` function is not serialized
  - The auto-increment of global variable `request_count` is also not serialized
- Lack of serialization leads to errors on many shared memory multi-processor platforms...
  - Note that this problem is indicative of a large class of errors in concurrent programs...
- The following slides compare and contrast a series of techniques that address this problem

Explicit Synchronization Mechanisms

- One approach for serialization uses OS mutual exclusion mechanisms explicitly, *e.g.*,

```
// at file scope
mutex_t lock; // SunOS 5.x synchronization mechanism

// ...
handle_log_record (ACE_HANDLE in_h, ACE_HANDLE out_h)
{
  // in method scope ...
  mutex_lock (&lock);
  if (ACE_OS::write (out_h, lr.buf, lr.size) == -1)
    return -1;
  mutex_unlock (&lock);
  // ...
}
```

- However, adding these `mutex` calls explicitly causes problems...

Problem: Explicit `mutex_*` Calls

- *Inelegant* → "Impedance mismatch" with C/C++
- *Obtrusive*
  - Must find and lock all uses of `write()`
  - Can yield inheritance anomaly
- *Error-prone*
  - C++ exception handling and multiple method exit points
  - Thread mutexes won't work for separate processes
  - Global mutexes may not be initialized correctly
- *Non-portable* → Hard-coded to Solaris 2.x
- *Inefficient* → *e.g.*, expensive for certain platforms/designs

Solution: Synchronization Wrapper Facades

```
class ACE_Thread_Mutex
{
public:
  ACE_Thread_Mutex (void) {
    mutex_init (&lock_, USYNCH_THREAD, 0);
  }
  ~ACE_Thread_Mutex (void) { mutex_destroy (&lock_);
  int acquire (void) { return mutex_lock (&lock_); }
  int tryacquire (void)
     { return mutex_trylock (&lock_); }
  int release (void) { return mutex_unlock (&lock_);

private:
  // SunOS 5.x serialization mechanism.
  mutex_t lock_;
  void operator= (const ACE_Thread_Mutex &);
  ACE_Thread_Mutex (const ACE_Thread_Mutex &);
};
```

Note how we prevent improper copying and assignment by using C++ access control specifiers

Porting ACE_Thread_Mutex to Windows NT

```
class ACE_Thread_Mutex
{
public:
  ACE_Thread_Mutex (void) {
    lock_ = CreateMutex (0, FALSE, 0);
  }
  ~ACE_Thread_Mutex (void) {
    CloseHandle (lock_);
  }
  int acquire (void) {
    return WaitForSingleObject (lock_, INFINITE);
  }
  int tryacquire (void) {
    return WaitForSingleObject (lock_, 0);
  }
  int release (void) {
    return ReleaseMutex (lock_);
  }
private:
  ACE_HANDLE lock_; // Windows locking mechanism.
  // ...
```

Using the C++ Mutex Wrapper Facade

- Using C++ wrapper facades improves *portability* and *elegance*

```
// at file scope.
ACE_Thread_Mutex lock; // Implicitly unlocked.

// ...
handle_log_record (ACE_HANDLE in_h, ACE_HANDLE out_h) {
  // in method scope ...

  lock.acquire ();
  if (ACE_OS::write (out_h, lr.buf, lr.size) == -1)
    return -1;
  lock.release ();
  // ...
```

- However, this doesn't really solve the *tedium* or *error-proneness* problems
  - www.cs.wustl.edu/~schmidt/PDF/ObjMan.pdf

Automated Mutex Acquisition and Release

- To ensure mutexes are locked and unlocked, we'll define a template class that acquires and releases a mutex automatically

```
template <class LOCK>
class ACE_Guard
{
public:
  ACE_Guard (LOCK &m): lock_ (m) { lock_.acquire (); }
  ~ACE_Guard (void) { lock_.release (); }
  // ... other methods omitted ...

private:
  LOCK &lock_;
}
```

- `ACE_Guard` uses the *Scoped Locking* idiom whereby a *constructor acquires a resource* and the *destructor releases the resource*

The ACE_GUARD Macros

- ACE defines a set of macros that simplify the use of the `ACE_Guard`, `ACE_Write_Guard`, and `ACE_Read_Guard` classes
  - These macros test for deadlock and detect when operations on the underlying locks fail

```
#define ACE_GUARD(MUTEX,OB,LOCK) \
  ACE_Guard<MUTEX> OB (LOCK); if (OB.locked () == 0) return;
#define ACE_GUARD_RETURN(MUTEX,OB,LOCK,RET) \
  ACE_Guard<MUTEX> OB (LOCK); if (OB.locked () == 0) return RET;
#define ACE_WRITE_GUARD(MUTEX,OB,LOCK) \
  ACE_Write_Guard<MUTEX> OB (LOCK); if (OB.locked () == 0) return;
#define ACE_WRITE_GUARD_RETURN(MUTEX,OB,LOCK,RET) \
  ACE_Write_Guard<MUTEX> OB (LOCK); if (OB.locked () == 0) return RET;
#define ACE_READ_GUARD(MUTEX,OB,LOCK) \
  ACE_Read_Guard<MUTEX> OB (LOCK); if (OB.locked () == 0) return;
#define ACE_READ_GUARD_RETURN(MUTEX,OB,LOCK,RET) \
  ACE_Read_Guard<MUTEX> OB (LOCK); if (OB.locked () == 0) return RET;
```

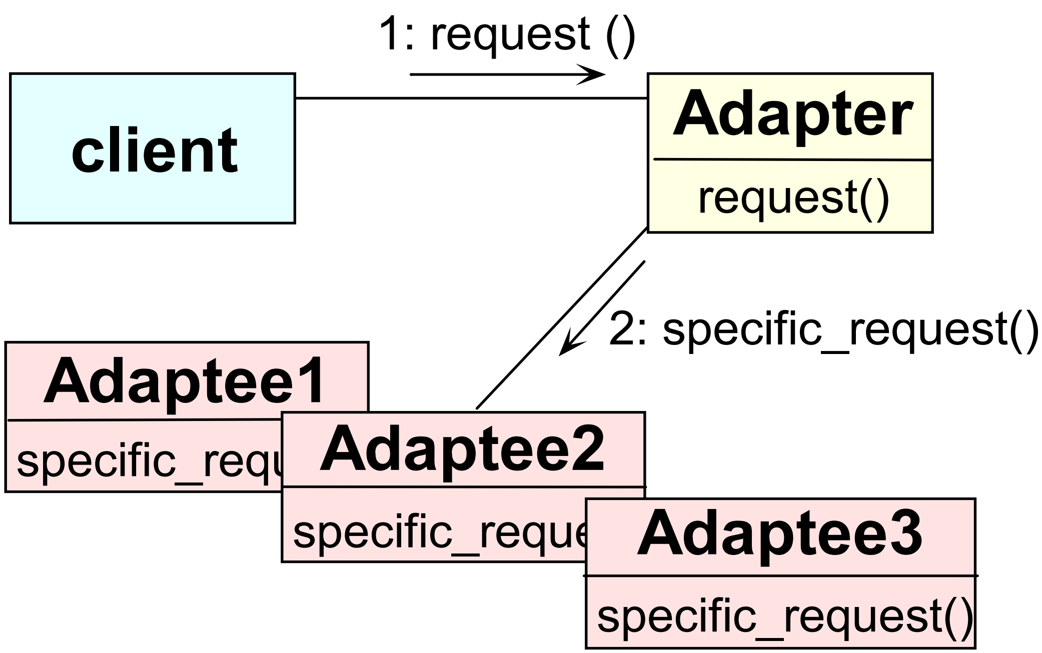
Thread-safe handle_log_record() Function

```
template <class LOCK = ACE_Thread_Mutex> ssize_t
handle_log_record (ACE_HANDLE in, ACE_HANDLE out) {
  // beware static initialization...
  static LOCK lock;
  ACE_UINT_32 len;
  ACE_Log_Record lr;

  // The first recv reads the length (stored as a
  // fixed-size integer) of adjacent logging record.
  ssize_t n = s.recv_n ((char *) &len, sizeof len);
  if (n <= 0) return n;

  len = ntohl (len); // Convert byte-ordering
  // Perform sanity check!
  if (len > sizeof (lr)) return -1;

  // The second recv then reads <len> bytes to
  // obtain the actual record.
  s.recv_n ((char *) &lr, sizeof lr);

  // Decode and print record.
  decode_log_record (&lr);
  // Automatically acquire mutex lock.
  ACE_GUARD_RETURN (LOCK, guard, lock, -1);
  if (ACE_OS::write (out, lr.buf, lr.size) == -1)
    return -1; // Automatically release mutex lock.
  return 0;
}
```

Design Interlude: Motivating the `ACE_Guard` Design

- Q: *Why is `ACE_Guard` parameterized by the type of* `LOCK`?
- A: since many different flavors of locking can benefit from the Scoped Locking protocol
  - *e.g.*, non-recursive vs. recursive mutexes, intra-process vs. inter-process mutexes, readers/writer mutexes, POSIX and System V semaphores, file locks, and the null mutex
- Q: *Why are templates used, as opposed to inheritance/polymorphism?*
- A: since they are more efficient and can reside in shared memory
- All ACE synchronization wrapper facades use the Adapter pattern to provide identical interfaces to facilitate parameterization

The Adapter Pattern



Intent

- *Convert the interface of a class into another interface client expects*

Force resolved:

- Provide an interface that captures similarities between different OS mechanisms, *e.g.*, locking or IPC

Remaining Caveats

```
int Logging_Handler::handle_input (void)
{
  ssize_t n = handle_log_record
    (peer ().get_handle (), ACE_STDOUT);
  if (n > 0)
    // Count # of logging records.
    ++request_count;
    // Danger, race condition!!!

  return n <= 0 ? -1 : 0;
}
```

A more elegant solution incorporates parameterized types, overloading, and the Strategized Locking pattern, as discussed in C++NPv1

- There is a race condition when incrementing the `request_count` variable
- Solving this problem using the `ACE_Thread_Mutex` or `ACE_Guard` classes is still *tedious*, *low-level*, and *error-prone*

Transparently Parameterizing Synchronization Using C++

Use the *Strategized Locking* pattern, C++ templates, and operator overloading to define "atomic operators"

```
template <class LOCK = ACE_Thread_Mutex,
          class TYPE = u_long>
class ACE_Atomic_Op {
public:
  ACE_Atomic_Op (TYPE c = 0) { count_ = c; }
  TYPE operator++ (void) {
    ACE_GUARD (LOCK, guard, lock_); return ++count_;
  }
  operator TYPE () {
    ACE_GUARD (LOCK, guard, lock_); return count_;
  }
  // Other arithmetic operations omitted...
private:
  LOCK lock_;
  TYPE count_;
};
```

Final Version of Concurrent Logging Server

- Using the `Atomic_Op` class, only one change is made

```
// At file scope.
typedef ACE_Atomic_Op<> COUNTER; // Note default parameters...
COUNTER request_count;
```

- `request_count` is now serialized automatically

```
  for (; ; ++request_count) // ACE_Atomic_Op::operator++
    handle_log_record (get_handle (), ACE_STDOUT);
```

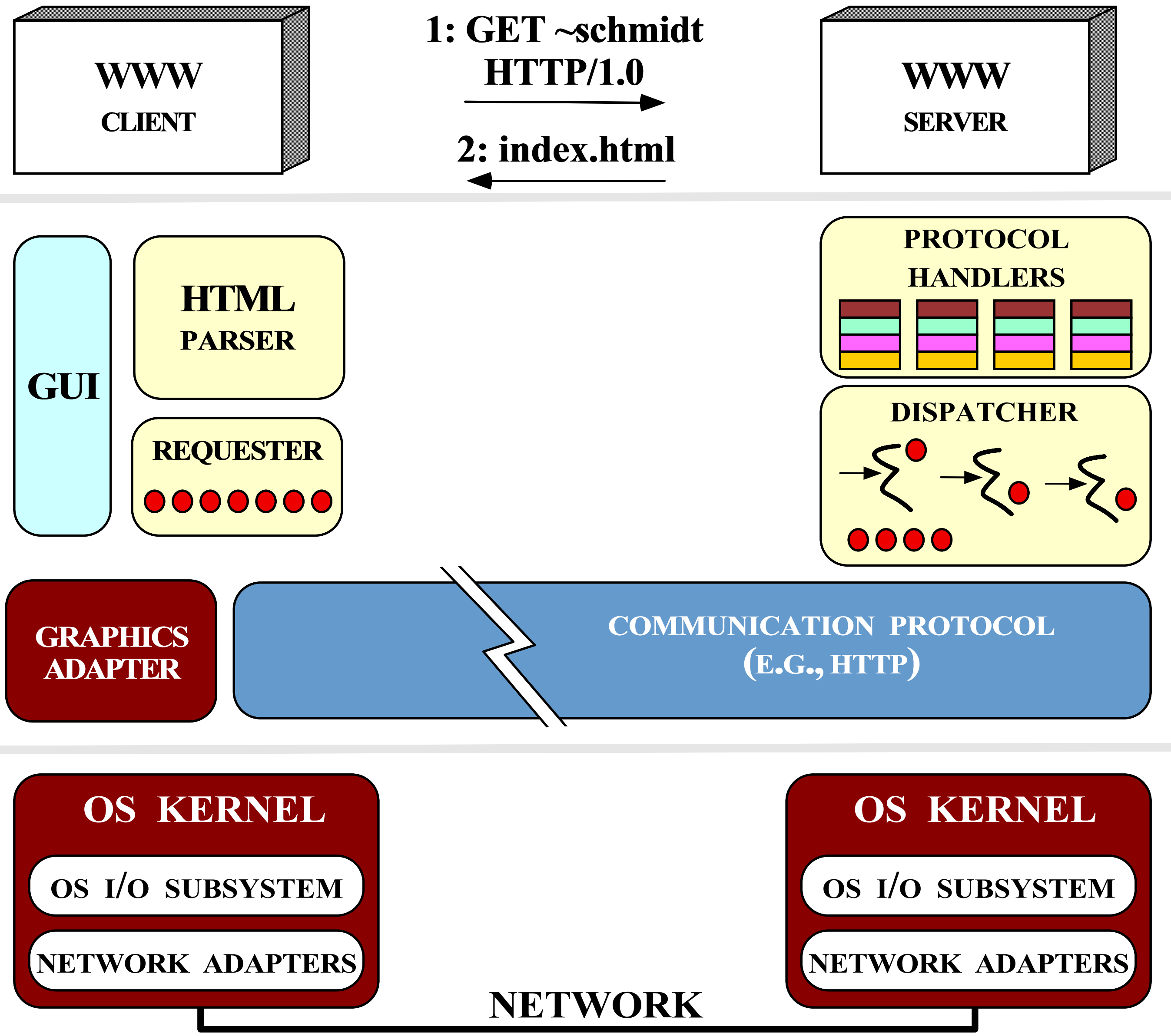
- The original non-threaded version may be supported efficiently as follows:

```
typedef ACE_Atomic_Op<Null_Mutex> COUNTER;
//...
  for (; ; ++request_count)
    handle_log_record<Null_Mutex>
      (get_handle (), ACE_STDOUT);
```

Concurrent Web Client/Server Example

- The following example illustrates a concurrent OO architecture for a high-performance Web client/server
- Key functional and non-functional system requirements are:
  - Robust implementation of HTTP 1.0 protocol
    - *i.e.*, resilient to incorrect or malicious Web clients/servers
  - Extensible for use with other protocols
    - *e.g.*, DICOM, HTTP 1.1, CORBA Simple Flow Protocol (SFP)
  - Leverage multi-processor hardware and OS software
    - *e.g.*, Support various concurrency patterns

General Web Client/Server Interactions



www.cs.wustl.edu/˜jxh/research/

Pseudo-code for Concurrent Web Server

- Pseudo-code for master server

```
void master_server (void)
{
  initialize queue and acceptor at port 80
  spawn pool of worker threads
  foreach (pending work request from clients) {
          receive and queue request on queue
  }
  exit process
}
```

- Pseudo-code for thread pool workers

```
void worker (void)
{
  foreach (work request on queue)
    dequeue and process request
  exit thread
}
```

- As usual, make sure to avoid the “grand mistake”

Design Interlude: Motivating a Request Queue

- Q: *Why use a request queue to store messages, rather than directly reading from I/O handles?*
- A:
  - Promotes more efficient use of multiple CPUs via load balancing
  - Enables transparent interpositioning and prioritization
  - Makes it easier to shut down the server correctly and portably
  - Improves robustness to “denial of service” attacks
  - Moves queueing into the application process rather than OS
- *Drawbacks*
  - Using a message queue may lead to greater *context switching* and *synchronization* overhead...
  - Single point for bottlenecks

Thread Entry Point

```
typedef ACE_Unbounded_Queue<Message> MESSAGE_QUEUE;
typedef u_long COUNTER;
// Track the number of requests
COUNTER request_count; // At file scope.

// Entry point into the Web HTTP 1.0 protocol,
// which runs in each thread in the thread pool.
void *worker (MESSAGE_QUEUE *msg_queue)
{
  Message mb; // Message containing HTTP request.

  while (msg_queue->dequeue_head (mb)) > 0) {
    // Keep track of number of requests.
    ++request_count;

    // Print diagnostic
    cout << "got new request"
         << ACE_OS::thr_self ()
         << endl;

    // Identify and perform Web Server
    // request processing here...
  }
  return 0;
}
```

Master Server Driver Function

```
// Thread function prototype.
typedef void *(*THR_FUNC)(void *);

int main (int argc, char *argv[]) {
  parse_args (argc, argv);
  // Queue client requests.
  MESSAGE_QUEUE msg_queue;

  // Spawn off NUM_THREADS to run in parallel.
  for (int i = 0; i < NUM_THREADS; i++)
    thr_create (0, 0,
                THR_FUNC (&worker),
                (void *) &msg_queue,
                THR_BOUND, 0);

  // Initialize network device and
  // recv HTTP work requests.
  thr_create (0, 0, THR_FUNC (&recv_requests),
              (void *) &msg_queue,
              THR_BOUND, 0);

  // Wait for all threads to exit (BEWARE)!
  while (thr_join (0, &t_id, (void **) 0) == 0)
    continue; // ...
}
```

Pseudo-code for `recv_requests()`

```
void recv_requests (MESSAGE_QUEUE *msg_queue)
{
  initialize socket acceptor at port 80

  foreach (incoming request})
  {
    use select to wait for new
      connections or data
    if (connection)
      establish connections using accept()
    else if (data) {
      use sockets calls to
      read() HTTP requests into msg
      msg_queue.enqueue_tail (msg);
    }
  }
}
```

This is the “supplier” thread

Limitations with the Web Server

- The algorithmic decomposition tightly couples application-specific *functionality* with various configuration-related characteristics, *e.g.*,
  - The HTTP 1.0 protocol
  - The number of services per process
  - The time when services are configured into a process
- The solution is not portable since it hard-codes
  - SunOS 5.x threading
  - sockets and `select()`
- There are *race conditions* in the code

Overcoming Limitations via OO

- The algorithmic decomposition illustrated above specifies too many low-level details
  - Moreover, the excessive coupling complicates reusability, extensibility, and portability...
- In contrast, OO focuses on decoupling *application-specific* behavior from reusable *application-independent* mechanisms
- The OO approach described below uses reusable *framework* components and commonly recurring *patterns*

Eliminating Race Conditions

- Problem
  - A naive implementation of `MESSAGE_QUEUE` will lead to race conditions
    * *e.g.*, when messages in different threads are enqueued and dequeued concurrently
- Forces
  - Producer/consumer concurrency is common, but requires careful attention to avoid overhead, deadlock, and proper control
- Solution
  - Utilize the *Monitor Object* pattern and *condition variables*

The Monitor Object Pattern

Intent

- *Synchronizes method execution to ensure only one method runs within an object at a time. It also allows an object's methods to cooperatively schedule their execution sequences.*

Monitor Object

+ synchronized_method_1()
...
+ synchronized_method_m()
# monitor_lock_
# monotor_condition_1_
...
monitor_condition_n_

`~schmidt/POSA/`

Forces Resolved

- Synchronization corresponds to methods
- Objects, not clients, are responsible for synchronization
- Cooperative method scheduling

Overview of Condition Variables

- Condition variables (CVs) are used to “sleep/wait” until a particular condition involving shared data is signaled
  - CVs can wait on arbitrarily complex C++ expressions
  - Sleeping is often more efficient than busy waiting...
- This allows more complex scheduling decisions, compared with a mutex
  - *i.e.*, a mutex makes *other* threads wait, whereas a condition variable allows a thread to make *itself* wait for a particular condition involving shared data

Condition Variable Usage Patterns

```
// Initially unlocked.
static ACE_Thread_Mutex lock;
static ACE_Condition_Thread_Mutex
       cond (lock);

// synchronized
void acquire_resources (void) {
  // Automatically acquire lock.
  ACE_GUARD (ACE_Thread_Mutex, g, lock);

  // Check condition in loop
  while (condition expression false)
    // Sleep.
    cond.wait ();

  // Atomically modify shared
  // information.

  // Destructor releases lock.
}
```

Note how the use of the Scoped Locking idiom simplifies the solution since we can't forget to release the lock!

```
// synchronized
void release_resources (void) {
  // Automatically acquire lock.
  ACE_GUARD (ACE_Thread_Mutex, g, lock);

  // Atomically modify shared
  // information...

  cond.signal ();
  // Could use cond.broadcast() here.

  // guard automatically
  // releases lock.
}
```

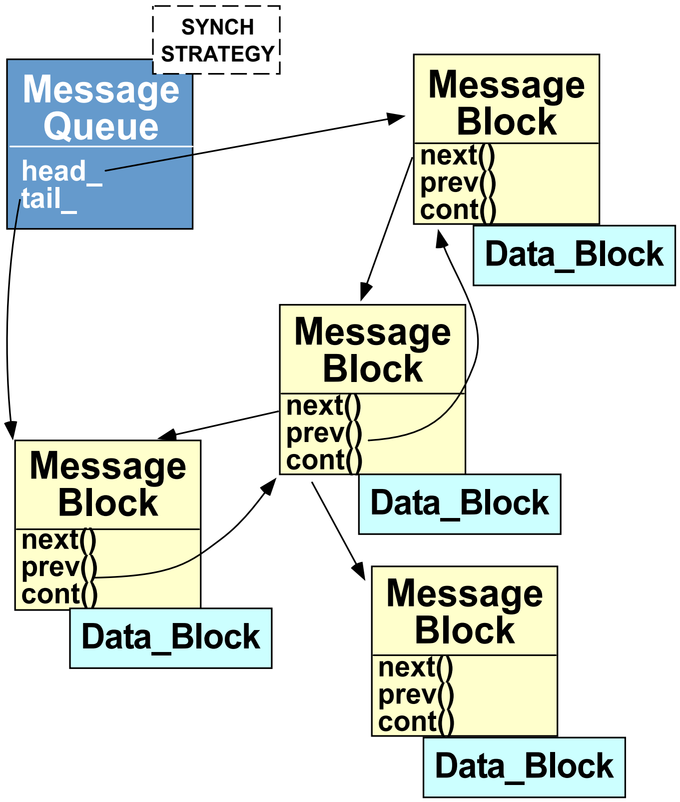
ACE Condition Variable Interface

```
class ACE_Condition_Thread_Mutex
public:
    // Initialize the CV.
  ACE_Condition_Thread_Mutex
    (const ACE_Thread_Mutex &);
    // Implicitly destroy the CV.
  ~ACE_Condition_Thread_Mutex (void);
    // Block on condition, or until
    // time passes.  If time == 0 block.
  int wait (ACE_Time_Value *time = 0);
    // Signal one waiting thread.
  int signal (void);
    // Signal *all* waiting threads.
  int broadcast (void) const;
private:
  cond_t cond_; // Solaris CV.
  const ACE_Thread_Mutex &mutex_;
};
```

The `ACE_Condition_Thread_Mutex` class is a wrapper for the native OS condition variable abstraction

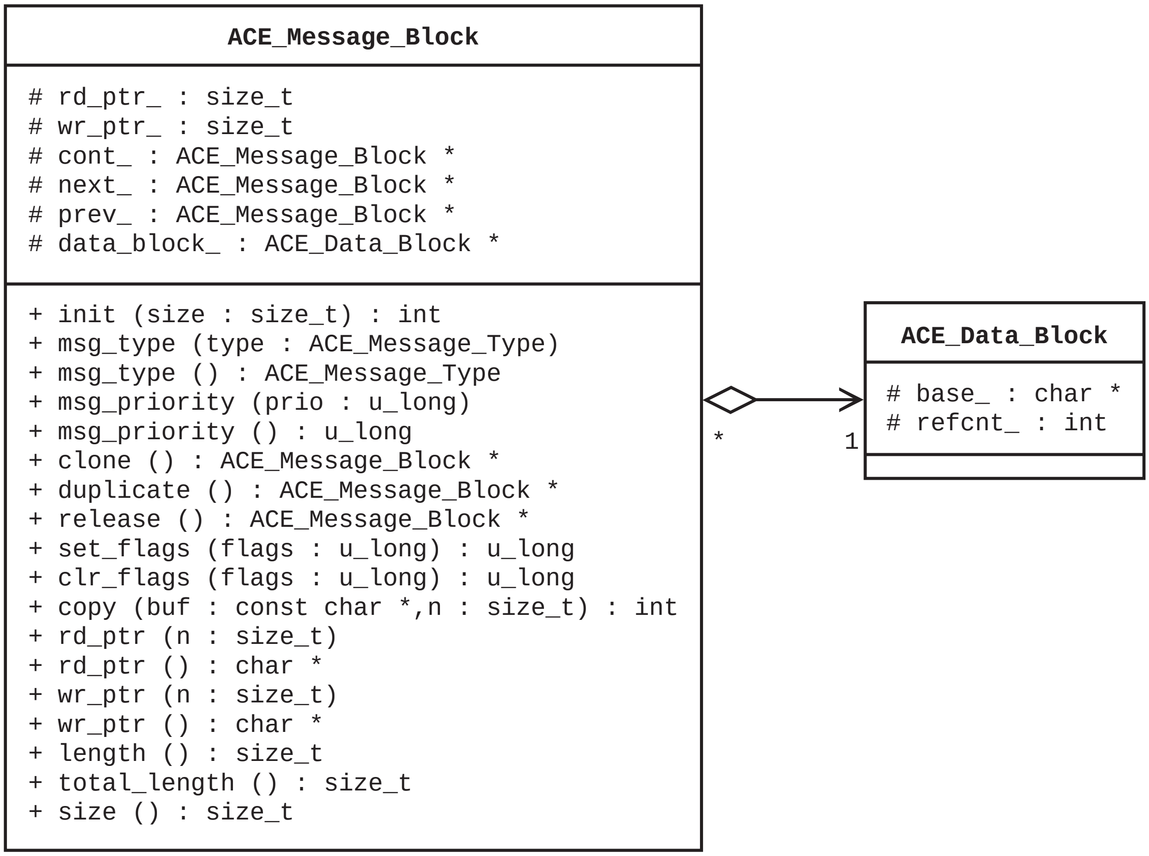
- *e.g.*, `cond_t` on SunOS 5.x, `pthread_cond_t` for POSIX, and a custom implementation on Windows and VxWorks

Overview of ACE_Message_Queue and ACE_Message_Block



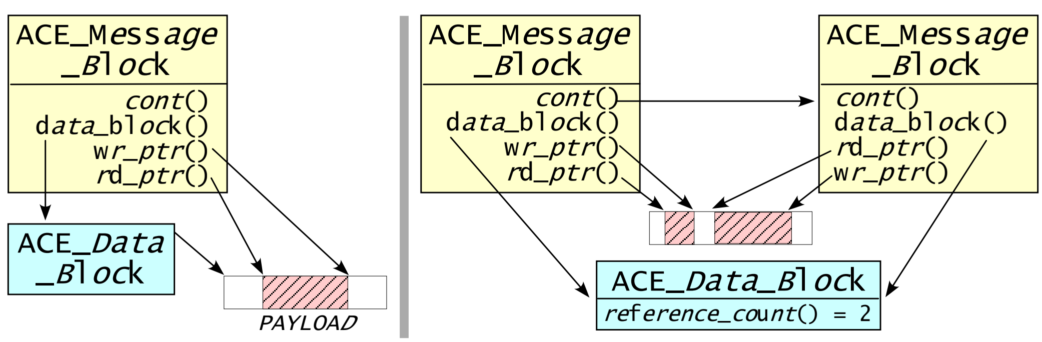
- An ACE_Message_Queue is a list of ACE_Message_Blocks
  - Efficiently handles arbitrarily-large message payloads
- An ACE_Message_Block is a *Composite*
  - Similar to BSD mbufs or SVR4 STREAMS m_blks
- Design parameterizes synchronization and allocation aspects

The ACE_Message_Block Class



Class characteristics

- Hide messaging implementations from clients



(1) SIMPLE MESSAGE STRUCTURE (2) COMPOSITE MESSAGE STRUCTURE

The ACE_Message_Queue Class

```
                                                    SYNCH_STRATEGY
                          ACE_Message_Queue
# head_ : ACE_Message_Block *
# tail_ : ACE_Message_Block *
# high_water_mark_ : size_t
# low_water_mark_ : size_t

+ ACE_Message_Queue (high_water_mark : size_t = DEFAULT_HWM,
                     low_water_mark : size_t = DEFAULT_LWM,
                     notify : ACE_Notification_Strategy * = 0)
+ open (high_water_mark : size_t = DEFAULT_HWM,
        low_water_mark : size_t = DEFAULT_LWM,
        notify : ACE_Notification_Strategy * = 0) : int
+ flush () : int
+ notification_strategy (s : ACE_Notification_Strategy *) : void
+ is_empty () : int
+ is_full () : int
+ enqueue_tail (item : ACE_Message_Block *,
               timeout : ACE_Time_Value * = 0) : int
+ enqueue_head (item : ACE_Message_Block *,
               timeout : ACE_Time_Value * = 0) : int
+ enqueue_prio (item : ACE_Message_Block *,
               timeout : ACE_Time_Value * = 0) : int
+ dequeue_head (item : ACE_Message_Block *&,
               timeout : ACE_Time_Value * = 0) : int
+ dequeue_tail (item : ACE_Message_Block *&,
               timeout : ACE_Time_Value * = 0) : int
+ high_water_mark (new_hwm : size_t) : void
+ high_water_mark (void) : size_t
+ low_water_mark (new_lwm : size_t) : void
+ low_water_mark (void) : size_t
+ close () : int
+ deactivate () : int
+ activate () : int
+ pulse () : int
+ state () : int
```

Class characteristics

- Note how the synchronization aspect can be strategized!

The ACE_Message_Queue Public Interface

```
template <class SYNCH_STRAT = ACE_MT_SYNCH>
         // Synchronization aspect
class ACE_Message_Queue
{
public:
    // Default high and low water marks.
  enum {
    DEFAULT_LWM = 0,
    DEFAULT_HWM = 4096
  };

    // Initialize a Message_Queue.
  Message_Queue (size_t hwm = DEFAULT_HWM,
                 size_t lwm = DEFAULT_LWM);
    // Check if full or empty (hold locks)
  int is_empty (void) const;
  int is_full (void) const;

    // Enqueue and dequeue Message_Block *'s.
  int enqueue_prio (ACE_Message_Block *, ACE_Time_Value *);
  int enqueue_tail (ACE_Message_Block *, ACE_Time_Value *);
  int dequeue_head (ACE_Message_Block *&, ACE_Time_Value *);
  int dequeue_tail (ACE_Message_Block *&, ACE_Time_Value *);
```

Design Interlude: Parameterizing Synchronization Strategies

- Q: *What is `ACE_MT_SYNCH` and how does it work?*
- A: `ACE_MT_SYNCH` provides a thread-safe synchronization strategy for a `ACE_Svc_Handler`
  - *e.g.*, it ensures that an `ACE_Svc_Handler`'s `ACE_Message_Queue` is thread-safe
  - Any `ACE_Task` that accesses shared state can use the `ACE_MT_SYNCH` *traits*

Note the use of *traits*:

```
struct ACE_MT_SYNCH {
  typedef ACE_Thread_Mutex
    MUTEX;
  typedef
    ACE_Condition_Thread_Mutex
    COND;
};

struct ACE_NULL_SYNCH {
  typedef ACE_Null_Mutex
    MUTEX;
  typedef
    ACE_Null_Condition COND;
};
```

ACE_Message_Queue Class Private Interface

```
private:
    // Check boundary conditions & don't hold locks.
  int is_empty_i (void) const;
  int is_full_i (void) const;

    // Routines that actually do the enqueueing
    // and dequeueing and don't hold locks.
  int enqueue_prio_i (ACE_Message_Block *);
  int enqueue_tail_i (ACE_Message_Block *);
  int dequeue_head_i (ACE_Message_Block *&);
  int dequeue_tail_i (ACE_Message_Block *&);
    // ...
    // Parameterized types for synchronization
    // primitives that control concurrent access.
    // Note use of C++ traits
  typename SYNCH_STRAT::MUTEX lock_;
  typename SYNCH_STRAT::COND not_empty_cond_;
  typename SYNCH_STRAT::COND not_full_cond_;

  size_t high_water_mark_;
  size_t low_water_mark_;
  size_t cur_bytes_;
  size_t cur_count_;
};
```

Design Interlude: Tips for Intra-class Locking

- Q: *How should locking be performed in an OO class?*
- A: Apply the *Thread-Safe Interface* pattern:
  - "Interface functions should lock and do no work – implementation functions should do the work and not lock "
    - This pattern helps to avoid intra-class method deadlock
  - This is actually a variant on a common OO pattern that "public functions should check, private functions should trust"
    - Naturally, there are exceptions to this rule...
  - This pattern avoids the following surprises
    - Unnecessary overhead from recursive mutexes
    - Deadlock if recursive mutexes aren't used
- `www.cs.wustl.edu/~schmidt/POSA/`

ACE_Message_Queue Class Implementation

```
template <class SYNCH_STRAT>
ACE_Message_Queue<SYNCH_STRAT>::ACE_Message_Queue
  (size_t hwm, size_t lwm)
  : not_empty_cond_ (lock_), not_full_cond_ (lock_),
    ... {}

template <class SYNCH_STRAT> int
ACE_Message_Queue<SYNCH_STRAT>::is_empty_i (void) const
{ return cur_bytes_ == 0 && cur_count_ == 0; }

template <class SYNCH_STRAT> int
ACE_Message_Queue<SYNCH_STRAT>::is_full_i (void) const
{ return cur_bytes_ > high_water_mark_; }

template <class SYNCH_STRAT> int
ACE_Message_Queue<SYNCH_STRAT>::is_empty (void) const
{
  ACE_GUARD_RETURN (SYNCH_STRAT::MUTEX, g, lock_, -1);
  return is_empty_i ();
}

template <class SYNCH_STRAT> int
ACE_Message_Queue<SYNCH_STRAT>::is_full (void) const
{
  ACE_GUARD_RETURN (SYNCH_STRAT::MUTEX, g, lock_, -1);
  return is_full_i ();
}
```

ACE_Message_Queue Operations

```
template <class SYNCH_STRAT> int
ACE_Message_Queue<SYNCH_STRAT>::
enqueue_tail (ACE_Message_Block *item,
              ACE_Time_Value *tv) {
  ACE_GUARD_RETURN (SYNCH_STRAT::MUTEX,
                    guard, lock_, -1);
  // Wait while the queue is full.
  while (is_full_i ()) {
    // Release the <lock_> and wait
    // for timeout, signal, or space
    // to become available in the list.
    if (not_full_cond_.wait (tv) == -1)
      return -1;
  }
  // Actually enqueue the message at
  // the end of the list.
  enqueue_tail_i (item);

  // Tell blocked threads that
  // list has a new item!
  not_empty_cond_.signal ();
}
```

```
template <class SYNCH_STRAT> int
ACE_Message_Queue<SYNCH_STRAT>::
dequeue_head (ACE_Message_Block *&item,
              ACE_Time_Value *tv) {
  ACE_GUARD_RETURN (SYNCH_STRAT::MUTEX,
                    guard, lock_, -1);
  // Wait while the queue is empty.
  while (is_empty_i ()) {
    // Release lock_ and wait for timeout,
    // signal, or a new message being
    // placed in the list.
    if (not_empty_cond_.wait (tv) == -1)
      return -1;
  }
  // Actually dequeue the first message.
  dequeue_head_i (item);

  // Tell blocked threads that list
  // is no longer full.
  if (cur_bytes_ <= low_water_mark_)
    not_full_cond_.signal ();
}
```

Overcoming Algorithmic Decomposition Limitations

- Previous slides illustrate *tactical* techniques and patterns that:
  - *Reduce accidental complexity e.g.*,
    - Automate synchronization acquisition and release (Scoped Locking idiom)
    - Improve synchronization mechanisms (Adapter, Wrapper Facade, Monitor Object, Thread-Safe Interface, Strategized Locking patterns)
  - *Eliminate race conditions*
- Next, we describe *strategic* patterns, frameworks, and components to:
  - *Increase reuse and extensibility e.g.*,
    - Decoupling service, IPC, and demultiplexing
  - *Improve the flexibility of concurrency control*

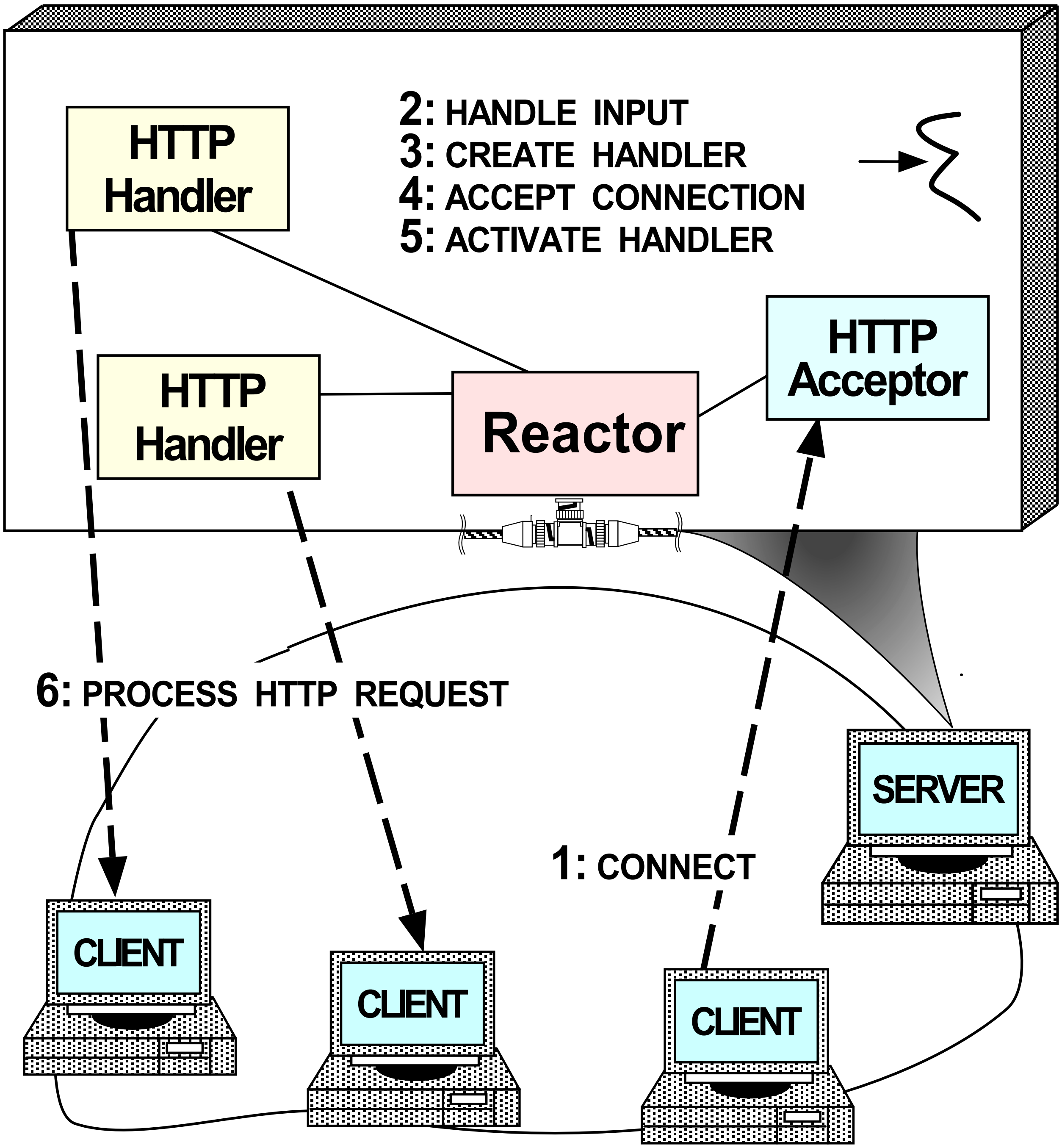
Selecting the Server's Concurrency Architecture

- Problem
  - A very strategic design decision for high-performance Web servers is selecting an efficient *concurrency architecture*
- Forces
  - No single concurrency architecture is optimal
  - Key factors include OS/hardware platform and workload
- Solution
  - Understand key alternative *concurrency* patterns

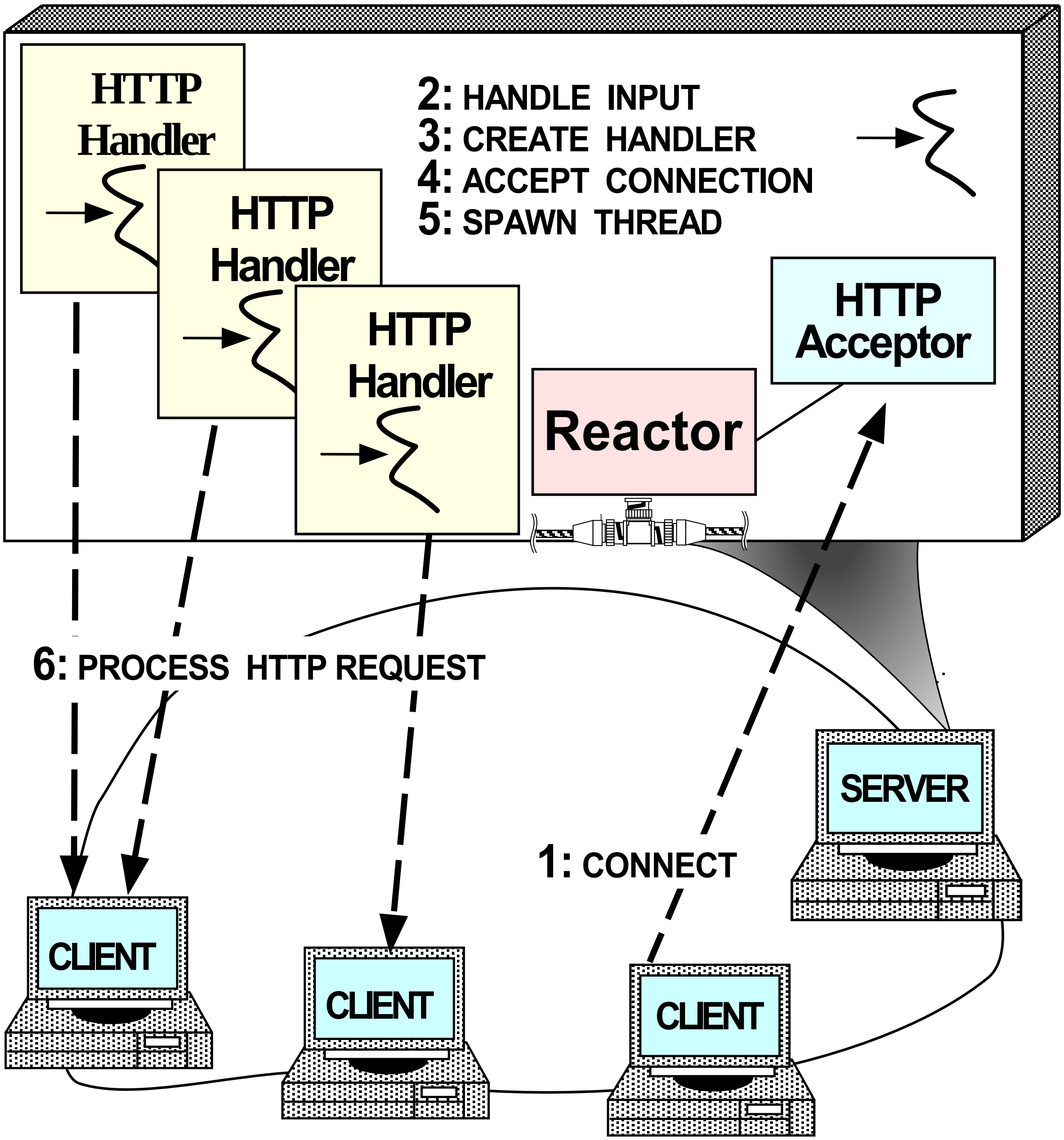
Concurrency Patterns in the Web Server

- The following example illustrates the *patterns* and *framework components* in an OO implementation of a concurrent Web Server
- There are various architectural patterns for structuring concurrency in a Web Server
  - *Reactive*
  - *Thread-per-request*
  - *Thread-per-connection*
  - *Synchronous Thread Pool*
    - Leader/Followers Thread Pool
    - Half-Sync/Half-Async Thread Pool
  - *Asynchronous Thread Pool*

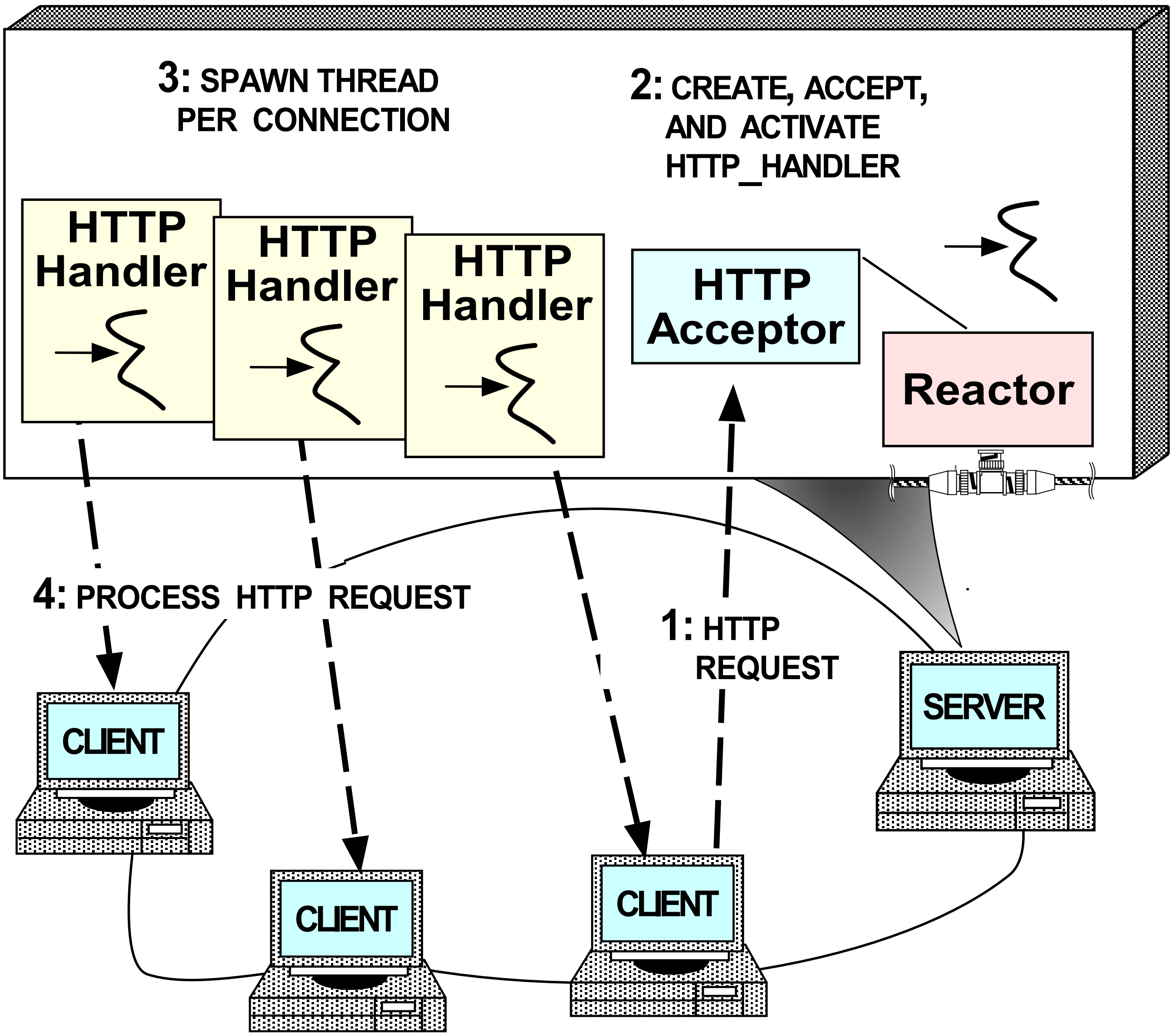
Reactive Web Server



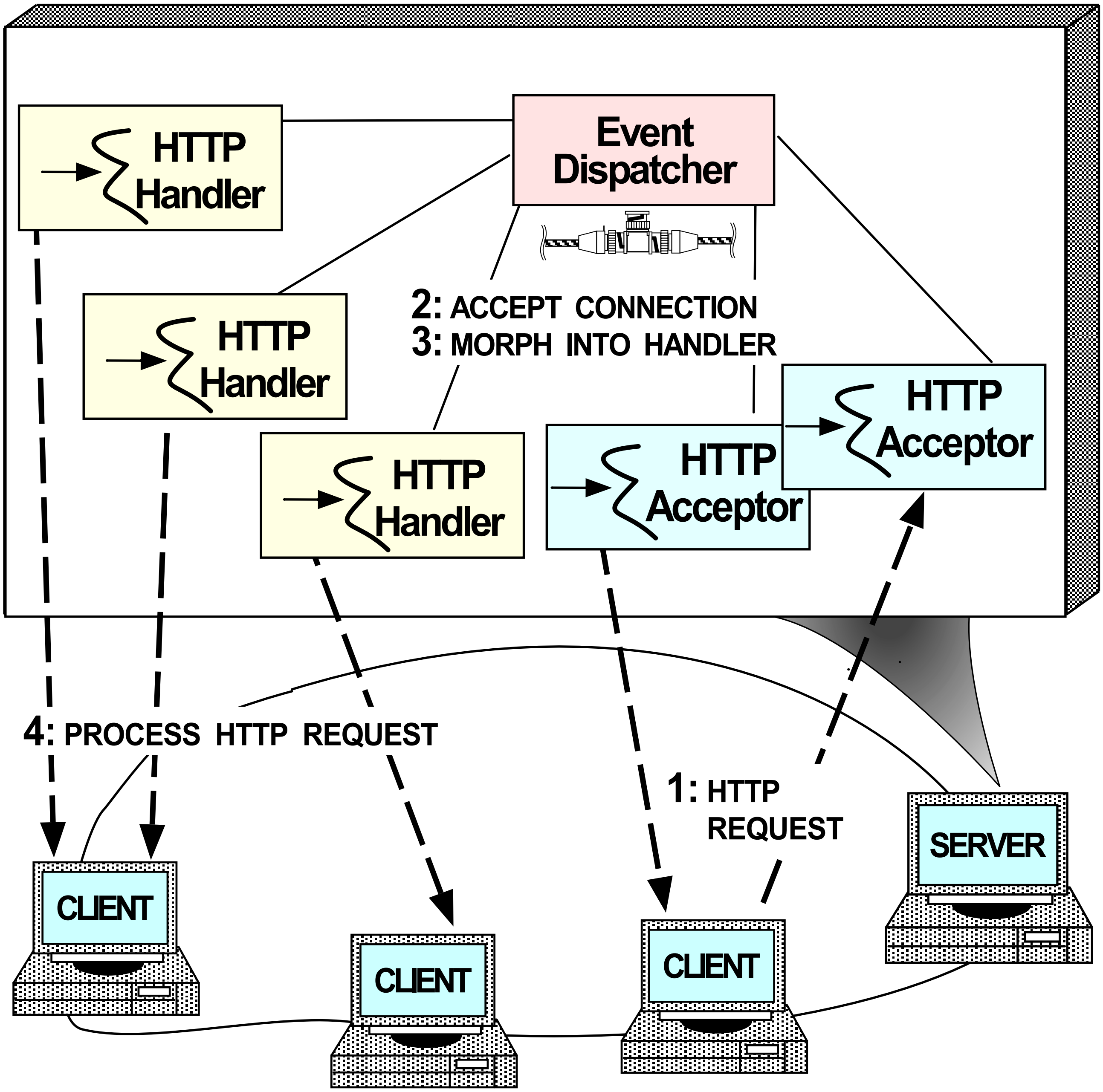
Thread-per-Request Web Server



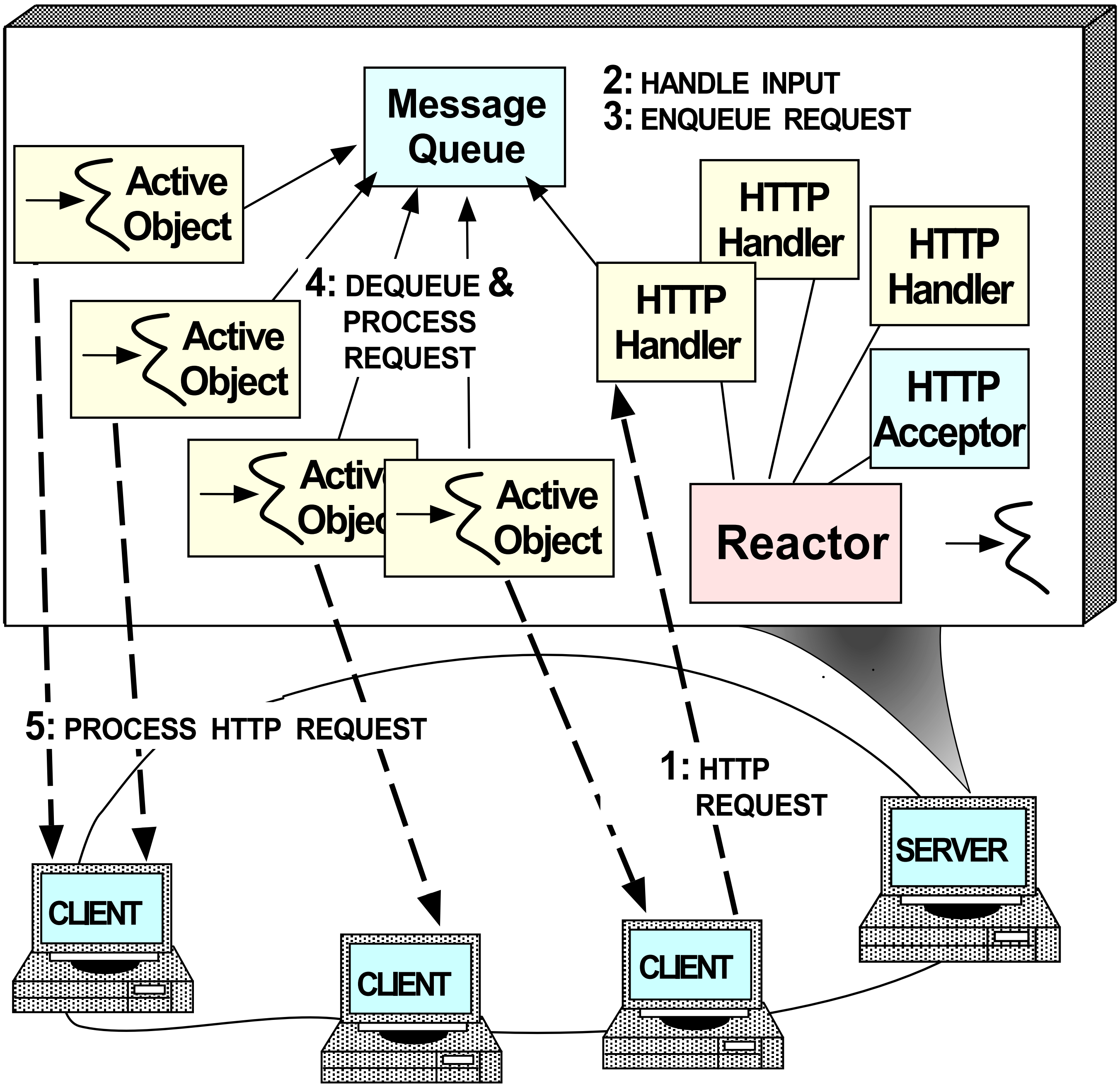
Thread-per-Connection Web Server



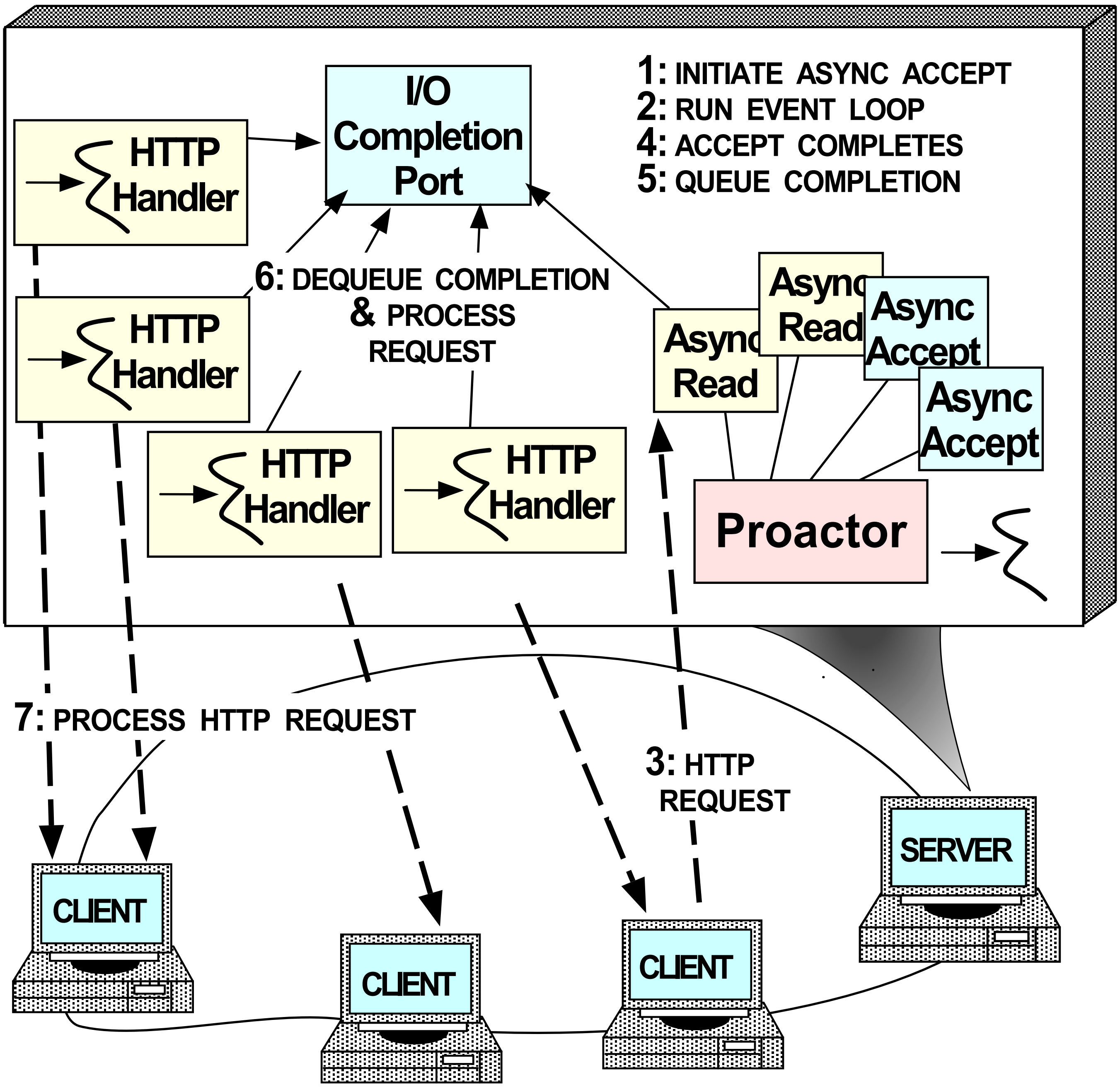
Leader/Followers Synchronous Thread Pool Web Server



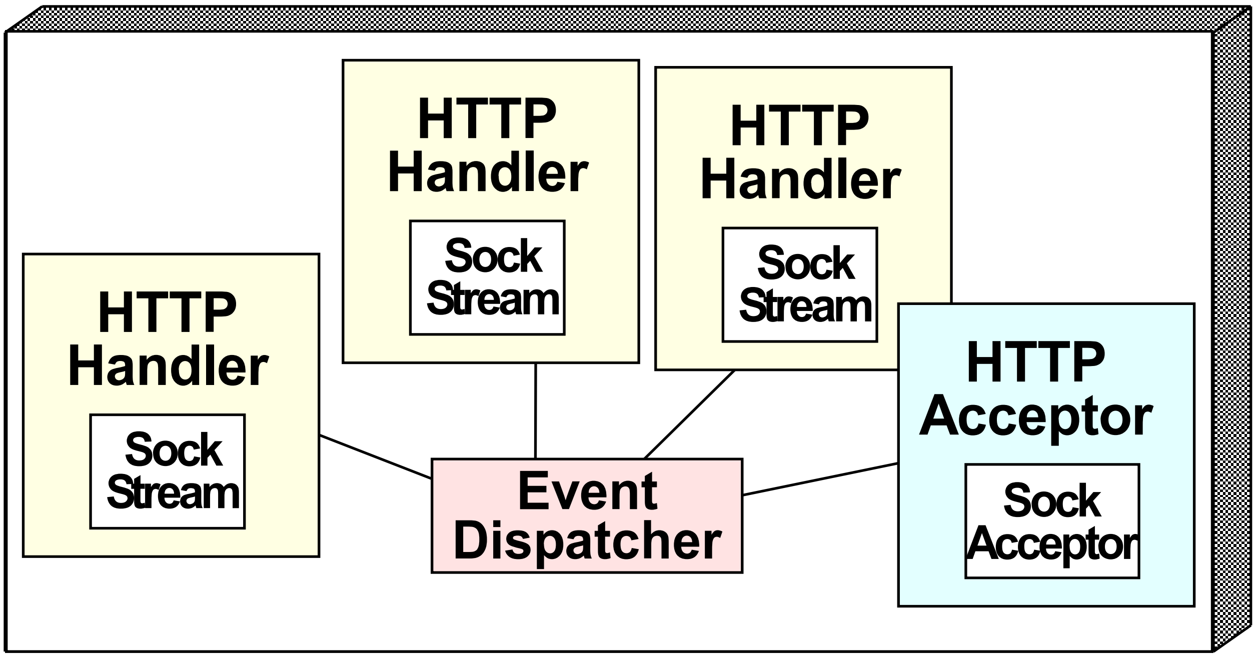
Half-Sync/Half-Async Synchronous Thread Pool Web Server



Asynchronous Thread Pool Web Server

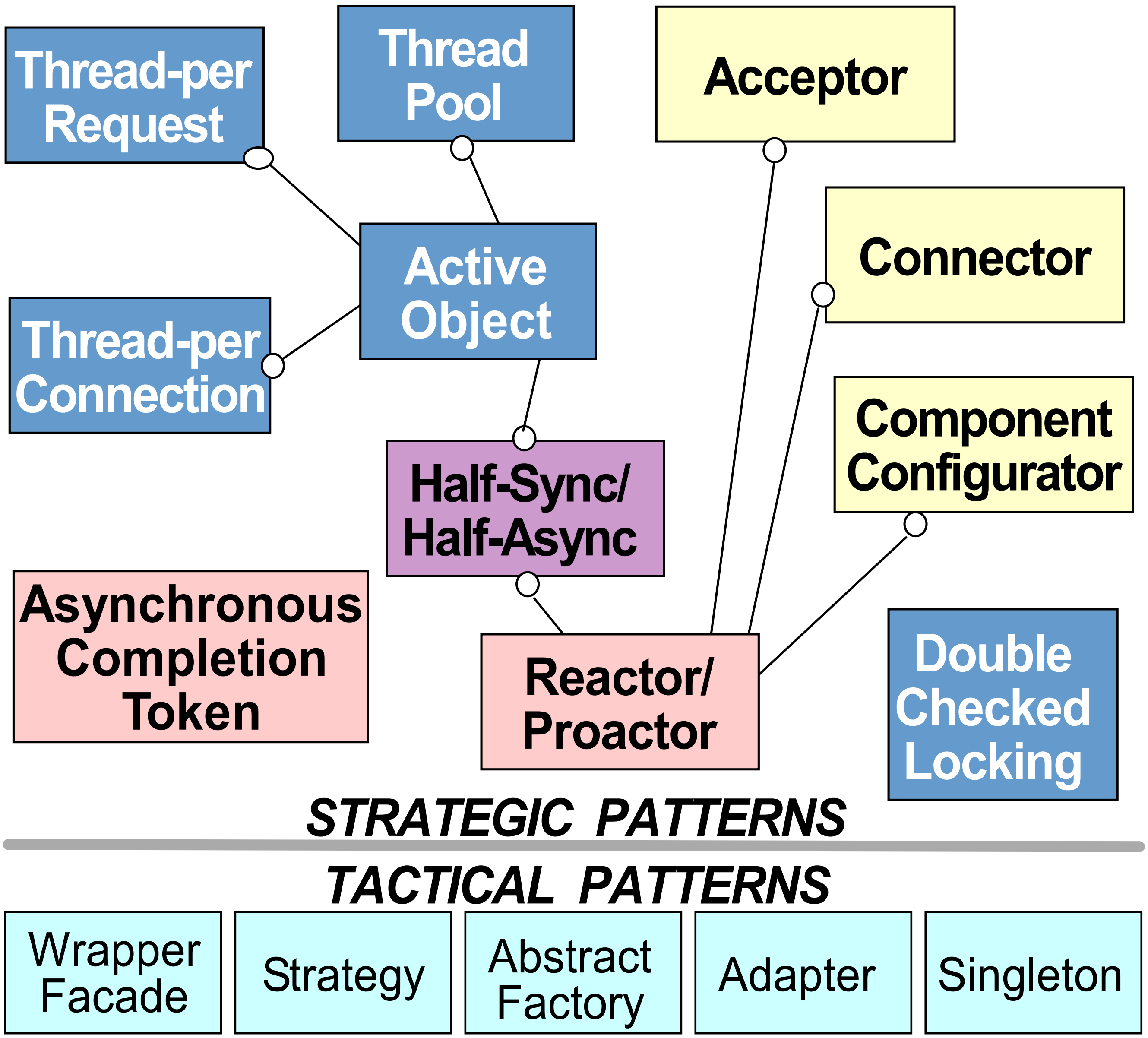


Web Server Software Architecture



- Event Dispatcher
  - Encapsulates Web server concurrency and dispatching strategies
- HTTP Handlers
  - Parses HTTP headers and processes requests
- HTTP Acceptor
  - Accepts connections and creates HTTP Handlers

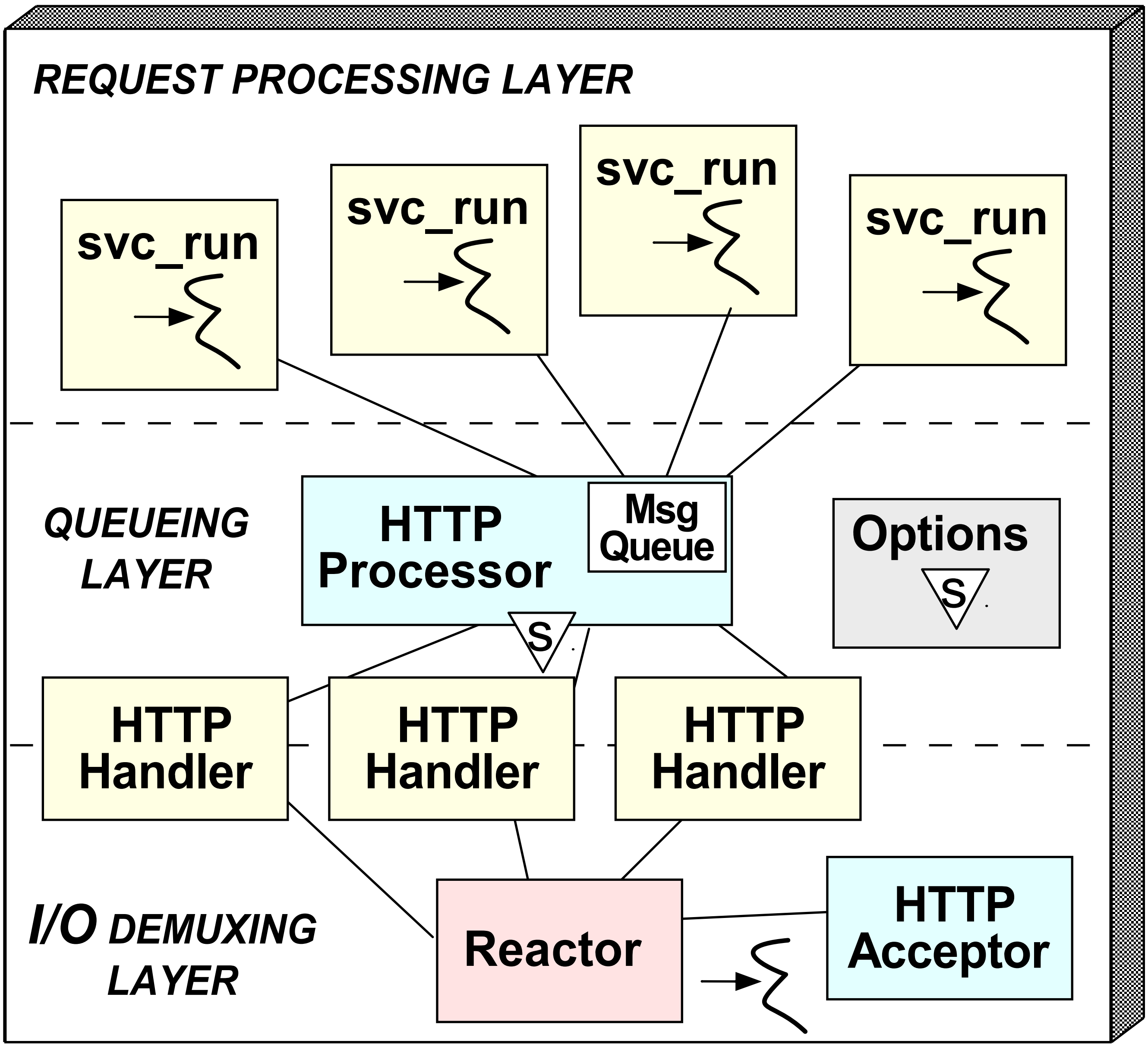
Patterns in the Web Server Implementation



Patterns in the Web Client/Server (cont'd)

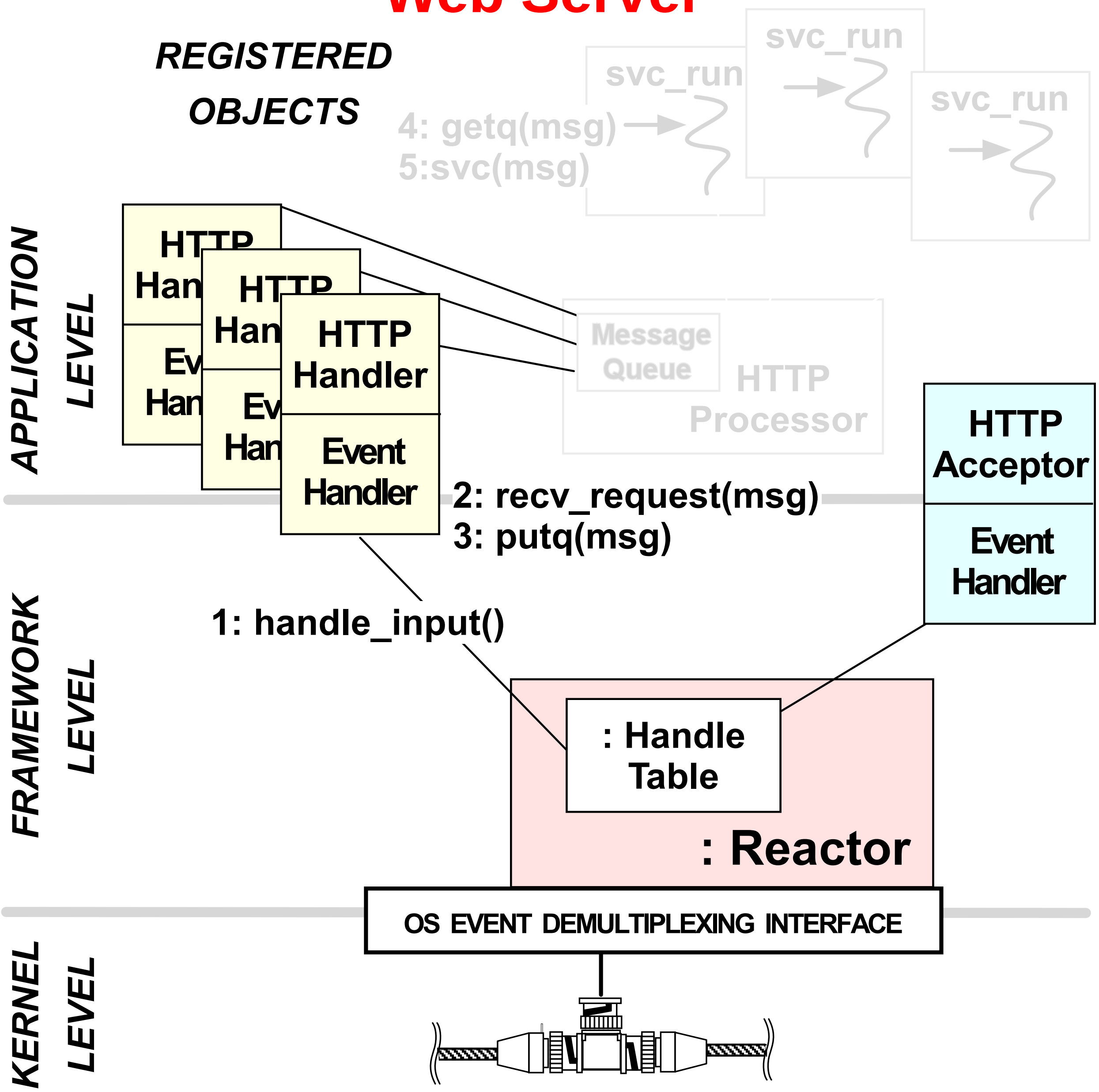
- The Web Client/Server uses same patterns as distributed logger
  - *i.e.*, Reactor, Component Configurator, Active Object, and Acceptor
- It also contains patterns with the following intents:
  - *Connector* $\rightarrow$ "Decouple the active connection and initialization of a peer service in a distributed system from the processing performed once the peer service is connected and initialized"
  - *Double-Checked Locking Optimization* $\rightarrow$ "Allows atomic initialization, regardless of initialization order, and eliminates subsequent locking overhead"
  - *Half-Sync/Half-Async* $\rightarrow$ "Decouples synchronous I/O from asynchronous I/O in a system to simplify concurrent programming effort without degrading execution efficiency"

Architecture of Our Web Server



www.cs.wustl.edu/˜schmidt/PDF/HPL.pdf

An Integrated Reactive/Active Web Server



We're focusing on the Reactive layer here

HTTP_Handler Public Interface

```
template <class ACCEPTOR>
class HTTP_Handler : public
  ACE_Svc_Handler<ACCEPTOR::PEER_STREAM,
                  ACE_NULL_SYNCH> {
public:
    // Entry point into <HTTP_Handler>,
    // called by <HTTP_Acceptor>.
  virtual int open (void *)
  {
    // Register with <ACE_Reactor>
    // to handle input.
    reactor ()->register_handler
      (this, ACE_Event_Handler::READ_MASK);
    // Register timeout in case client
    // doesn't send any HTTP requests.
    reactor ()->schedule_timer
      (this, 0, ACE_Time_Value (CLIENT_TIMEOUT));
  }
```

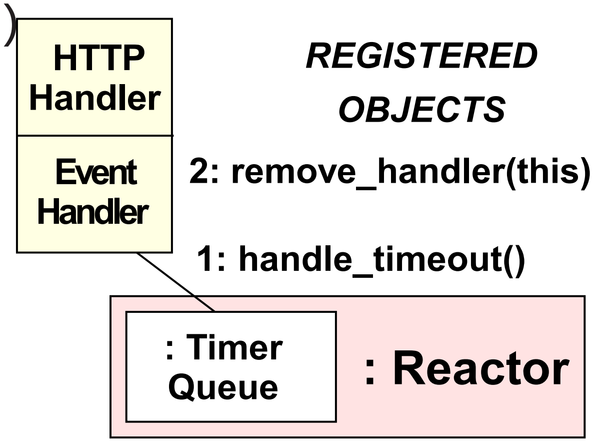
The `HTTP_Handler` is the Proxy for communicating with clients (e.g., Web browsers like Netscape or *i.e.*,)

- It implements the asynchronous portion of Half-Sync/Half-Async pattern

HTTP_Handler Protected Interface

```
protected:
  // Reactor dispatches this
  // method when clients timeout.
  virtual int handle_timeout
    (const ACE_Time_Value &, const void *)
  {
    // Remove from the Reactor.
    reactor ()->remove_handler
      (this,
       ACE_Event_Handler::READ_MASK);
  }
    // Reactor dispatches this method
    // when HTTP requests arrive.
  virtual int handle_input (ACE_HANDLE);
    // Receive/frame client HTTP
    // requests (e.g., GET).
  int recv_request (ACE_Message_Block *&);
};
```

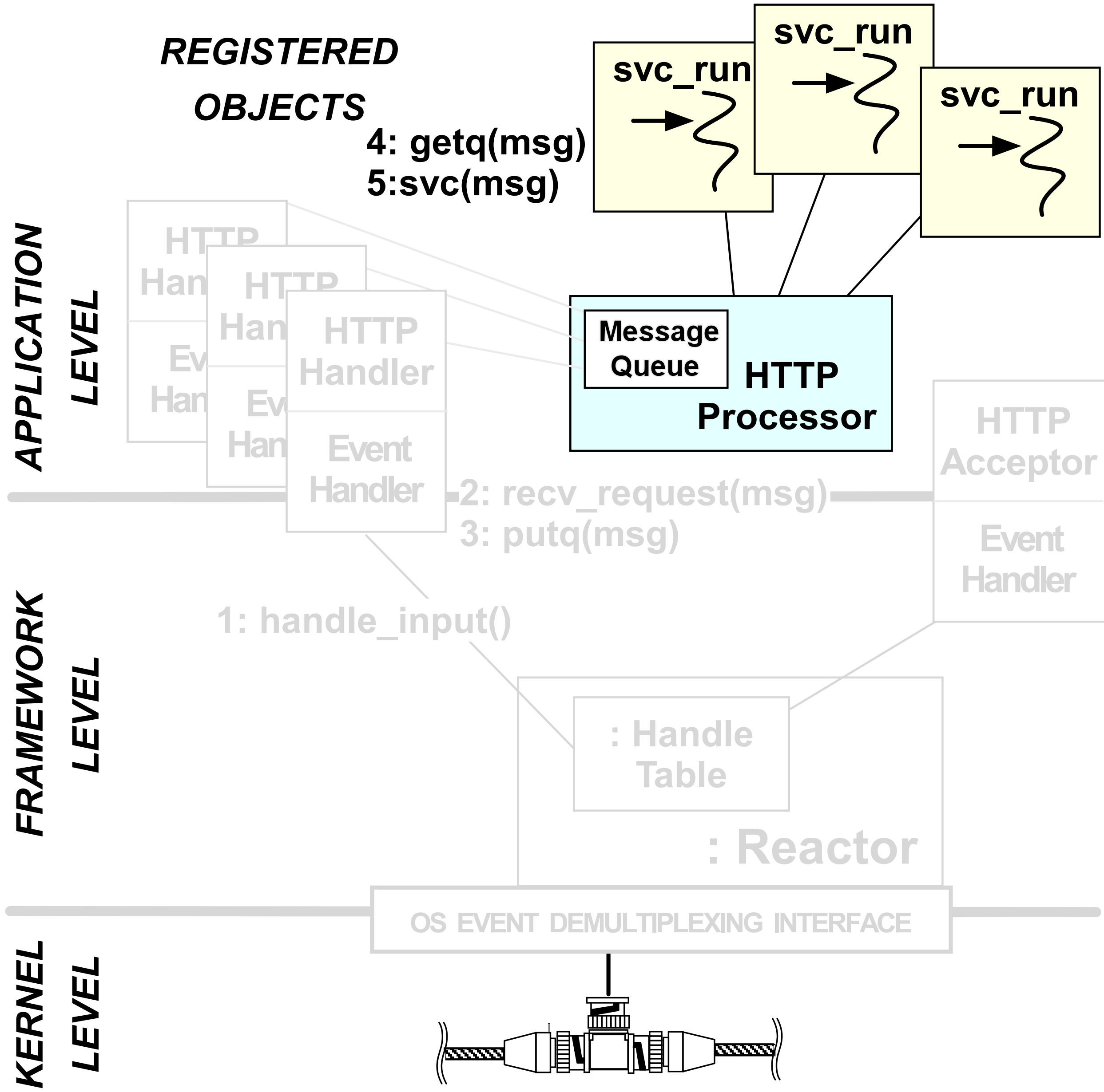
These methods are invoked by callbacks from `ACE_Reactor`



Integrating Multi-threading

- Problem
  - Multi-threaded Web servers are needed since Reactive Web servers are often inefficient and non-robust
- Forces
  - Multi-threading can be very hard to program
  - No single multi-threading model is always optimal
- Solution
  - Use the *Active Object* pattern to allow multiple concurrent server operations in an OO-manner

Using the Active Object Pattern and ACE Task Framework in the Web Server



We're focusing on the Active Object layer here

The HTTP_Processor Class

```
class HTTP_Processor
  : public ACE_Task<ACE_MT_SYNCH> {
private: HTTP_Processor (void);
public:
    // Singleton access point.
  static HTTP_Processor *instance (void);
    // Pass a request to the thread pool.
  virtual int put (ACE_Message_Block *,
                   ACE_Time_Value *);
    // Entry point into a pool thread.
  virtual int svc (void)
  {
    ACE_Message_Block *mb = 0;

    // Wait for messages to arrive.
    for (;;) {
      getq (mb); // Inherited from <ACE_Task>
      // Identify and perform HTTP
      // Server request processing...
```

- Processes HTTP requests using the “Thread-Pool” concurrency model
- This method implements the synchronous task portion of the Half-Sync/Half-Async pattern

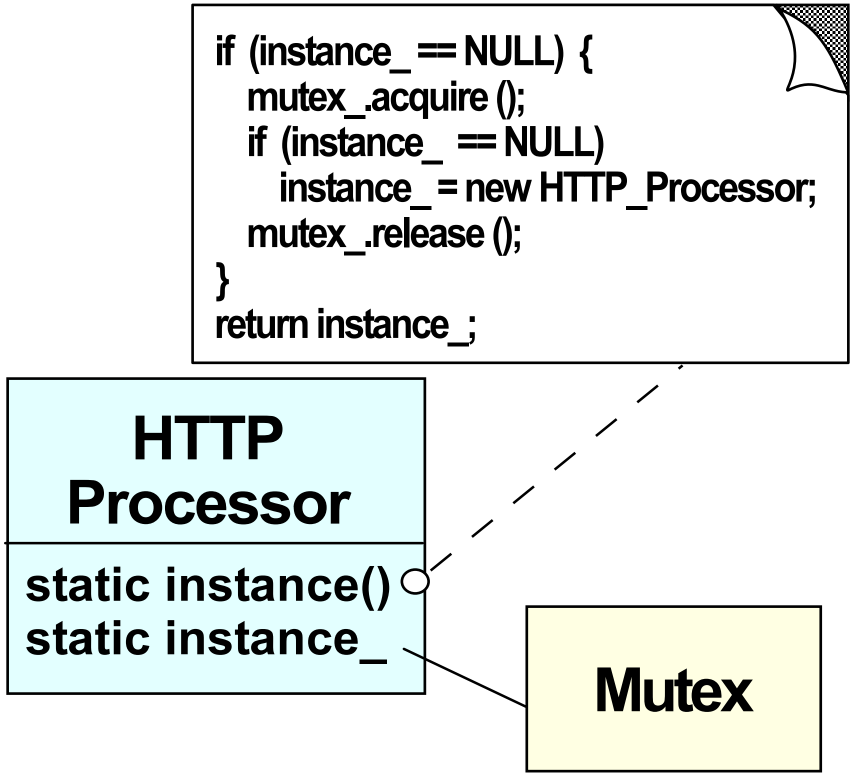
Using the Singleton Pattern

```
// Singleton access point.

HTTP_Processor *
HTTP_Processor::instance (void)
{
  // Beware of race conditions!
  if (instance_ == 0)
    // Create the Singleton "on-demand."
    instance_ = new HTTP_Processor;

  return instance_;
}

// Constructor creates the thread pool.

HTTP_Processor::HTTP_Processor (void)
{
  // Inherited from class Task.
  activate (THR_BOUND,
            Options::instance ()->threads ());
}
```

Subtle Concurrency Woes with the Singleton Pattern

- Problem
  - The canonical Singleton implementation has subtle “bugs” in multi-threaded applications
- Forces
  - Too much locking makes Singleton too slow...
  - Too little locking makes Singleton unsafe...
- Solution
  - Use the *Double-Checked Locking* optimization pattern to minimize locking **and** ensure atomic initialization

The Double-Checked Locking Optimization Pattern



www.cs.wustl.edu/~schmidt/POSA/

Intent

- *Allows atomic initialization, regardless of initialization order, and eliminates subsequent locking overhead*

Forces Resolved:

- Ensures atomic object initialization
- Minimizes locking overhead

Caveat!

- This pattern assumes *atomic* memory access

The ACE Singleton Template

```
template <class TYPE, class LOCK>
class ACE_Singleton : public ACE_Cleanup {
public:
  static TYPE *instance (void) {
    // Memory barrier could go here...
    if (s_ == 0) {
      ACE_GUARD_RETURN (LOCK, g,
        ACE_Object_Manager
        ::get_singleton_lock (), -1);
      if (s_ == 0)
        s_ = new ACE_Singleton<TYPE>;
        // Memory barrier could go here.
      ACE_Object_Manager::at_exit (s_);
    }
    return s_->instance_;
  }
  virtual void cleanup (void *param = 0);
protected:
  ACE_Singleton (void);
  TYPE instance_;
  static ACE_Singleton<TYPE, LOCK> *s_;
};
```

Features

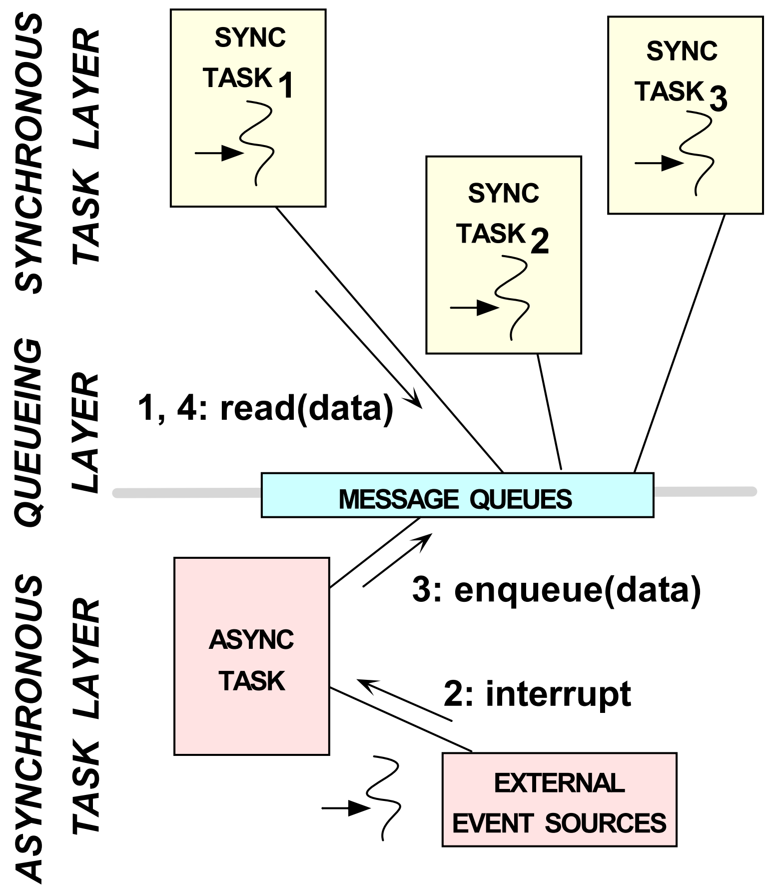
- Turns any class into a singleton
- Automates Double-Checked Locking Optimization
- Ensures automatic cleanup when process exits

`www.cs.wustl.edu/~schmidt/PDF/ObjMan.pdf`

Integrating Reactive and Multi-threaded Layers

- Problem
  - Justifying the hybrid design of our Web server can be tricky
- Forces
  - Engineers are never satisfied with the status quo ;-)
  - Substantial amount of time is spent re-discovering the *intent* of complex concurrent software design
- Solution
  - Use the *Half-Sync/Half-Async* pattern to explain and justify our Web server concurrency architecture

The Half-Sync/Half-Async Pattern



Intent

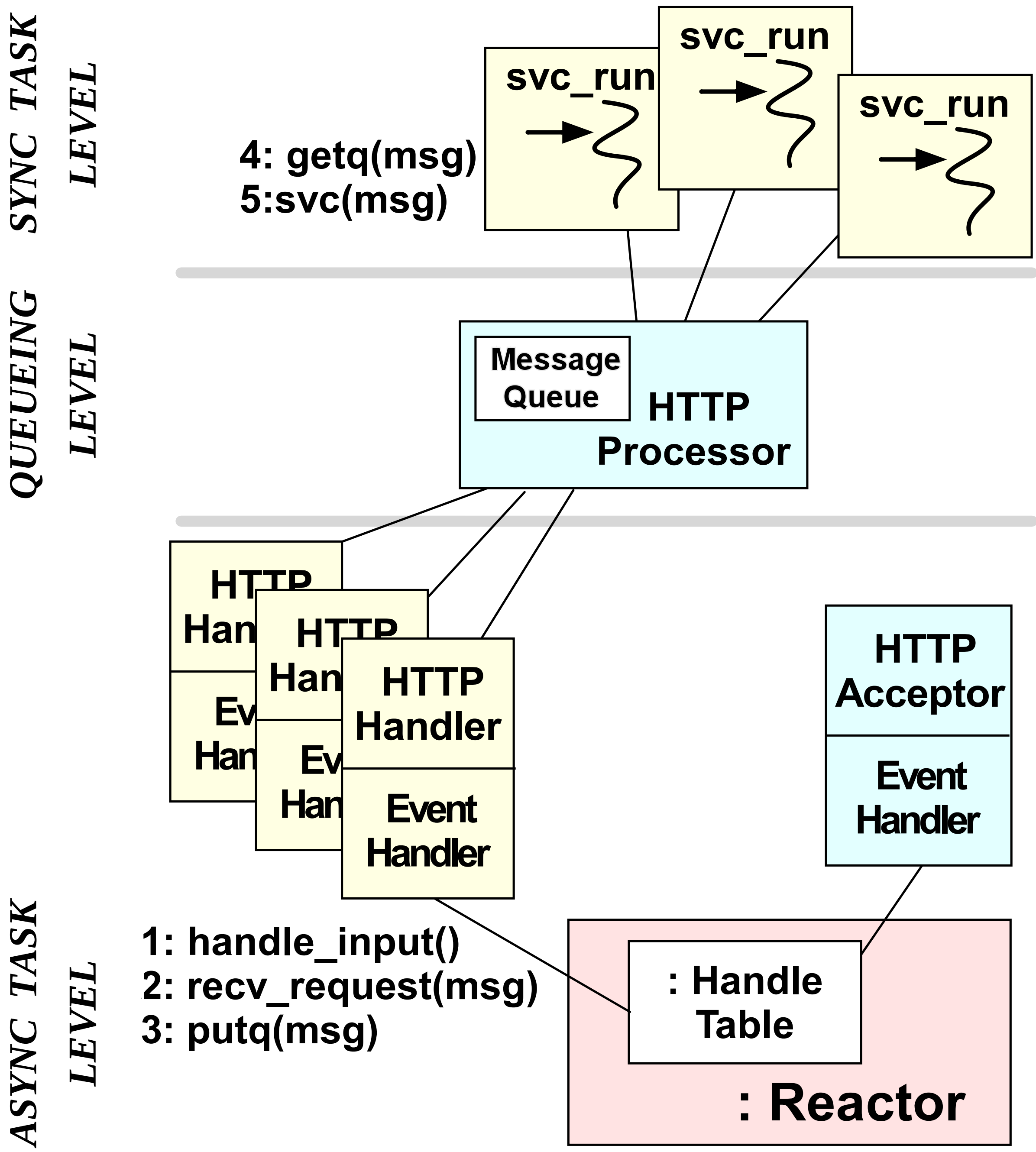
- *Decouples synchronous I/O from asynchronous I/O in a system to simplify concurrent programming effort without degrading execution efficiency*

Forces Resolved:

- Simplify programming
- Ensure efficient I/O

`www.cs.wustl.edu/˜schmidt/POSA/`

Using the Half-Sync/Half-Async Pattern in the Web Server



Joining Async and Sync Tasks in the Web Server

```
// The following methods form the boundary
// between the Async and Sync layers.

template <class PA> int
HTTP_Handler<PA>::handle_input (ACE_HANDLE h)
{
  ACE_Message_Block *mb = 0;

  // Try to receive and frame message.
  if (recv_request (mb) == HTTP_REQUEST_COMPLETE) {
    reactor ()->remove_handler
      (this, ACE_Event_Handler::READ_MASK);
    reactor ()->cancel_timer (this);
    // Insert message into the Queue.
    HTTP_Processor<PA>::instance ()->put (mb);
  }
}

int HTTP_Processor::put (ACE_Message_Block *msg,
                         ACE_Time_Value *timeout)
{
  // Insert the message on the Message_Queue
  // (inherited from class Task).
  putq (msg, timeout);
}
```

Optimizing Our Web Server for Asynchronous Operating Systems

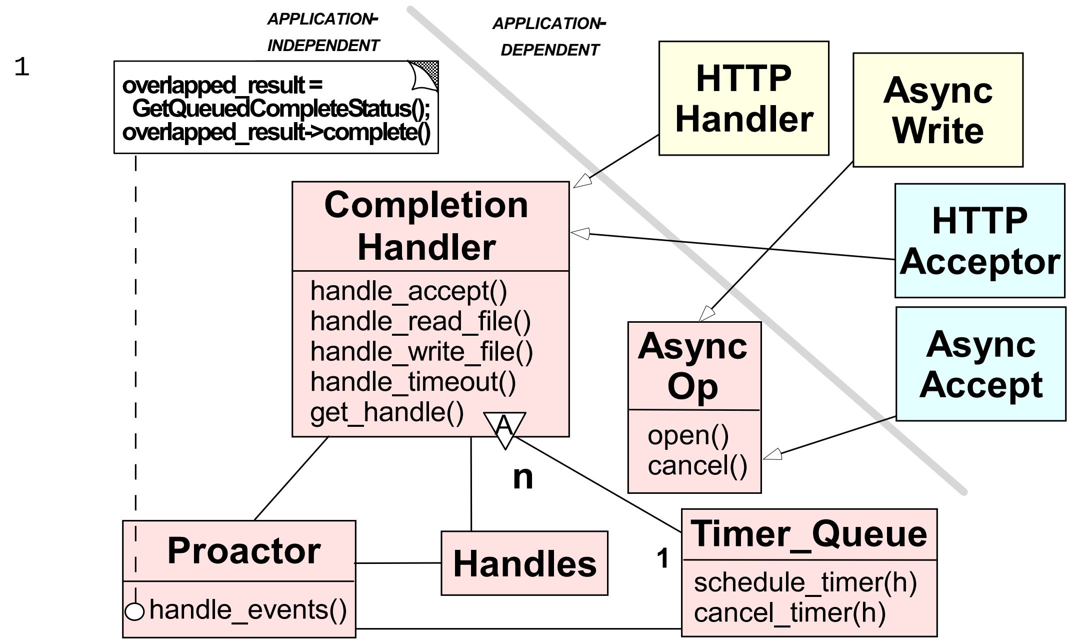
- Problem
  - Synchronous multi-threaded solutions are not always the most efficient
- Forces
  - Purely asynchronous I/O is quite powerful on some OS platforms
    - *e.g.*, Windows NT 4.x or UNIX with `aio_()*` calls
  - Good designs should be adaptable to new contexts
- Solution
  - Use the *Proactor* pattern to maximize performance on Asynchronous OS platforms

The Proactor Pattern

Intent

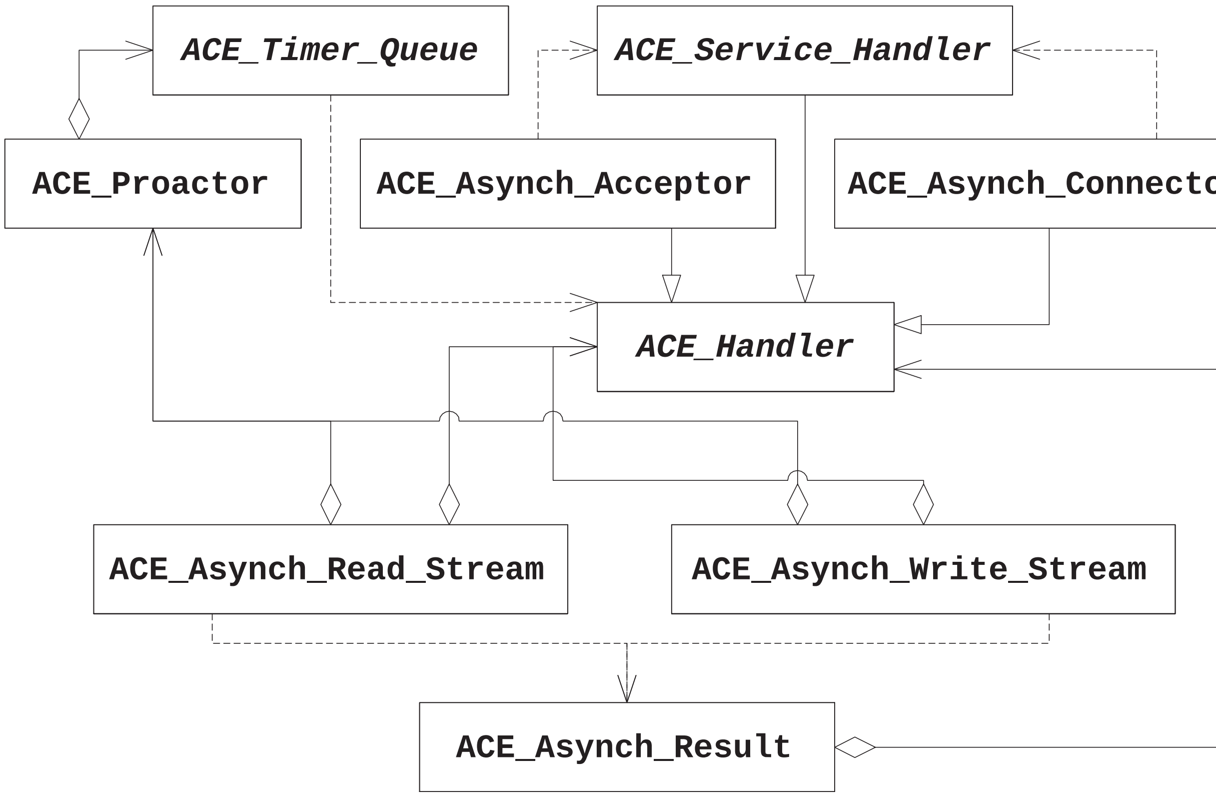
- *Demultiplexes and dispatches service requests that are triggered by the completion of asynchronous operations*

Resolves same forces as Reactor



www.cs.wustl.edu/˜schmidt/POSA/

Structure of the ACE Proactor Framework

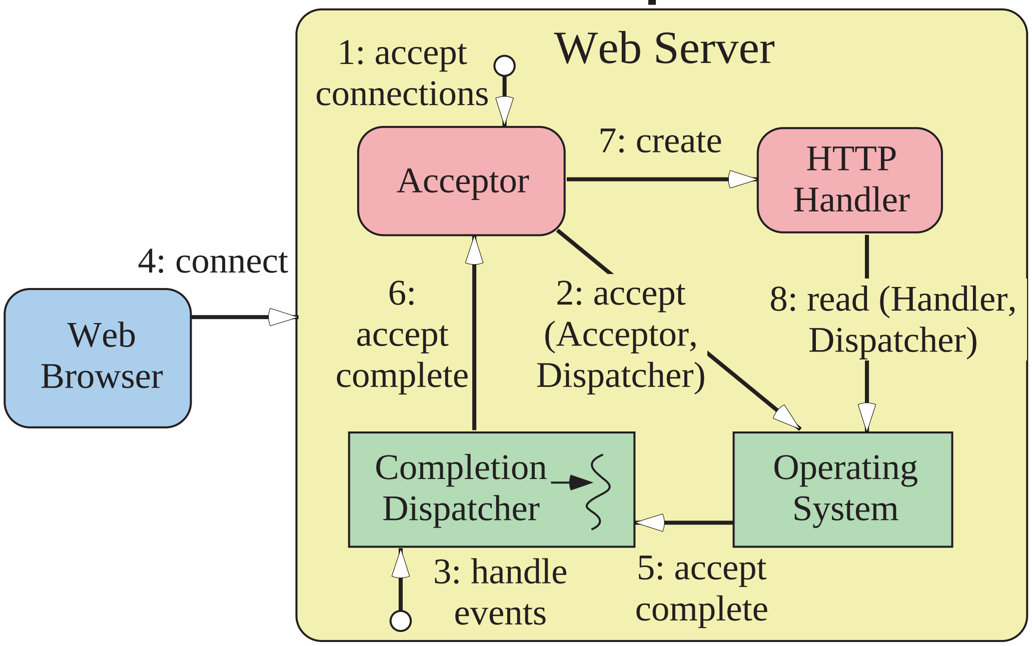


Framework characteristics

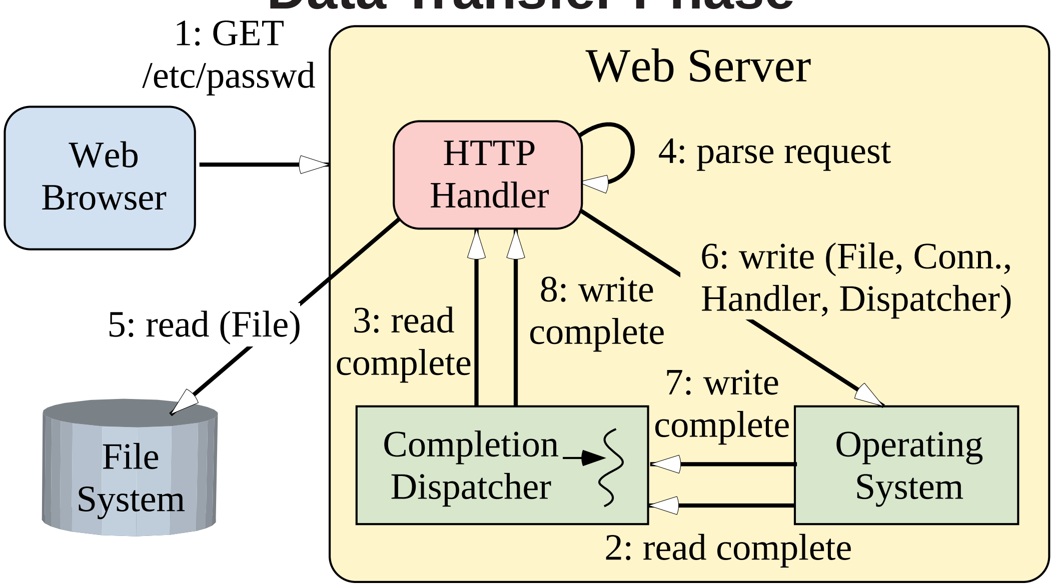
- Similar to the ACE Reactor framework, except behavior is "inverse"
- Portable to Windows and various UNIX platforms that support `aio_*()` family of methods

Using the ACE Proactor Framework for the Web Server

Connection Setup Phase



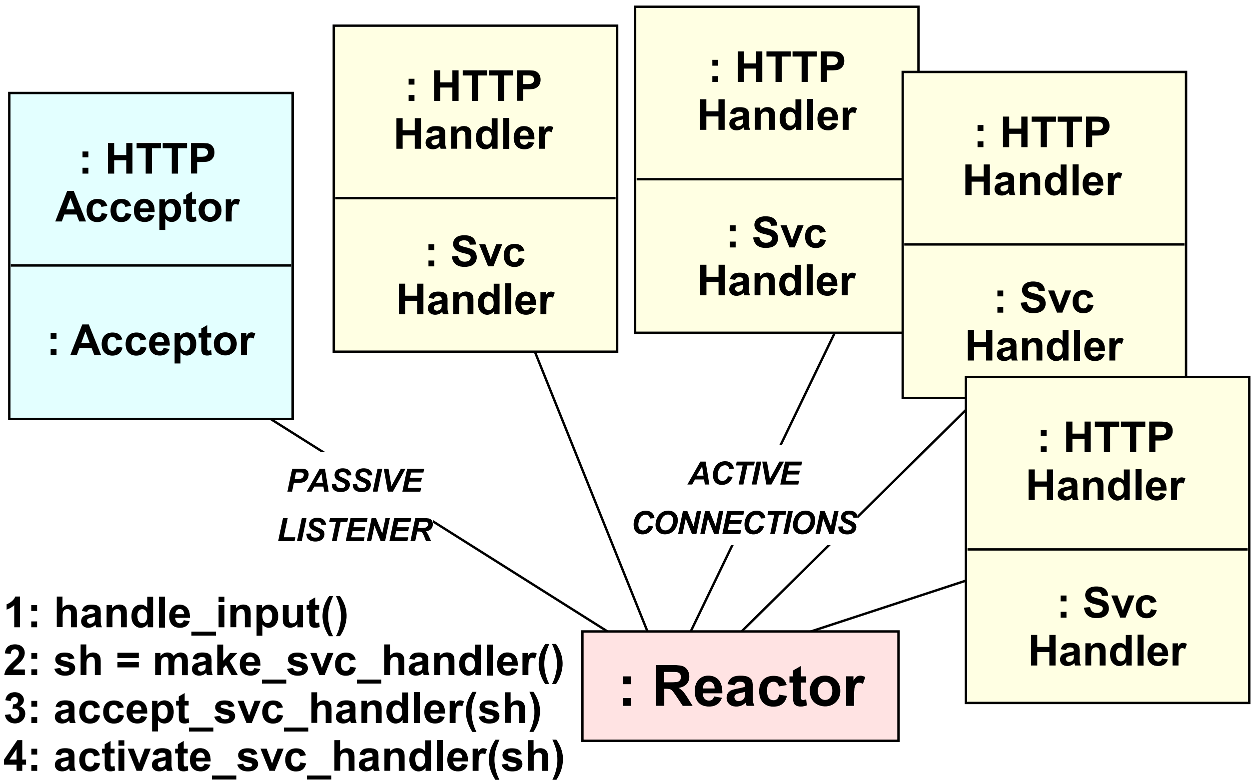
Data Transfer Phase



Structuring Service Initialization

- Problem
  - The *communication protocol* used between clients and the Web server is often orthogonal to the *initialization protocol*
- Forces
  - Low-level connection establishment APIs are tedious, error-prone, and non-portable
  - Separating *initialization* from *use* can increase software reuse substantially
- Solution
  - Use the *Acceptor* and *Connector* patterns to decouple passive service initialization from run-time protocol

Using the ACE_Acceptor in the Web Server



The `HTTP_Acceptor` is a *factory* that *creates*, *connects*, and *activates* an `HTTP_Handler`

HTTP_Acceptor Class Interface

```
template <class ACCEPTOR>
class HTTP_Acceptor :
  public ACE_Acceptor<HTTP_Handler<
             ACCEPTOR::PEER_STREAM>,
             // Note use of a "trait".
   ACCEPTOR>
{
public:
    // Called when <HTTP_Acceptor> is
    // dynamically linked.
  virtual int init (int argc, char *argv[]);
    // Called when <HTTP_Acceptor> is
    // dynamically unlinked.
  virtual int fini (void);
  // ...
};
```

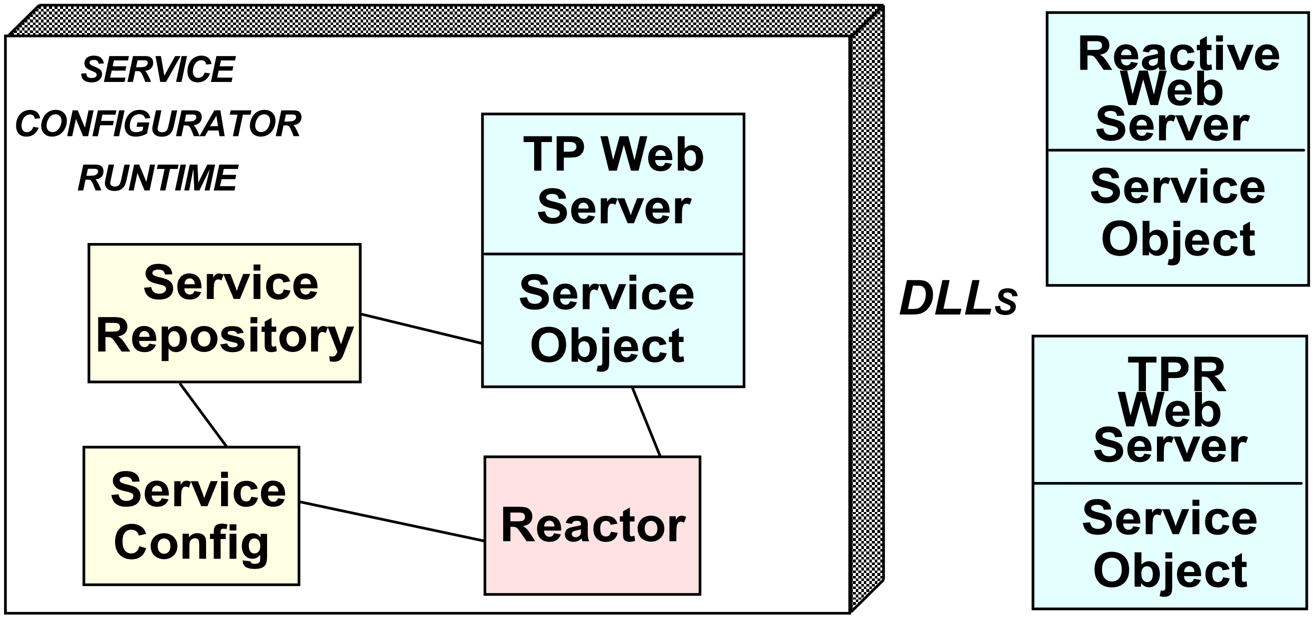
The `HTTP_Acceptor` class implements the Acceptor role

- *i.e.*, it accepts connections/initializes `HTTP_Handlers`

HTTP_Acceptor Class Implementation

```
// Initialize service when dynamically linked.

template <class PA> int
HTTP_Acceptor<PA>::init (int argc, char *argv[])
{
  Options::instance ()->parse_args (argc, argv);

  // Initialize the communication endpoint and
  // register to accept connections.
  peer_acceptor ().open (typename
    PA::PEER_ADDR (Options::instance ()->port ()),
     Reactor::instance ());
}

// Terminate service when dynamically unlinked.

template <class PA> int
HTTP_Acceptor<PA>::fini (void)
{
  // Shutdown threads in the pool.
  HTTP_Processor<PA>::instance ()->
    msg_queue ()->deactivate ();

  // Wait for all threads to exit.
  HTTP_Processor<PA>::instance ()->
    thr_mgr ()->wait ();
}
```

Using the ACE Service Configurator Framework in the Web Server



svc.conf FILE

```
dynamic Web_Server Service_Object *
  web_server:make_Web_Server() "-port 80"
```

Component Configurator Implementation in C++

The concurrent Web Server is configured and initialized via a configuration script

```
% cat ./svc.conf
dynamic Web_Server
  Service_Object *
  web_server:_make_Web_Server()
  "-p 80 -t $THREADS"
# .dll or .so suffix added to
#  "web_server" automatically
```

Factory function that dynamically allocates a Half-Sync/Half-Async Web Server object

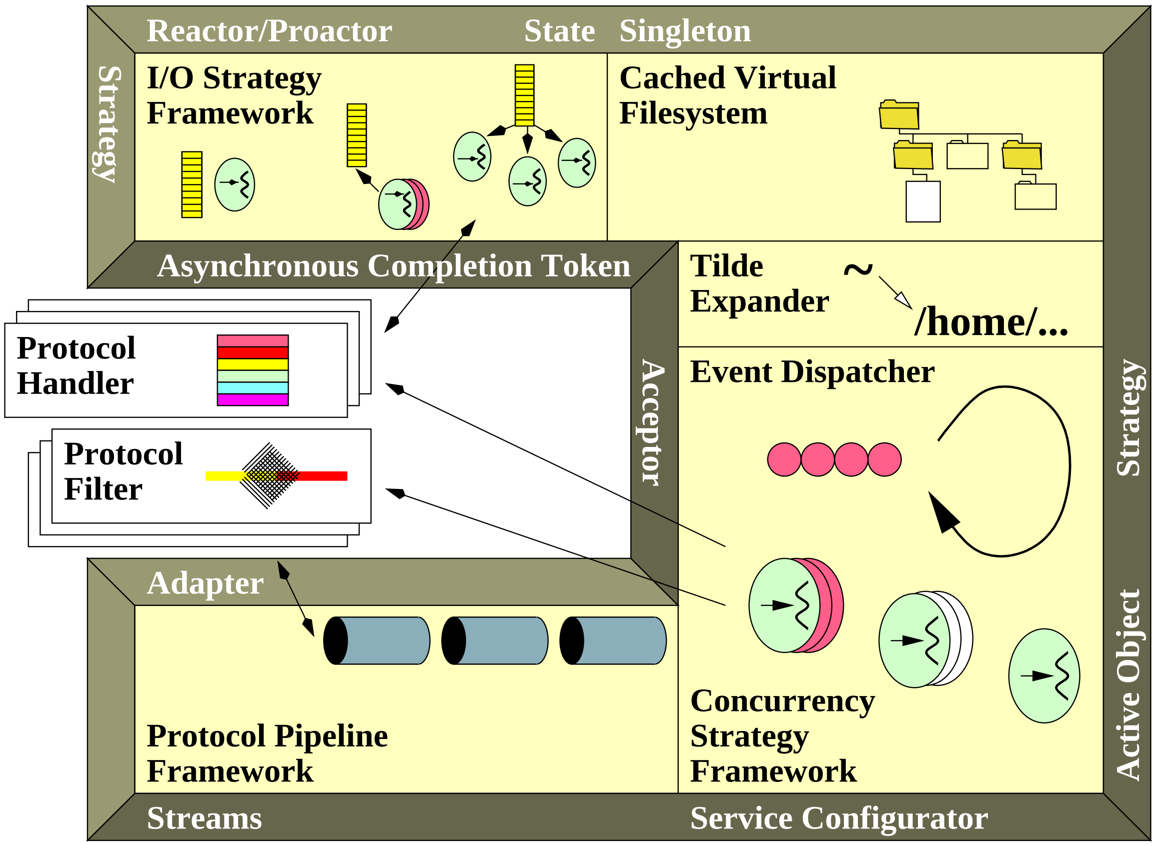
```
extern "C" ACE_Service_Object *
make_Web_Server (void);

ACE_Service_Object *
make_Web_Server (void)
{
  return new
    HTTP_Acceptor<ACE_SOCK_Acceptor>;
  // ACE dynamically unlinks and
  // deallocates this object.
}
```

Main Program for the Web Server

```
int main (int argc, char *argv[])
{
  // Initialize the daemon and
  // dynamically configure services.
  ACE_Service_Config::open (argc,
                            argv);
  // Loop forever, running services
  //  and handling reconfigurations.
  ACE_Reactor::instance ()->
    run_reactor_event_loop ();
  /* NOTREACHED */
}
```

- The `main()` function is totally generic!
- Dynamically configure & execute Web Server
- Make any application "Web-enabled"

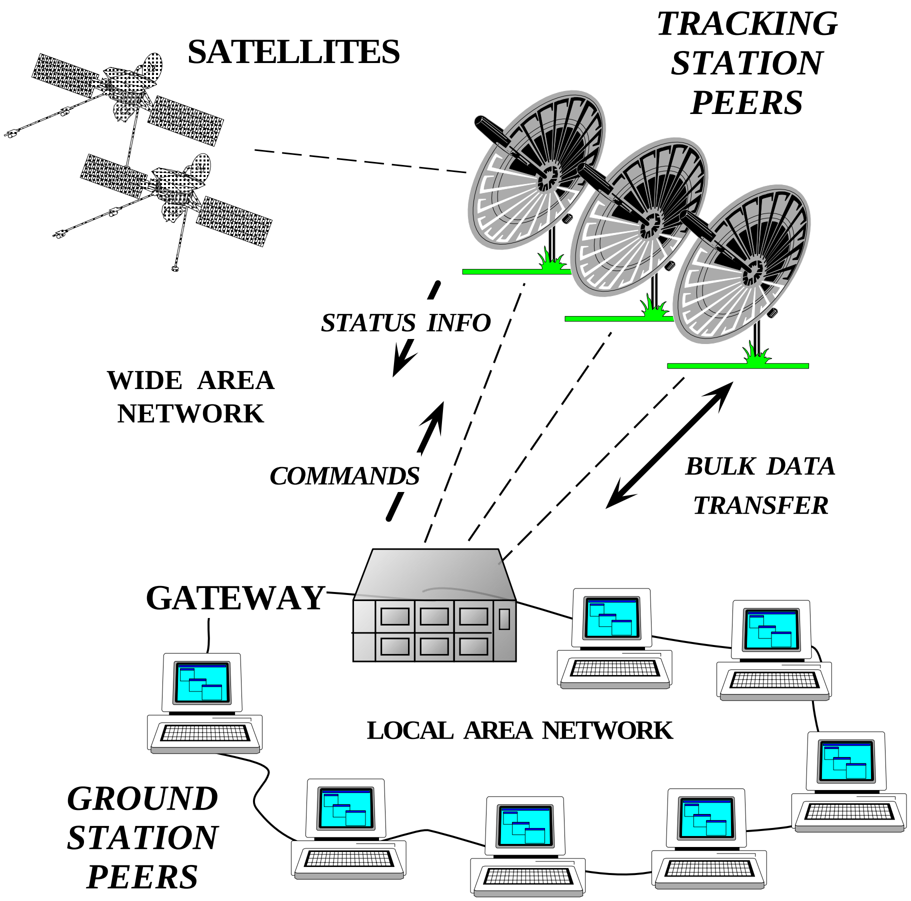
Optimizing the JAWS Framework



`www.cs.wustl.edu/~jxh/research/`

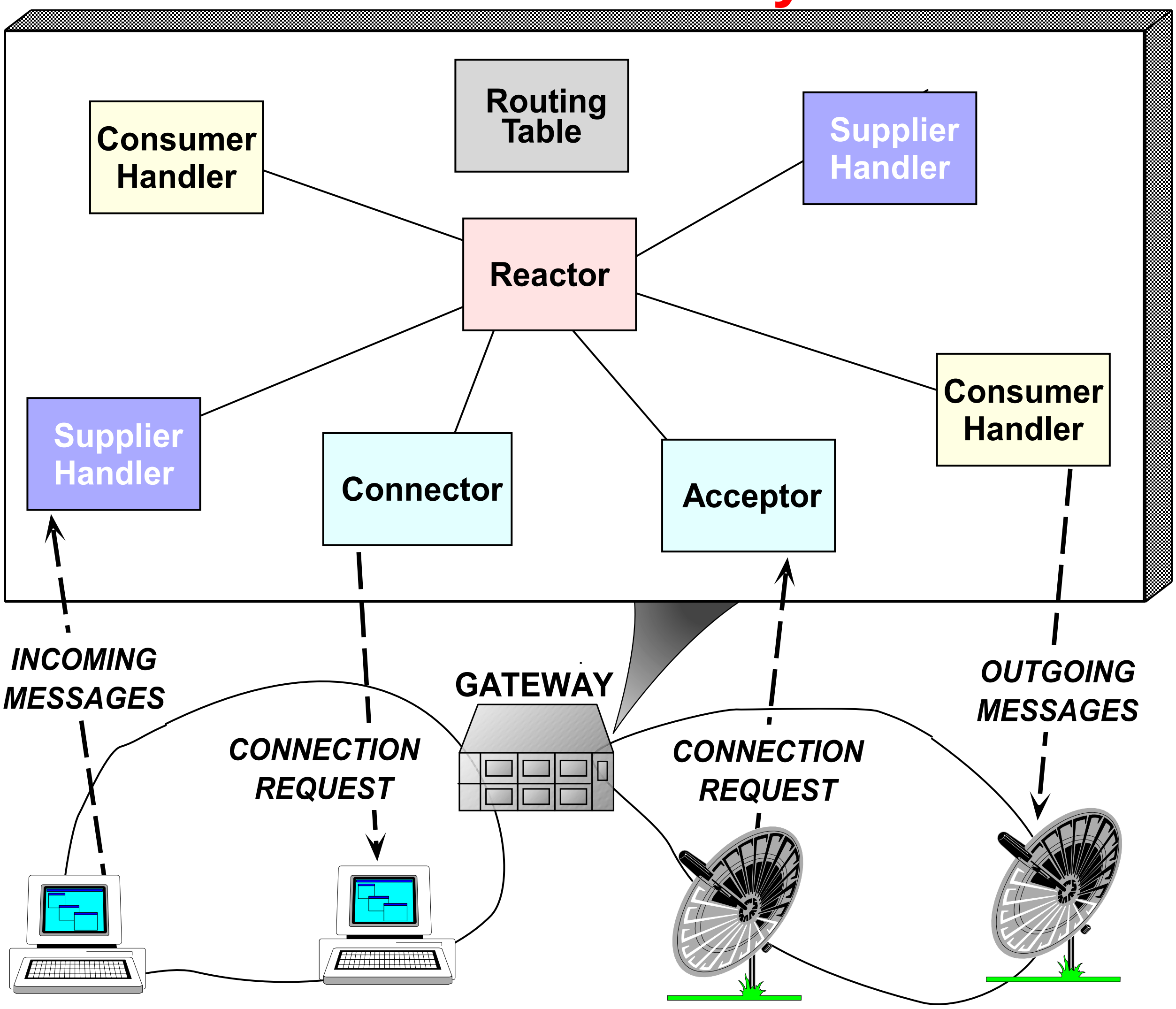
- Use lightweight concurrency
- Minimize locking
- Apply file caching and memory mapping
- Use “gather-write” mechanisms
- Minimize logging
- Pre-compute HTTP responses
- Avoid excessive `time()` calls
- Optimize the transport interface

Application-level Telecom Gateway Example



- This example explores the *patterns* and *reusable framework* components for an *application-level Gateway*
- The Gateway routes messages between Peers
- Gateway and Peers are connected via TCP/IP

OO Software Architecture of the Gateway



www.cs.wustl.edu/~schmidt/PDF/TAPOS-00.pdf

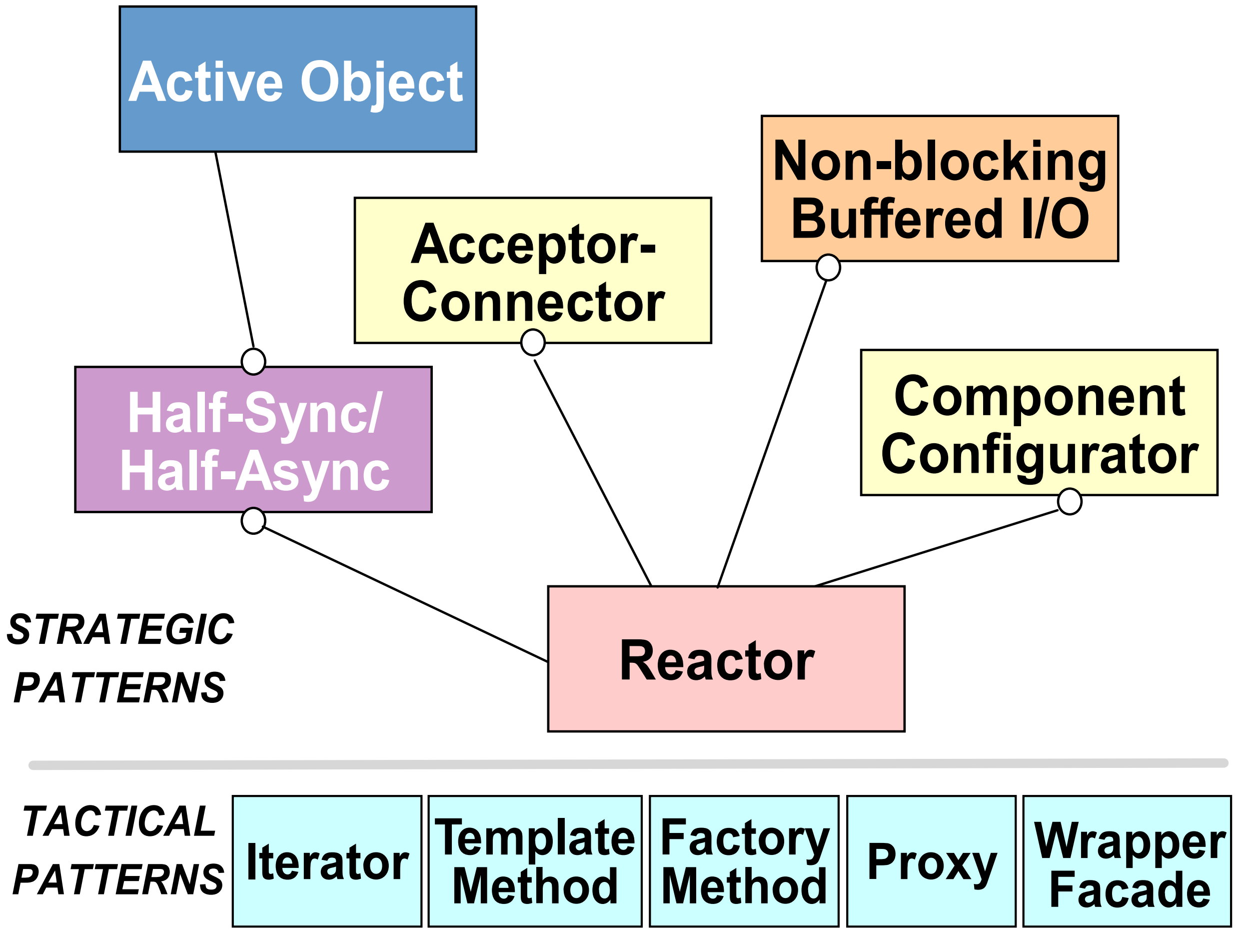
All components in this architecture are based on patterns from ACE

Gateway Behavior

- Components in the Gateway behave as follows:

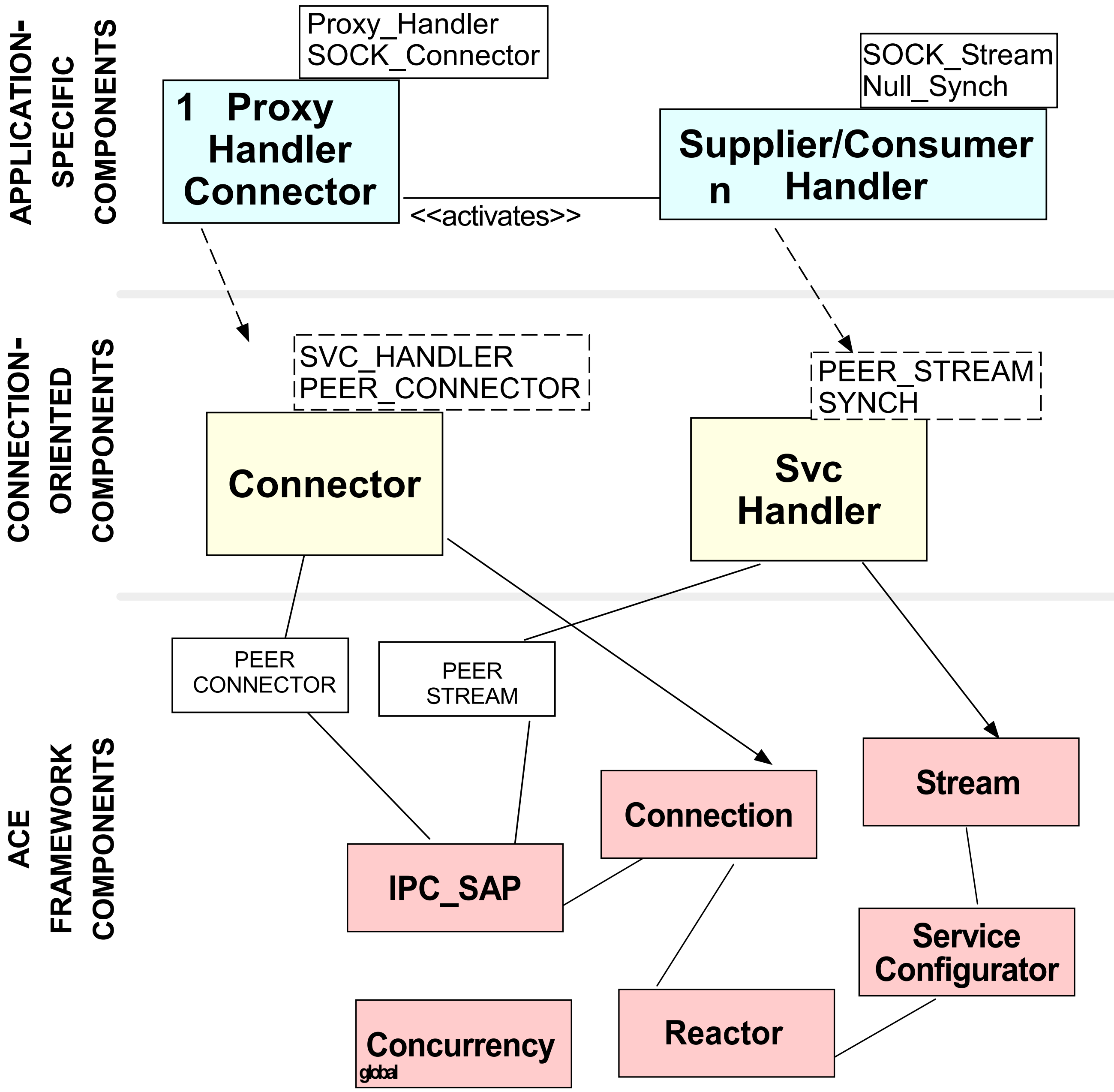
1. `Gateway` parses configuration files that specify which Peers to connect with and which routes to use
2. `Proxy_Handler_Connector` connects to Peers, then creates and activates `Proxy_Handler` subclasses (`Supplier_Handler` or `Consumer_Handler`)
3. Once connected, Peers send messages to the Gateway
   - Messages are handled by an `Supplier_Handler`
   - `Supplier_Handlers` work as follows:
     * Receive and validate messages
     * Consult a `Routing_Table`
     * Forward messages to the appropriate Peer(s) via `Consumer_Handlers`

Patterns in the Gateway



The Gateway components are based upon a common *pattern language*

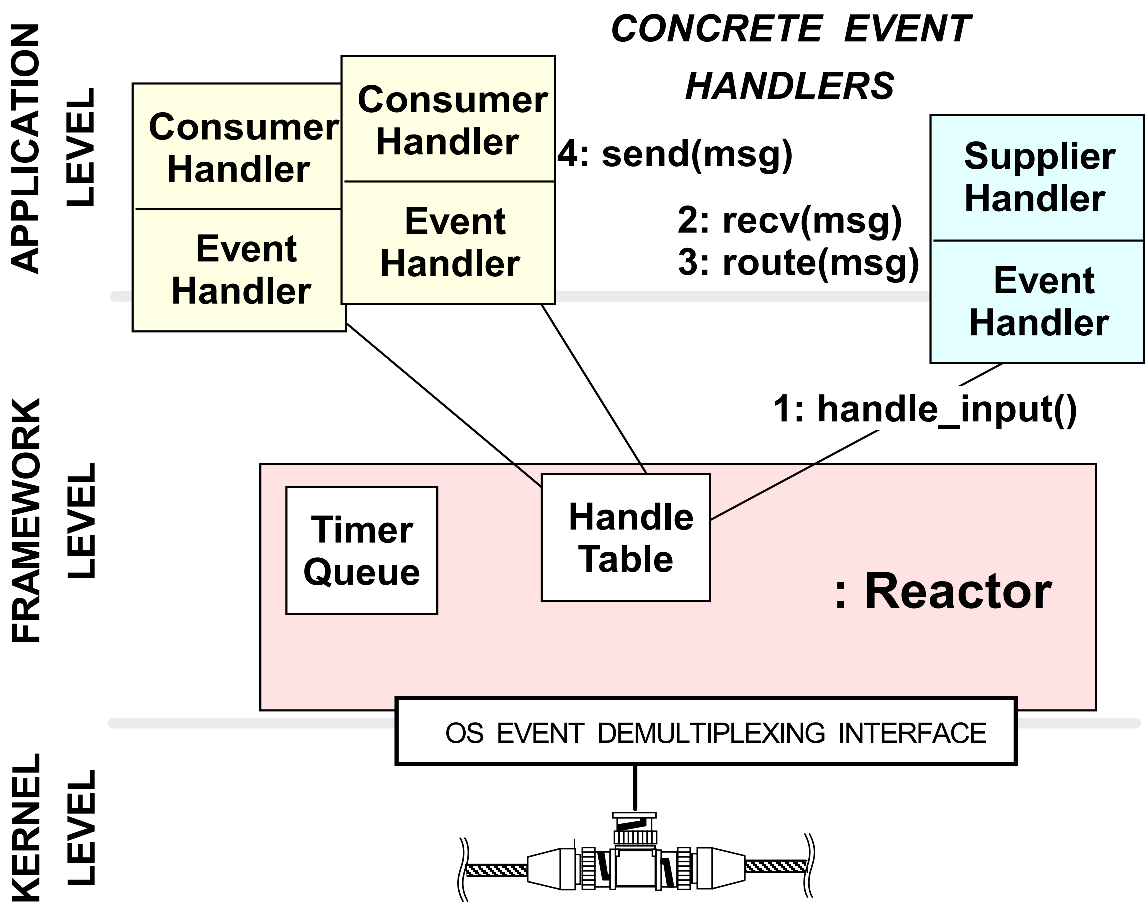
Class Diagram for Single-Threaded Gateway



OO Gateway Architecture

- *Application-specific components*
  - `Proxy_Handlers` route messages among Peers
- *Connection-oriented application components*
  - `ACE_Svc_Handler`
    - Performs I/O-related tasks with connected clients
  - `ACE_Connector` factory
    - Establishes new connections with clients
    - Dynamically creates an `ACE_Svc_Handler` object for each client and "activates" it
- *Application-independent ACE framework components*
  - Perform IPC, explicit dynamic linking, event demultiplexing, event handler dispatching, multi-threading, etc.

Using the ACE Reactor Framework for the Gateway



Benefits

- Straightforward to program
- Concurrency control is trivial

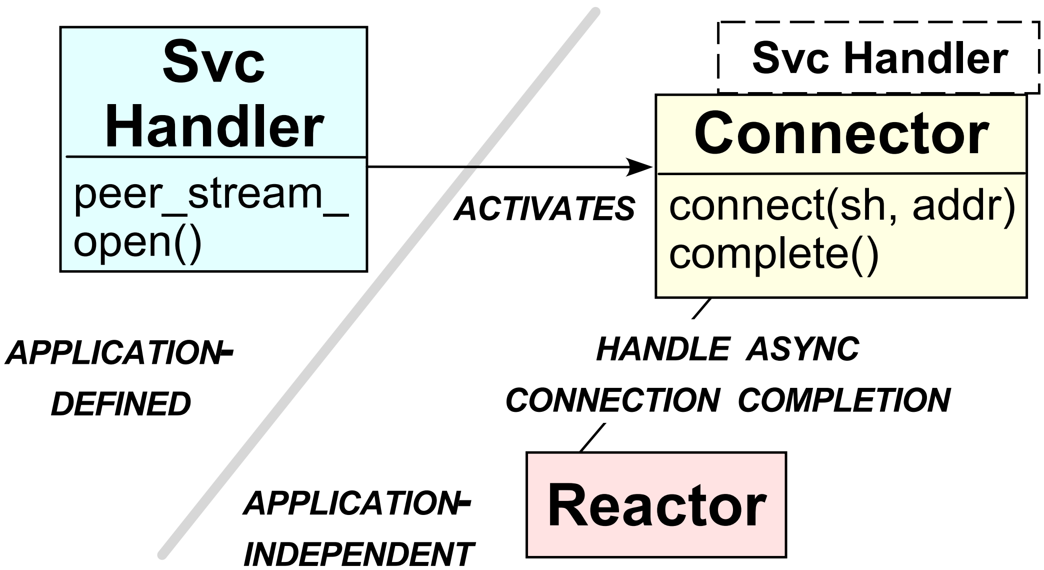
Liabilities

- Design is "brittle"
- Can't leverage multi-processors

Addressing Active Endpoint Connection and Initialization Challenges

- Problem
  - Application *communication* protocols are often orthogonal to their *connection establishment* and *service initialization* protocols
- Forces
  - Low-level connection APIs are error-prone and non-portable
  - Separating *initialization* from *processing* increases software reuse
  - Asynchronous connections are important over long-delay paths
- Solution
  - Use the *Acceptor-Connector* pattern to decouple connection and initialization protocols from the Gateway routing protocol

The Acceptor-Connector Pattern (Connector Role)



`www.cs.wustl.edu/˜schmidt/POSA/`

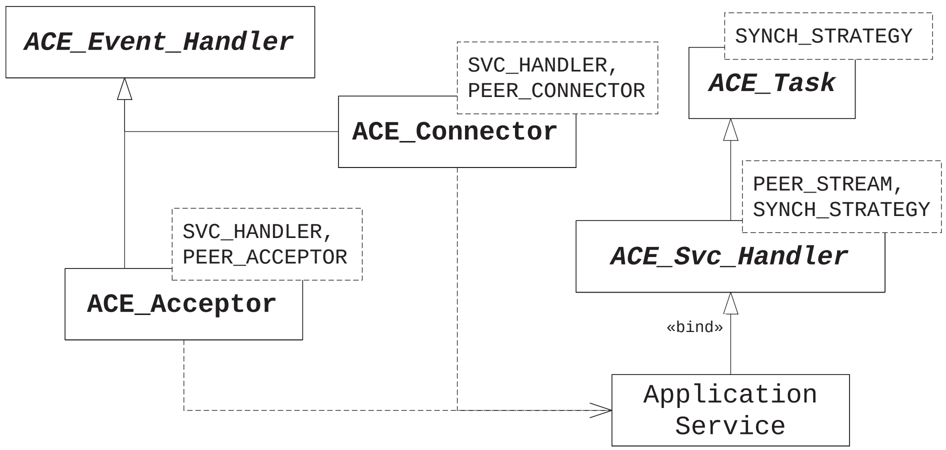
Intent of Connector Role

- *Decouple the active connection and initialization of a peer service in a distributed system from the processing performed once the peer service is connected and initialized*

Forces Resolved:

- Reuse connection code
- Efficiently setup connections with many peers or over long delay paths

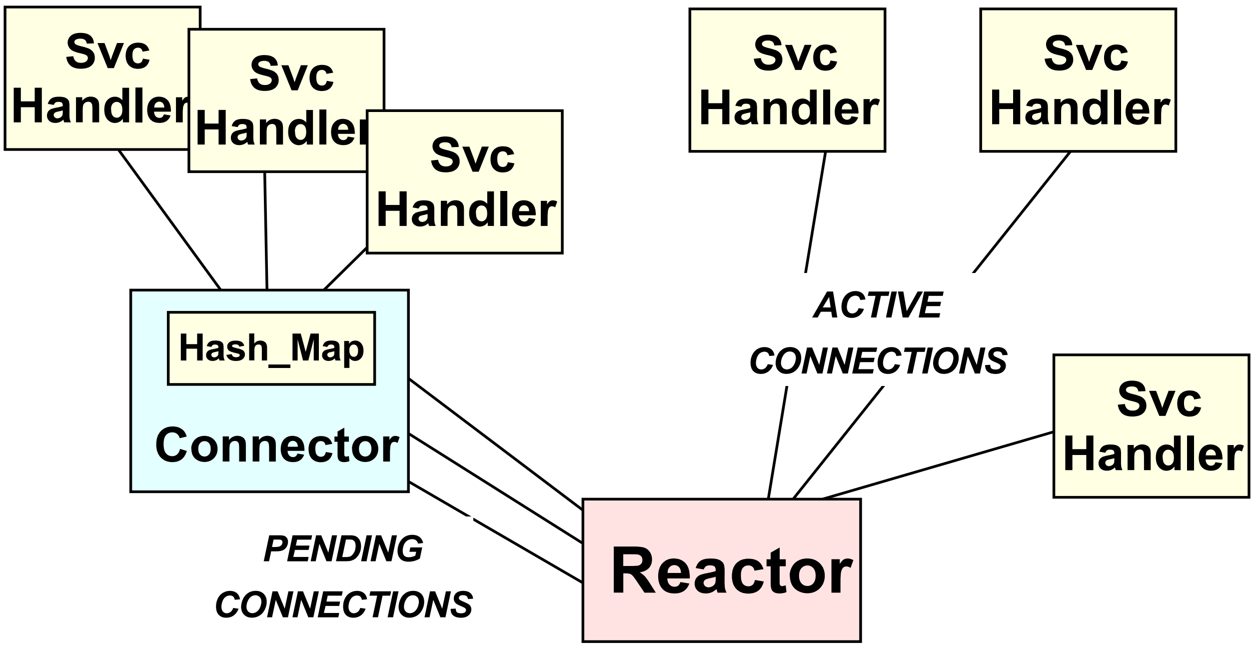
Structure of the Acceptor-Connector Pattern in ACE



Additional features of the `ACE_Connector`

- Uses C++ parameterized types to *strategize* IPC and service *aspects*
- Uses Template Method pattern to strategize creation, connection establishment, and concurrency policies

Using the ACE_Connector in the Gateway



- The `ACE_Connector` is a *factory*
  - *i.e.*, it *connects* and *activates* an `ACE_Svc_Handler`
- There's typically 1 `ACE_Connector` per-service

ACE_Connector Class Public Interface

A reusable template factory class that establishes connections with clients

```
template <class SVC_HANDLER,
          // Type of service
          class PEER_CONNECTOR>
          // Connection factory
class ACE_Connector : public ACE_Service_Object
{
public:
    // Initiate connection to Peer.
  virtual int connect
    (SVC_HANDLER *&svc_handler,
     typename const PEER_CONNECTOR::PEER_ADDR &ra,
     ACE_Synch_Options &synch_options);

    // Cancel a <svc_handler> that was
    // started asynchronously.
  virtual int cancel (SVC_HANDLER *svc_handler);
```

Design Interlude: Motivation for the ACE_Synch_Options Class

- Q: *What is the `ACE_Synch_Options` class?*
- A: This allows callers to define the synchrony/asynchrony policies, *e.g.*,

```
class ACE_Synch_Options {
  // Options flags for controlling
  // synchronization.
  enum { USE_REACTOR = 1, USE_TIMEOUT = 2 };

  ACE_Synch_Options
    (u_long options = 0,
     const ACE_Time_Value &timeout
       = ACE_Time_Value::zero,
     const void *act = 0);
    // This is the default synchronous setting.
  static ACE_Synch_Options synch;
    // This is the default asynchronous setting.
  static ACE_Synch_Options asynch;
};
```

ACE_Synch_Options and ACE_Connector Semantics

Reactor	Timeout	Behavior
Yes	0,0	Return −1 with errno EWOULDBLOCK; service handler is closed via reactor event loop.
Yes	time	Return −1 with errno EWOULDBLOCK; wait up to specified amount of time for completion using the reactor.
Yes	NULL	Return −1 with errno EWOULDBLOCK; wait for completion indefinitely using the reactor.
No	0,0	Close service handler directly; return −1 with errno EWOULDBLOCK.
No	time	Block in connect_svc_handler() up to specified amount of time for completion; if still not completed, return −1 with errno ETIME.
No	NULL	Block in connect_svc_handler() indefinitely for completion.

ACE_Connector Class Protected Interface

```
protected:
  // Make a new connection.
  virtual SVC_HANDLER *make_svc_handler (void);
  // Accept a new connection.
  virtual int connect_svc_handler
   (SVC_HANDLER *&sh,
    typename const PEER_CONNECTOR::PEER_ADDR &addr,
    ACE_Time_Value *timeout);
  // Activate a service handler.
  virtual int activate_svc_handler (SVC_HANDLER *);

  // Demultiplexing hooks.
  virtual int handle_output (ACE_HANDLE);// Success.
  virtual int handle_input (ACE_HANDLE); // Failure.
  virtual int handle_timeout (ACE_Time_Value &,
                              const void *);
  // Table maps I/O handle to an ACE_Svc_Tuple *.
  Hash_Map_Manager<ACE_HANDLE, ACE_Svc_Tuple *,
                   ACE_Null_Mutex> handler_map_;

  // Factory that establishes connections actively.
  PEER_CONNECTOR connector_;
};
```

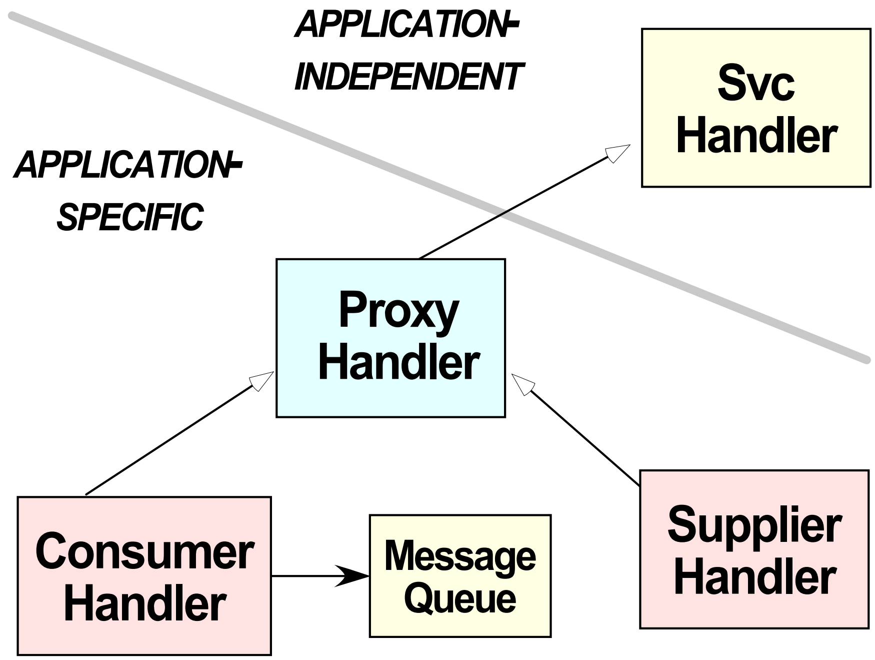
ACE_Connector Class Implementation

```
// Initiate connection using specified
// blocking semantics.
template <class SH, class PC> int
ACE_Connector<SH, PC>::connect
  (SH *&sh,
   const PC::PEER_ADDR &r_addr,
   ACE_Synch_Options &options)
{
  ACE_Time_Value *timeout = 0;
  int use_reactor =
    options[ACE_Synch_Options::USE_REACTOR];
  if (use_reactor)
    timeout = &ACE_Time_Value::zero;
  else
     timeout =
       options[ACE_Synch_Options::USE_TIMEOUT]
       ? (Time_Value *) &options.timeout () : 0;
  // Hook methods.
  if (sh == 0)
    sh = make_svc_handler ();
  if (connect_svc_handler (sh, raddr,
                           timeout) != -1)
    activate_svc_handler (sh);
}
```

ACE_Connector Hook Method Implementations

```
template <class SH, class PC> SH *
ACE_Connector<SH, PC>::make_svc_handler (void) {
  return new SH;
}

template <class SH, class PC> int
ACE_Connector<SH, PC>::connect_svc_handler (SH &*sh,
     typename const PEER_CONNECTOR::PEER_ADDR &addr,
     ACE_Time_Value *timeout) {
  // Peer_Connector factory initiates connection.
  if (connector_.connect (sh, addr, timeout) == -1)
    // If the connection hasn't completed, then
    // register with the Reactor to call us back.
    if (use_reactor && errno == EWOULDBLOCK)
      // Create <ACE_Svc_Tuple> for <sh> & return -1
  } else
    // Activate immediately if we're connected.
    activate_svc_handler (sh);
}

template <class SH, class PC> int
ACE_Connector<SH, PC>::activate_svc_handler (SH *sh)
{ if (sh->open ((void *)this) == -1) sh->close (); }
```

Specializing ACE_Connector and ACE_Svc_Handler



- Producing an application that meets Gateway requirements involves *specializing* ACE components
  - `ACE_Connector` → `ACE_Proxy_Handler_Connector`
  - `ACE_Svc_Handler` → `ACE_Proxy_Handler` → `ACE_Supplier_Handler` and `ACE_Consumer_Handler`

ACE_Proxy_Handler Class Public Interface

```
// Determine the type of threading mechanism.
#if defined (ACE_USE_MT)
typedef ACE_MT_SYNCH SYNCH;
#else
typedef ACE_NULL_SYNCH SYNCH;
#endif /* ACE_USE_MT */

// Unique connection id that denotes Proxy_Handler.
typedef short CONN_ID;

// This is the type of the Routing_Table.
typedef ACE_Hash_Map_Manager <Peer_Addr,
                              Routing_Entry,
                              SYNCH::MUTEX>
        ROUTING_TABLE;

class Proxy_Handler
  : public ACE_Svc_Handler<ACE_SOCK_Stream, SYNCH> {
public:
    // Initialize the handler (called by the
    // <ACE_Connector> or <ACE_Acceptor>).
  virtual int open (void * = 0);

    // Bind addressing info to Router.
  virtual int bind (const ACE_INET_Addr &, CONN_ID);
```

Design Interlude: Parameterizing Synchronization into the `ACE_Hash_Map_Manager`

- Q: *What's a good technique to implement a Routing Table?*
- A: Use a `ACE_Hash_Map_Manager` container
  - ACE provides a `ACE_Hash_Map_Manager` container that associates *external ids* with *internal ids*, *e.g.*,
    - External ids (keys) $\rightarrow$ URI
    - Internal ids (values) $\rightarrow$ pointer to memory-mapped file
- Hashing provides $O(1)$ performance in the average-case

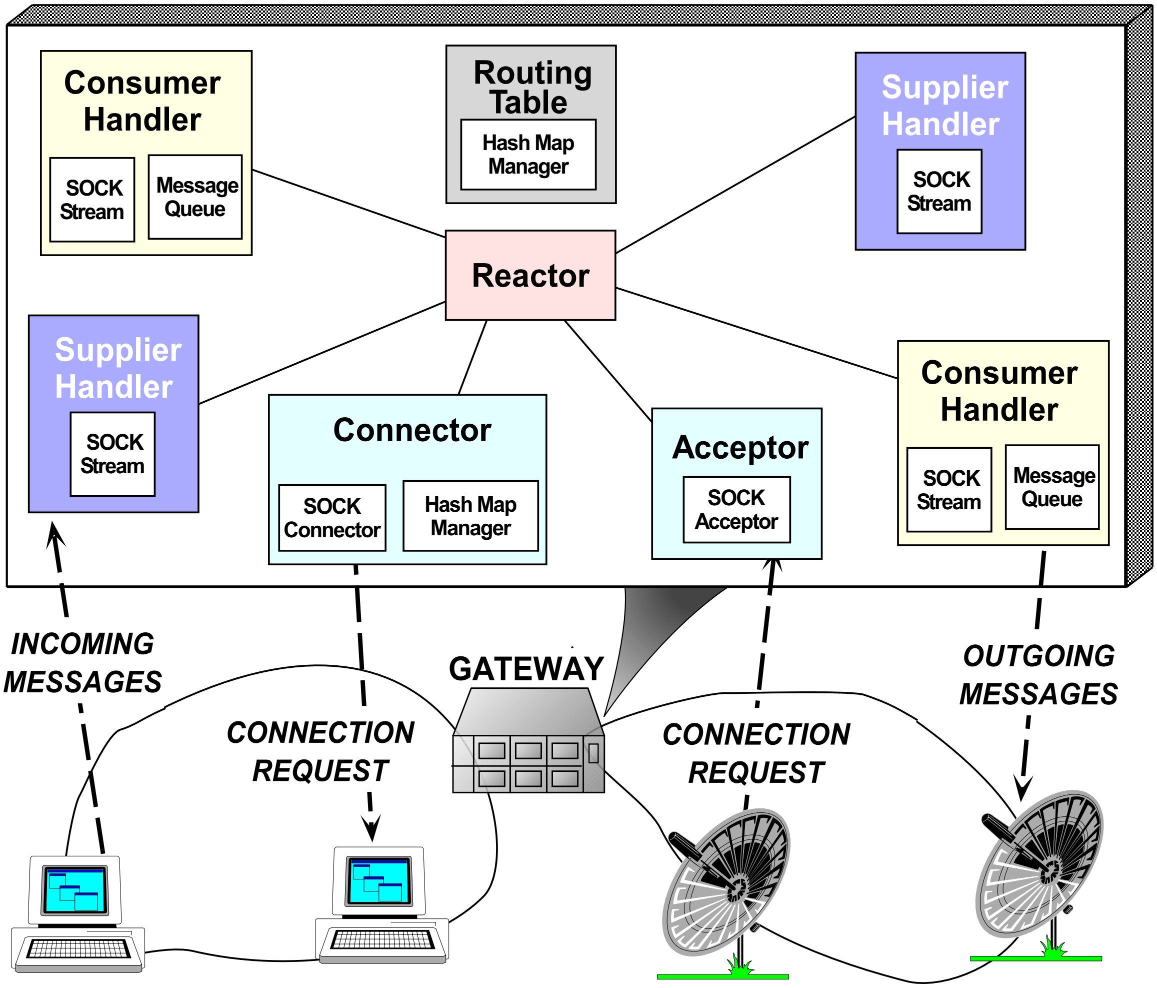
Applying the Strategized Locking pattern to the ACE_Hash_Map_Manager Class

```
template <class EXT_ID, class INT_ID,
          class LOCK>
class ACE_Hash_Map_Manager { public:
  bool bind (EXT_ID, INT_ID *);
  bool unbind (EXT_ID);
  bool find (EXT_ID ex, INT_ID &in)
  { // Exception-safe code...
    ACE_READ_GUARD (LOCK, g,
                    lock_, false);
    // lock_.read_acquire ();
    if (find_i (ex, in)) return true;
    else return false;
    // lock_.release ();
 }
private:
  LOCK lock_;
  bool find_i (EXT_ID, INT_ID &);
  // ...
};
```

ACE_Hash_Map_Manager uses the template-based Strategized Locking pattern to

- Enhance reuse
- Parameterize different synchronization strategies, *e.g.*:
  - ACE_Null_Mutex, ACE_Thread_Mutex, ACE_RW_Mutex, etc.

Detailed OO Architecture of the Gateway



Note the use of other ACE components, such as the socket wrapper facades and the `ACE_Hash_Map_Manager`

ACE_Supplier_Handler Interface

```
class Supplier_Handler : public Proxy_Handler
{
public:
  Supplier_Handler (void);

protected:
    // Receive and process Peer messages.
  virtual int handle_input (ACE_HANDLE);

    // Receive a message from a Peer.
  virtual int recv_peer (ACE_Message_Block *&);

    // Action that routes a message from a Peer.
  int route_message (ACE_Message_Block *);

    // Keep track of message fragment.
  ACE_Message_Block *msg_frag_;
};
```

ACE_Consumer_Handler Interface

```
class Consumer_Handler : public Proxy_Handler
{
public:
  Consumer_Handler (void);

    // Send a message to a Gateway
    // (may be queued).
  virtual int put (ACE_Message_Block *,
                   ACE_Time_Value * = 0);

protected:
    // Perform a non-blocking put().
  int nonblk_put (ACE_Message_Block *mb);

    // Finish sending a message when
    // flow control abates.
  virtual int handle_output (ACE_HANDLE);

    // Send a message to a Peer.
  virtual int send_peer (ACE_Message_Block *);
};
```

ACE_Proxy_Handler_Connector Class Interface

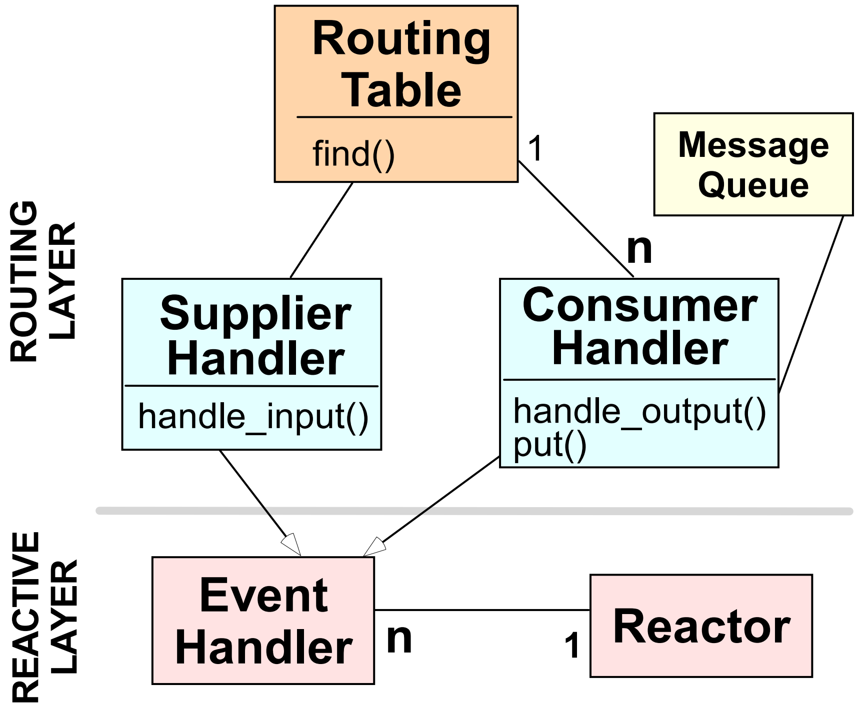
```
class Proxy_Handler_Connector :
  public ACE_Connector
         <Proxy_Handler,
         // Type of Svc Handler
         ACE_SOCK_Connector>
         // Connection factory
{
public:
    // Initiate (or reinitiate)
    // a connection on
    // the Proxy_Handler.
  int initiate_connection
    (Proxy_Handler *);
}
```

- `ACE_Proxy_Handler_Connector` is a concrete factory class that:
  - Establishes connections with Peers to produce `ACE_Proxy_Handlers`
  - Activates `ACE_Proxy_Handlers`, which then route messages
- `ACE_Proxy_Handler_Connector` also ensures reliability by restarting failed connections

ACE_Proxy_Handler_Connector Implementation

```
// (re)initiate a connection to a Proxy_Handler
int
Proxy_Handler_Connector::initiate_connection
  (Proxy_Handler *ph)
{
  // Use asynchronous connections...
  if (connect (ph,
               ph->addr (),
               ACE_Synch_Options::asynch) == -1) {
    if (errno == EWOULDBLOCK)
      // No error, we're connecting asynchronously.
      return -1;
   else
      // This is a real error, so reschedule
      // ourselves to reconnect.
      reactor ()->schedule_timer
        (ph, 0, ph->timeout ());
  }
  else // We're connected synchronously!
    return 0;
}
```

The Non-blocking Buffered I/O Pattern



`www.cs.wustl.edu/~schmidt/PDF/TAPOS-00.pdf`

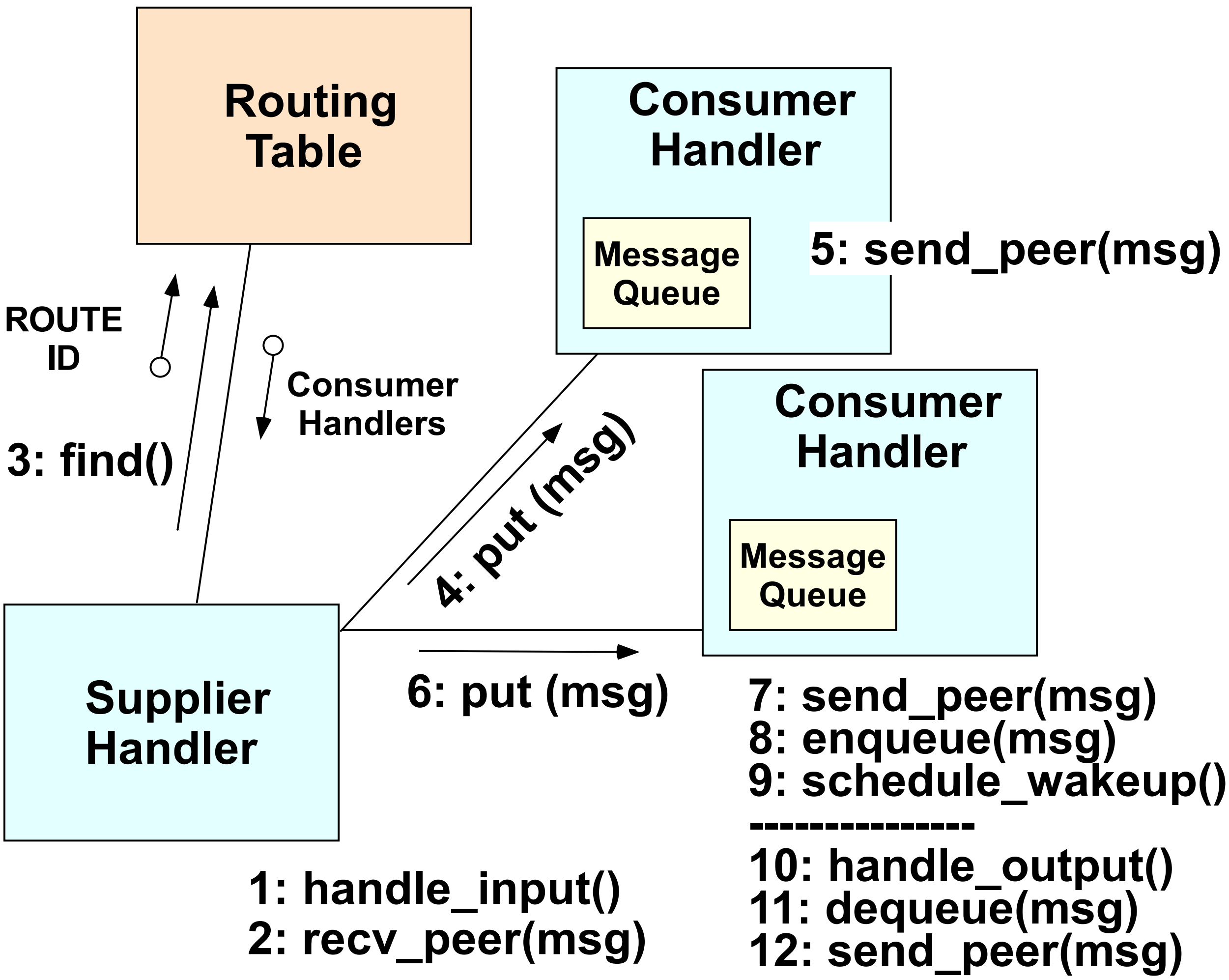
Intent

- *Decouple multiple input sources from multiple output sources to prevent blocking*

Forces Resolved:

- Keep misbehaving connections from disrupting the QoS for well-behaved connections
- Different concurrency strategies for `Supplier_Handlers` and `Consumer_Handlers`

Collaboration in Single-threaded Gateway Routing



Note the complex cooperative scheduling logic required to handle output flow control correctly

Supplier_Handler and Consumer_Handler Implementations

```
int Supplier_Handler::handle_input (ACE_HANDLE) {
  ACE_Message_Block *route_addr = 0;
  int n = recv_peer (route_addr);
  // Try to get the next message.
  if (n <= 0) {
    if (errno == EWOULDBLOCK) return 0;
    else return n;
  }
  else
    route_message (route_addr);
}

// Send a message to a Peer (queue if necessary).

int Consumer_Handler::put (ACE_Message_Block *mb,
                           ACE_Time_Value *) {
  if (msg_queue_->is_empty ())
    // Try to send the message *without* blocking!
    nonblk_put (mb);
  else // Messages are queued due to flow control.
    msg_queue_->enqueue_tail
      (mb, &ACE_Time_Value::zero);
}
```

Supplier_Handler Message Routing

```
// Route message from a Peer.
int Supplier_Handler::route_messages
      (ACE_Message_Block *route_addr)
{
  // Determine destination address.
  CONN_ID route_id =
    *(CONN_ID *) route_addr->rd_ptr ();
  const ACE_Message_Block *const data =
    route_addr->cont ();
  Routing_Entry *re = 0;

  // Determine route.
  Routing_Table::instance ()->find (route_id, re);

  // Initialize iterator over destination(s).
  Set_Iterator<Proxy_Handler *>
    si (re->destinations ());
  // Multicast message.
  for (Proxy_Handler *out_ph;
       si.next (out_ph) != -1;
       si.advance ()) {
    ACE_Message_Block *newmsg = data->duplicate ();
    if (out_ph->put (newmsg) == -1) // Drop message.
      newmsg->release (); // Decrement ref count.
  }
  delete route_addr;
}
```

Peer_Message Schema

```
// Peer address is used to identify the
// source/destination of a Peer message.
class Peer_Addr {
public:
  CONN_ID conn_id_; // Unique connection id.
  u_char logical_id_; // Logical ID.
  u_char payload_; // Payload type.
};

// Fixed sized header.
class Peer_Header { public: /* ... */ };

// Variable-sized message (sdu_ may be
// between 0 and MAX_MSG_SIZE).

class Peer_Message {
public:
    // The maximum size of a message.
  enum { MAX_PAYLOAD_SIZE = 1024 };
  Peer_Header header_; // Fixed-sized header.
  char sdu_[MAX_PAYLOAD_SIZE]; // Message payload.
};
```

Design Interlude: Tips on Handling Flow Control

- Q: *What should happen if put() fails?*
  - *e.g.*, if a queue becomes full?
- A: The answer depends on whether the error handling policy is different for each router object or the same...
  - Strategy pattern: *give reasonable default, but allow substitution*
- A related design issue deals with avoiding output blocking if a Peer connection becomes flow controlled

Supplier Handler Message Reception

```
// Pseudo-code for recv'ing msg via non-blocking I/O

int Supplier_Handler::recv_peer
      (ACE_Message_Block *&route_addr)
{
  if (msg_frag_ is empty) {
    msg_frag_ = new ACE_Message_Block;
    receive fixed-sized header into msg_frag_
    if (errors occur) cleanup
    else
      determine size of variable-sized msg_frag_
  } else
    determine how much of msg_frag_ to skip

  non-blocking recv of payload into msg_frag_
  if (entire message is now received) {
    route_addr = new Message_Block
      (sizeof (Peer_Addr), msg_frag_)
    Peer_Addr addr (id (),
                    msg_frag_->routing_id_, 0);
    route_addr->copy (&addr, sizeof (Peer_Addr));
    return to caller and reset msg_frag_
  }
  else if (only part of message is received)
    return errno = EWOULDBLOCK
  else if (fatal error occurs) cleanup
}
```

Design Interlude: Using the ACE_Reactor to Handle Flow Control

- Q: *How can a flow controlled Consumer_Handler know when to proceed again without polling or blocking?*
- A: Use the ACE_Event_Handler::handle_output() notification scheme of the Reactor
  - *i.e.*, via the ACE_Reactor's methods schedule_wakeup() and cancel_wakeup()
- This provides cooperative multi-tasking within a single thread of control
  - The ACE_Reactor calls back to the handle_output() hook method when the Proxy_Handler is able to transmit again

Performing a Non-blocking `put()` of a Message

```
int Consumer_Handler::nonblk_put
  (ACE_Message_Block *mb) {
  // Try sending message
  // via non-blocking I/O
  if (send_peer (mb) != -1
      && errno == EWOULDBLOCK) {
    // Queue in *front* of the
    // list to preserve order.
    msg_queue_->enqueue_head
      (mb, &ACE_Time_Value::zero);
    // Tell Reactor to call us
    // back it's ok to send again.
    reactor ()->schedule_wakeup
      (this, ACE_Event_Handler::WRITE_MASK);
  }
}
```

This method is called in two situations:

1. When first trying to send over a connection
2. When flow control abates

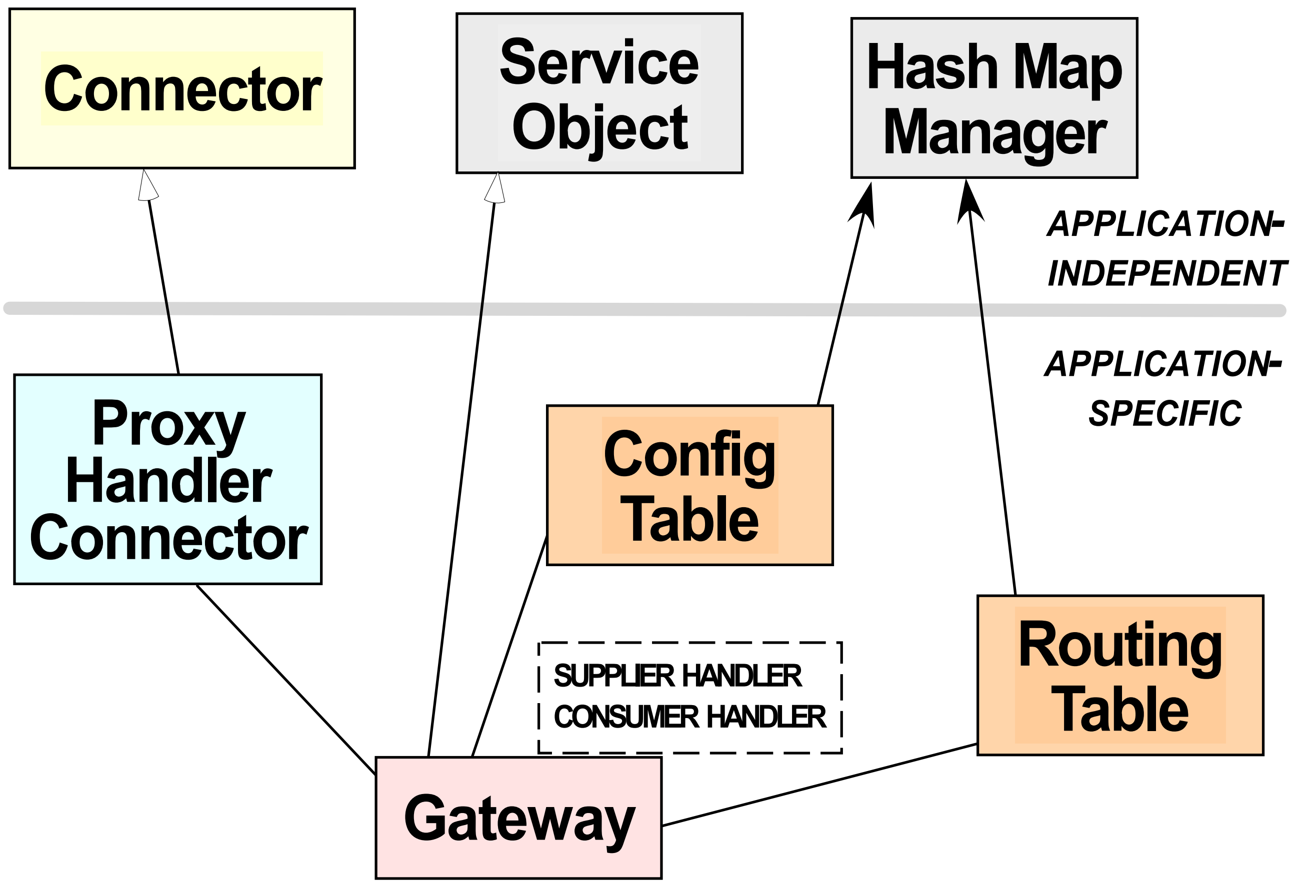
Sending a Message to a Consumer

```
int
Consumer_Handler::send_peer (ACE_Message_Block *mb)
{
  ssize_t n;
  size_t len = mb->length ();

  // Try to send the message.
  n = peer ().send (mb->rd_ptr (), len);

  if (n <= 0)
    return errno == EWOULDBLOCK ? 0 : n;
  else if (n < len)
    // Skip over the part we did send.
    mb->rd_ptr (n);
  else /* if (n == length) */ {
    // Decrement reference count.
    mb->release ();
    errno = 0;
  }
  return n;
}
```

Finish Sending when Flow Control Abates

```
// Finish sending a message when flow control
// conditions abate.  This method is automatically
// called by the Reactor.

int
Consumer_Handler::handle_output (ACE_HANDLE)
{
  ACE_Message_Block *mb = 0;

  // Take the first message off the queue.
  msg_queue_->dequeue_head
                   (mb, &ACE_Time_Value::zero);
  if (nonblk_put (mb) != -1
      || errno != EWOULDBLOCK) {
    // If we succeed in writing msg out completely
    // (and as a result there are no more msgs
    // on the <ACE_Message_Queue>), then tell the
    // <ACE_Reactor> not to notify us anymore.

    if (msg_queue_->is_empty ()
      reactor ()->cancel_wakeup
        (this, ACE_Event_Handler::WRITE_MASK);
  }
}
```

The `Gateway` Class



This class integrates other application-specific and application-independent components

Dynamically Configuring Gateway into an Application

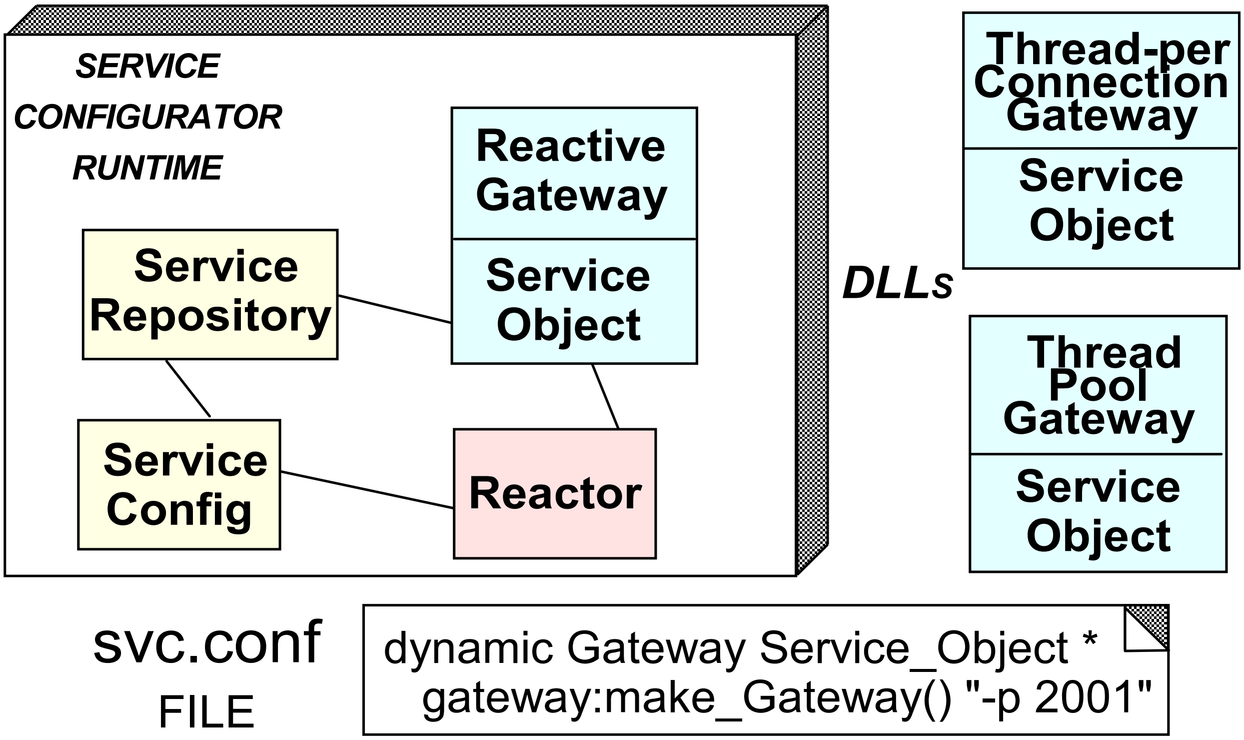
Parameterized by proxy handler

```
template
  <class SUPPLIER_HANDLER,
   class CONSUMER_HANDLER>
class Gateway
  : public Service_Object
{
public:
    // Perform initialization.
  virtual int init
    (int argc, char *argv[]);

    // Perform termination.
  virtual int fini (void);
```

Example of the Component Configurator pattern

```
int main (int argc, char *argv[])
{
  // Initialize the daemon and
  // dynamically configure services.
  ACE_Service_Config::open (argc,
                            argv);
  // Run forever, performing the
  // configured services.
  ACE_Reactor::instance ()->
    run_reactor_event_loop ();
  /* NOTREACHED */
}
```

Using the ACE Service Configurator Framework for the Gateway



We can replace the single-threaded Gateway with a multi-threaded Gateway

Dynamic Linking a Gateway Service

The Gateway service is configured via scripting in a `svc.conf` file:

```
% cat ./svc.conf
static Svc_Manager
  "-p 5150"
dynamic Gateway
Service_Object *
gateway:_make_Gateway()
        "-d -p $PORT"
# .dll or .so suffix
# added to "gateway"
# automatically
```

Dynamically linked factory function that allocates a new single-threaded Gateway

```
extern "C"
ACE_Service_Object *make_Gateway (void);

ACE_Service_Object *make_Gateway (void)
{
  return new
    Gateway<Supplier_Handler,
            Consumer_Handler>;
  // ACE automatically deletes memory.
}
```

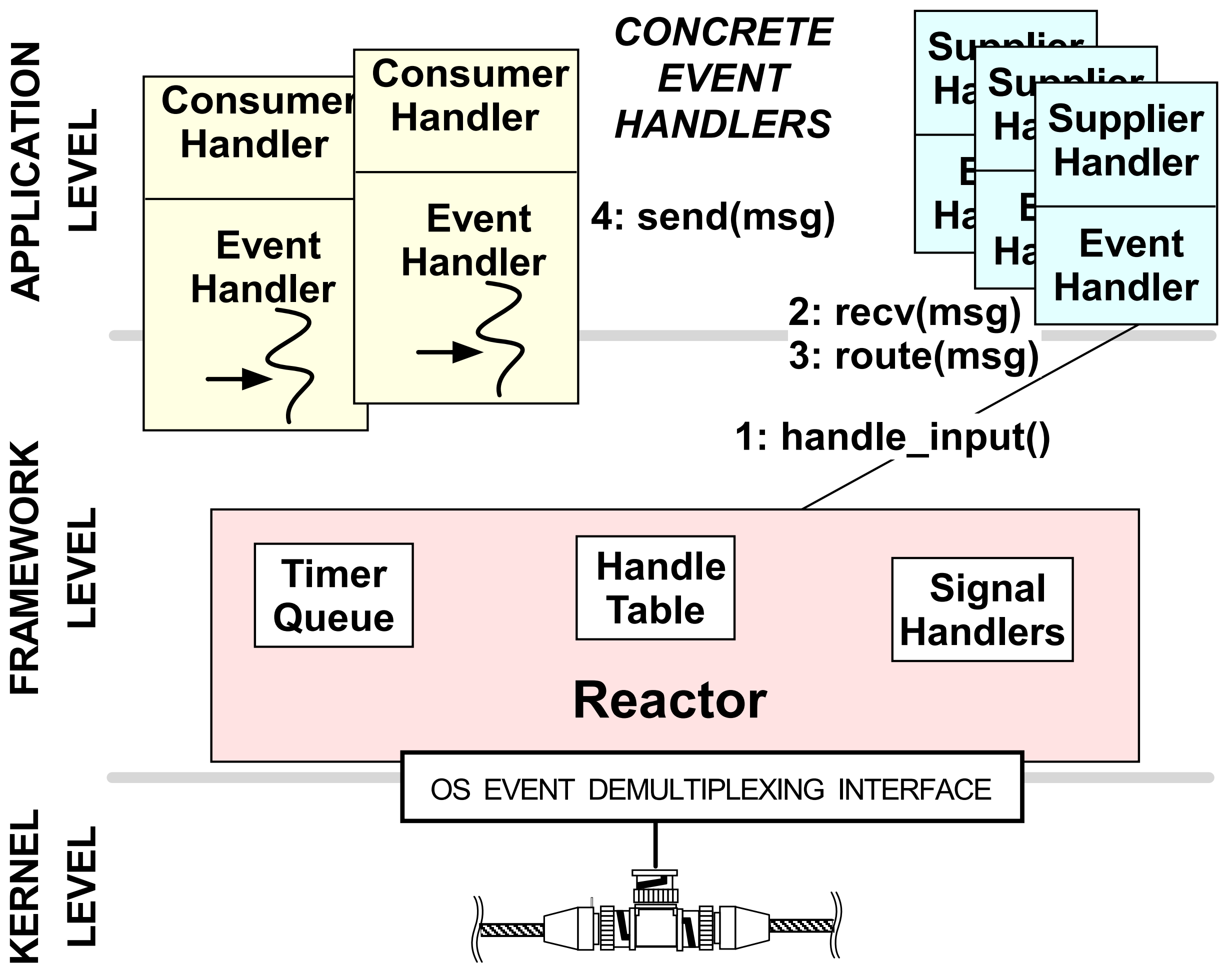
Concurrency Strategies for Patterns

- The Acceptor-Connector pattern does not constrain the concurrency strategies of a `ACE_Svc_Handler`
- There are three common choices:

1. *Run service in same thread of control*
2. *Run service in a separate thread*
3. *Run service in a separate process*

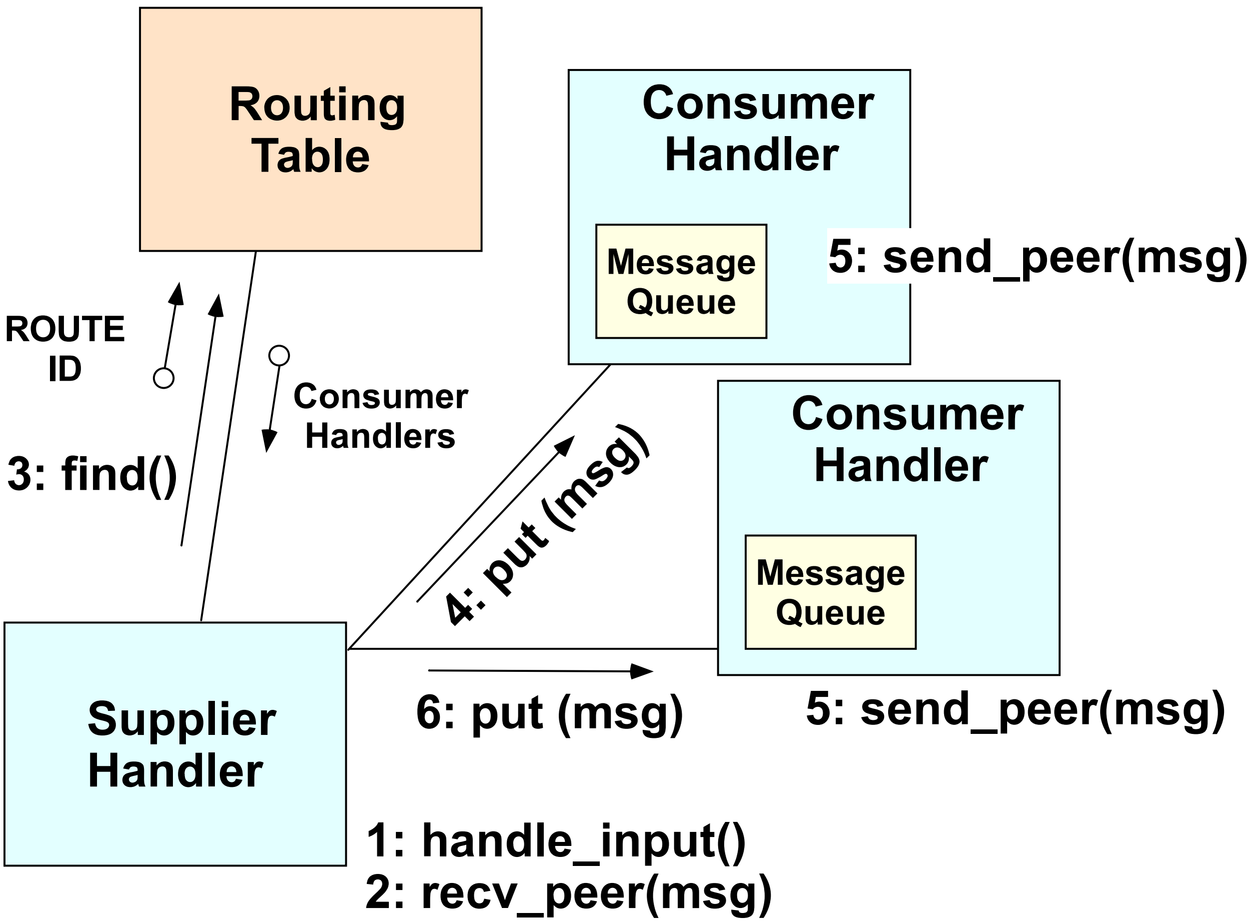
- Observe how our patterns and ACE framework push this decision to the “edges” of the design
  - This greatly increases reuse, flexibility, and performance tuning

Using the Active Object Pattern for the Gateway



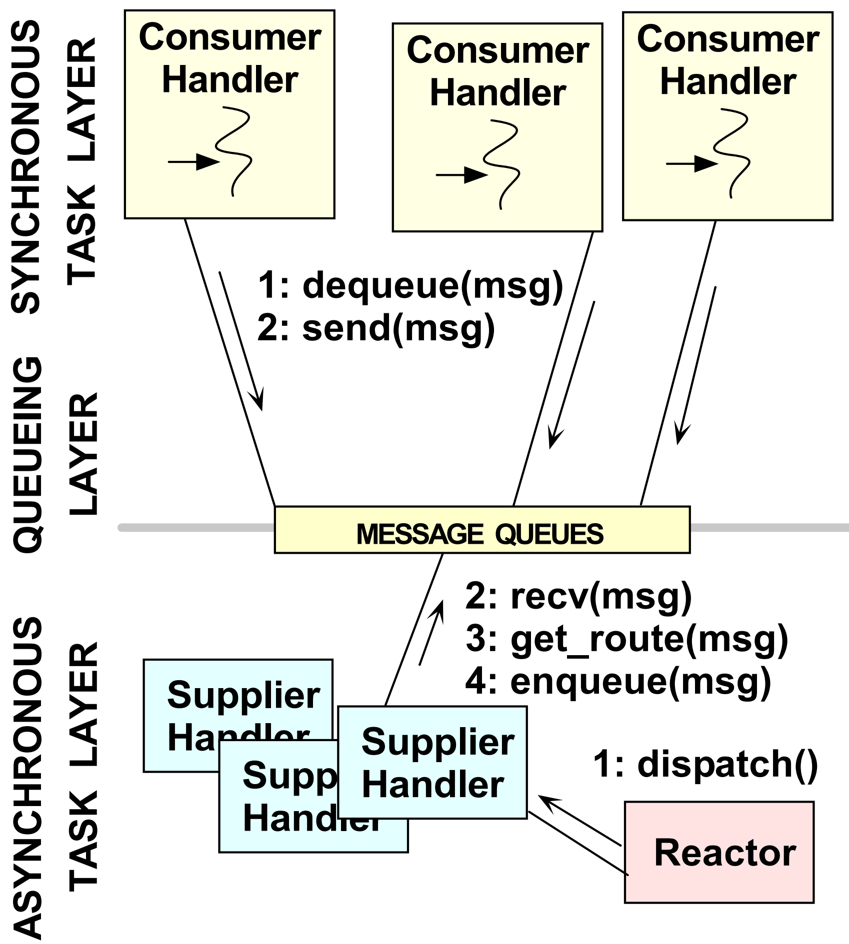
Each `Consumer_Handler` is implemented as an Active Object

Collaboration in Multi-threaded Gateway Routing



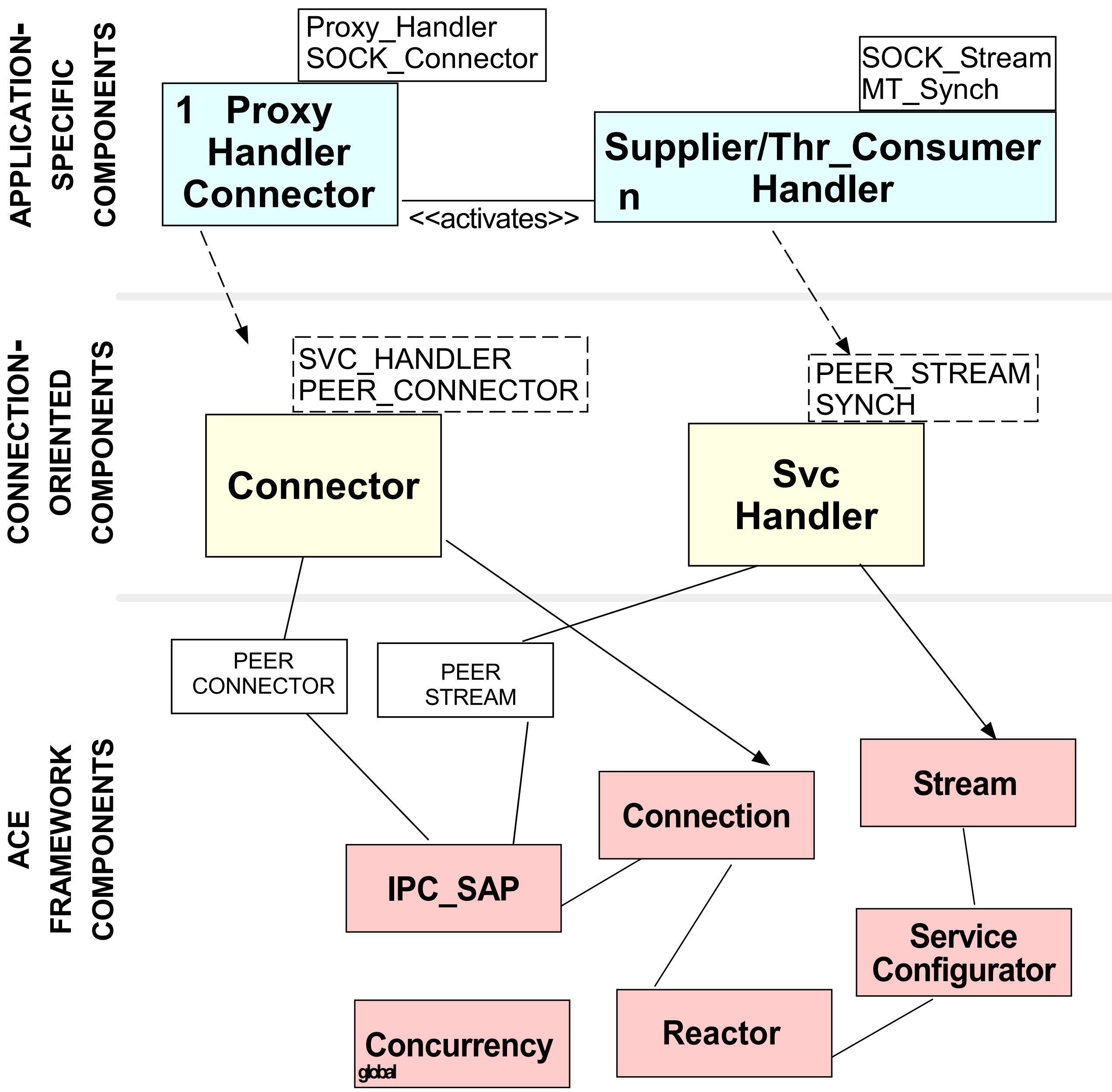
Note that this design is much simpler since the OS thread scheduler handles blocking

Using the Half-Sync/Half-Async Pattern in the Gateway



- `ACE_Reactor` plays the role of "async" layer
- `ACE_Task` active object plays the role of "sync" layer
- This particular configuration is a common variant of the Half-Sync/Half-Async pattern, as described in POSA2

Class Diagram for Multi-Threaded Gateway



Thr_Consumer_Handler Class Interface

```
#define ACE_USE_MT
#include Proxy_Handler.h

class Thr_Consumer_Handler
  : public Consumer_Handler
{
public:
    // Initialize the object and
    // spawn new thread.
  virtual int open (void *);
    // Send a message to a peer.
  virtual int put
    (ACE_Message_Block *,
     ACE_Time_Value *);
    // Transmit peer messages
    // in separate thread.
  virtual int svc (void);
};
```

New subclass of `Proxy_Handler` uses the Active Object pattern for the `Consumer_Handler`

- Uses multi-threading and synchronous I/O (rather than non-blocking I/O) to transmit message to Peers
- Transparently improve performance on a multi-processor platform and simplify design

Thr_Consumer_Handler Class Implementation

Override definition in the Consumer_Handler class

```
int
Thr_Consumer_Handler::open (void *)
{
  // Become an active object by
  // spawning a new thread to
  // transmit messages to Peers.

  activate (THR_DETACHED);
}
```

- The multi-threaded version of open() is slightly different since it spawns a new thread to become an active object!
- activate() is a pre-defined method on ACE_Task

Thr_Consumer_Handler Class Implementation

```
// Queue up a message for transmission.

int
Thr_Consumer_Handler::put (ACE_Message_Block *mb,
                           ACE_Time_Value *)
{
  // Perform non-blocking enqueue.
  msg_queue_->enqueue_tail (mb,
                            &ACE_Time_Value::zero);
}

// Transmit messages to the peer (note
// simplification resulting from threads...)

int
Thr_Consumer_Handler::svc (void)
{
  ACE_Message_Block *mb = 0;

  // Since this method runs in its own thread it
  // is OK to block on output.

  while (msg_queue_->dequeue_head (mb) != -1)
    send_peer (mb);
}
```

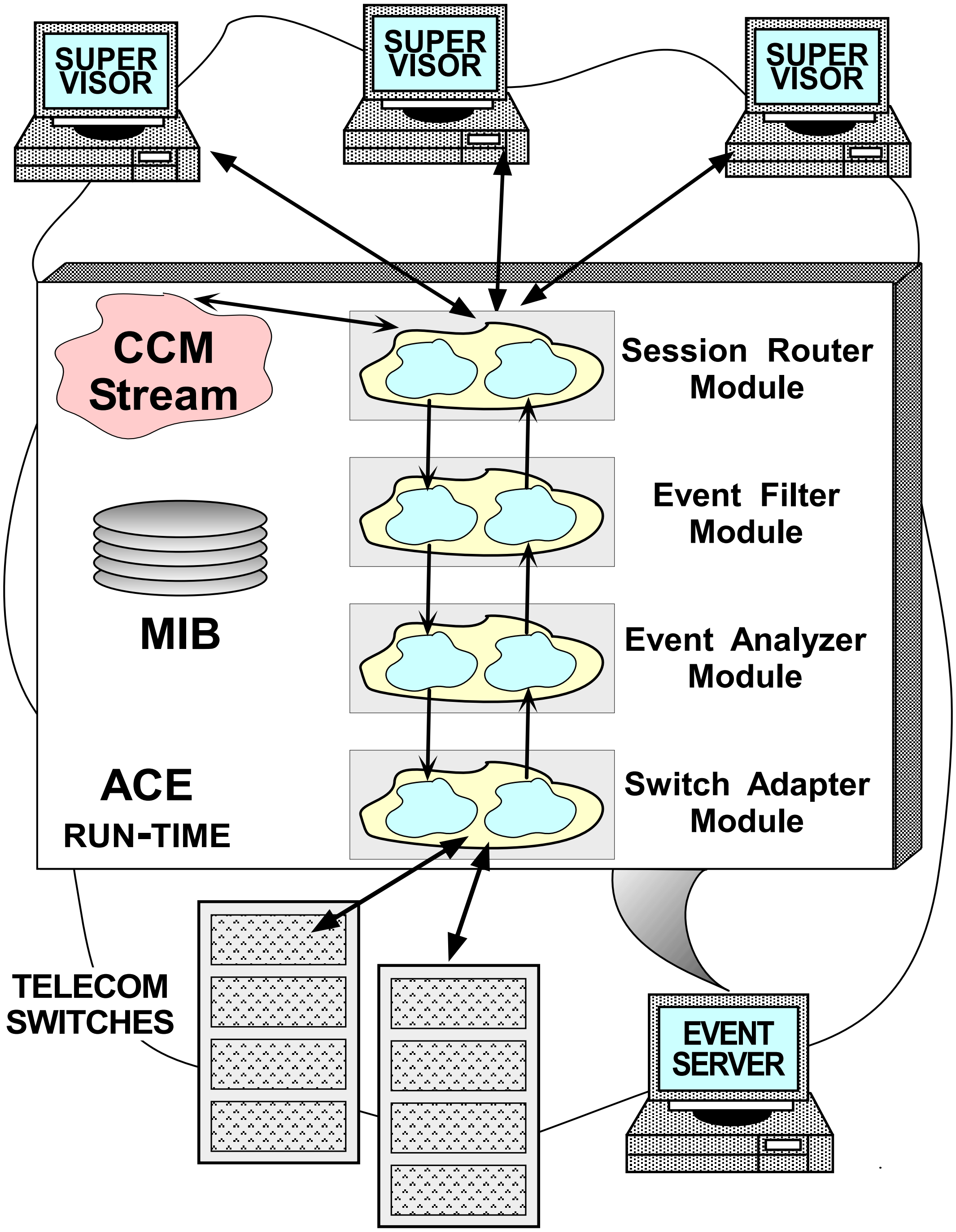
Dynamic Linking a Threaded Gateway Service

```
% cat ./svc.conf
remove Gateway
dynamic Gateway
Service_Object *
thr_gateway:_make_Gateway()
            "-d"
# .dll or .so suffix added
#  to  "thr_Gateway"
# automatically
```

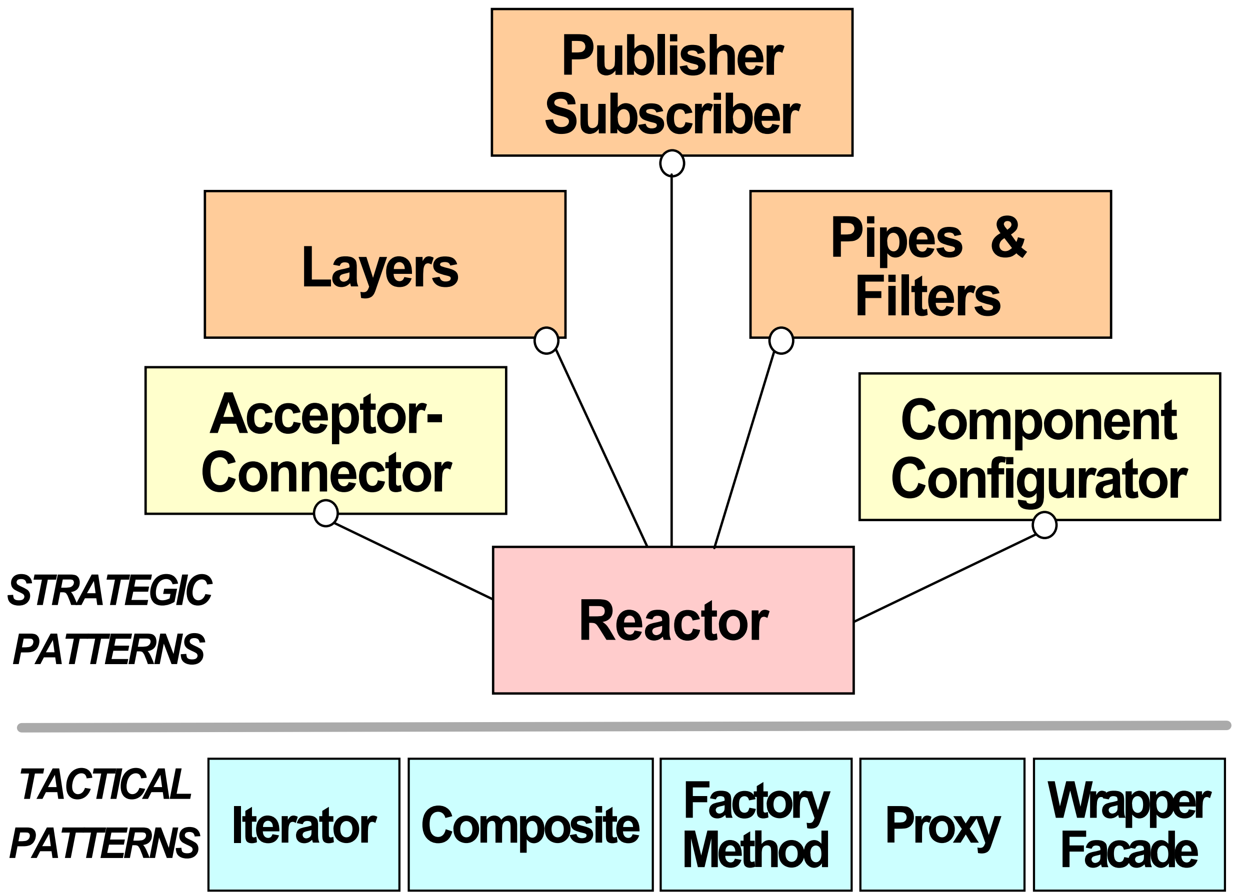
Dynamically linked factory function that allocates a multi-threaded Gateway object

```
extern "C"
ACE_Service_Object *make_Gateway (void);

ACE_Service_Object *make_Gateway (void)
{
  return new
    Gateway<Supplier_Handler,
            Thr_Consumer_Handler>;
  // ACE automatically deletes memory.
}
```

Call Center Manager (CCM) Event Server Example



Patterns in the CCM Event Server

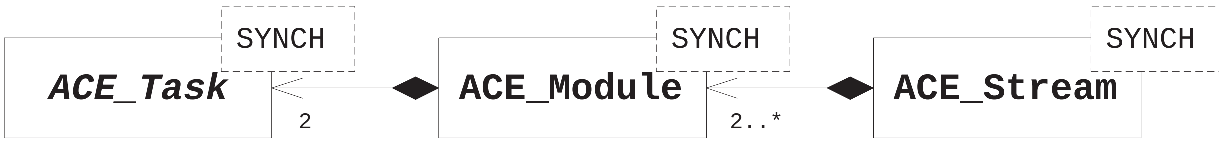


- The Event Server components are based upon a common *pattern language*
- `www.cs.wustl.edu/˜schmidt/PDF/DSEJ-94.pdf`

Overview of the ACE Streams Framework

- An `ACE_Stream` allows flexible configuration of layered processing modules
- It is an implementation of the *Pipes and Filters* architecture pattern
  - This pattern provides a structure for systems that process a stream of data
  - Each processing step is encapsulated in a filter `ACE_Module` component
  - Data is passed through pipes between adjacent filters, which can be re-combined
- The CCM Event Server was design and implemented using ACE Streams

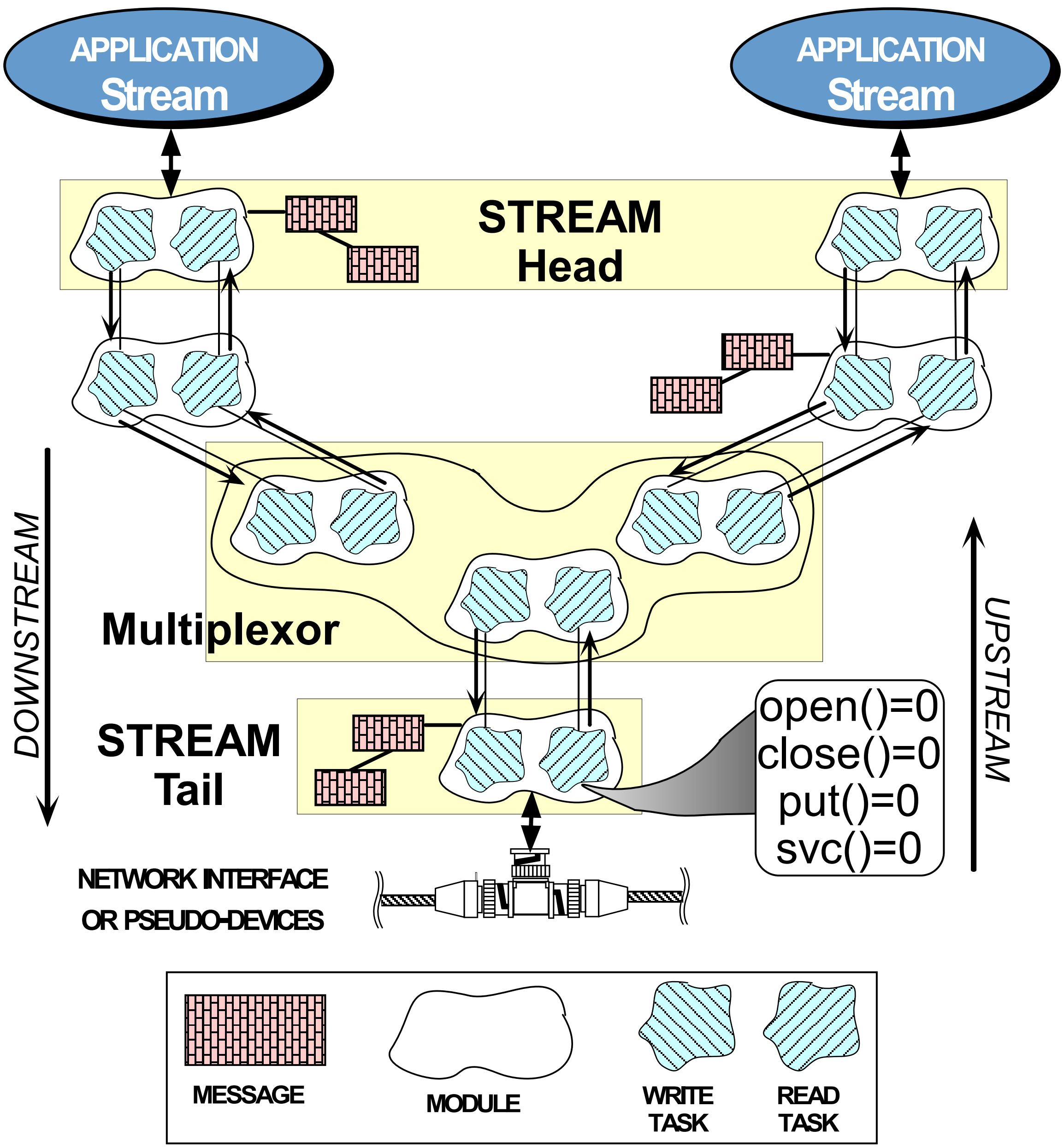
Structure of the ACE Streams Framework



Framework characteristics

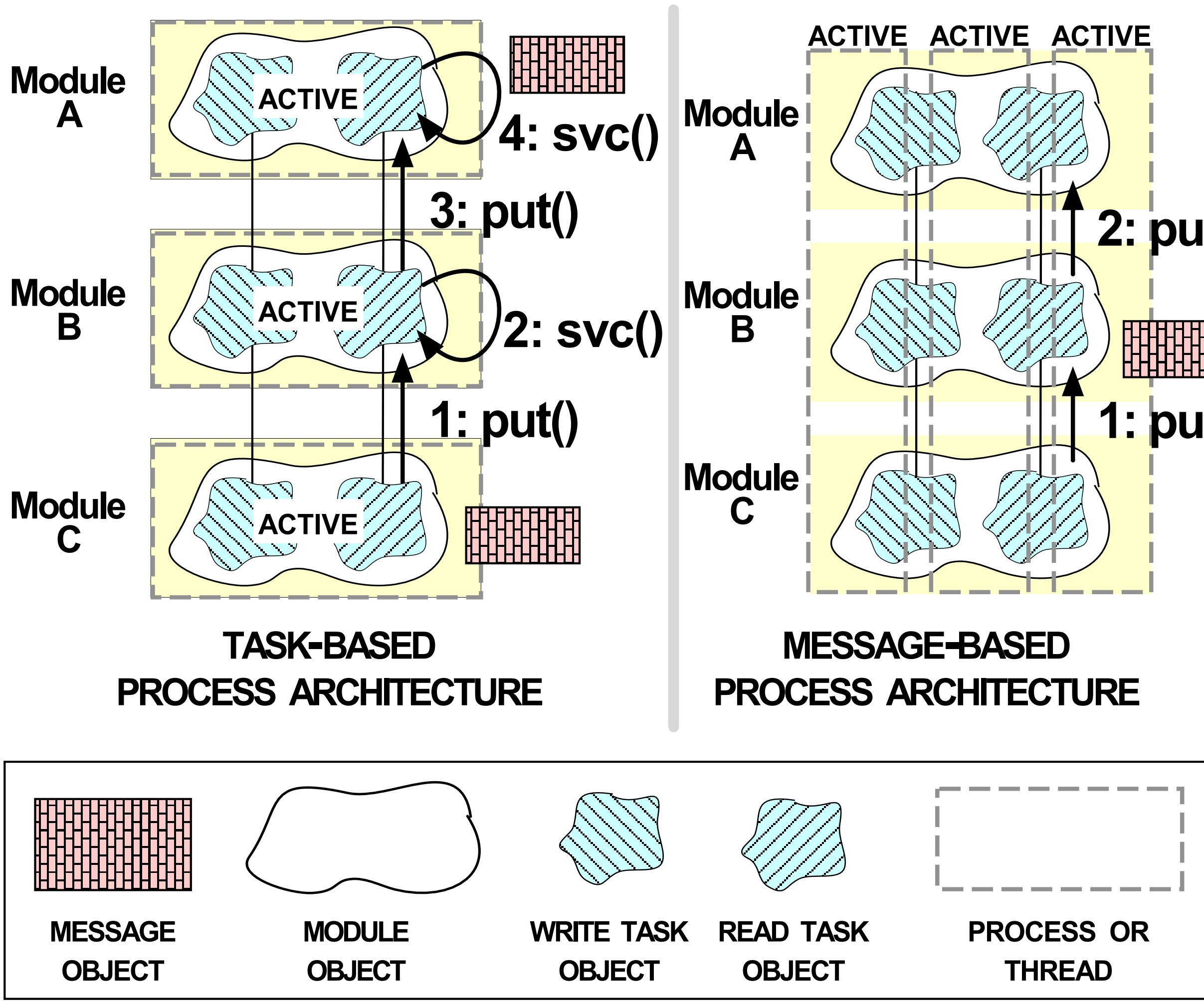
- An ACE_Stream contains a stack of ACE_Modules
- Each ACE_Module contains two ACE_Tasks
  - *i.e.*, a *read* task and a *write* task
- Each ACE_Task contains an ACE_Message_Queue and a pointer to an ACE_Thread_Manager

Implementing a Stream in ACE



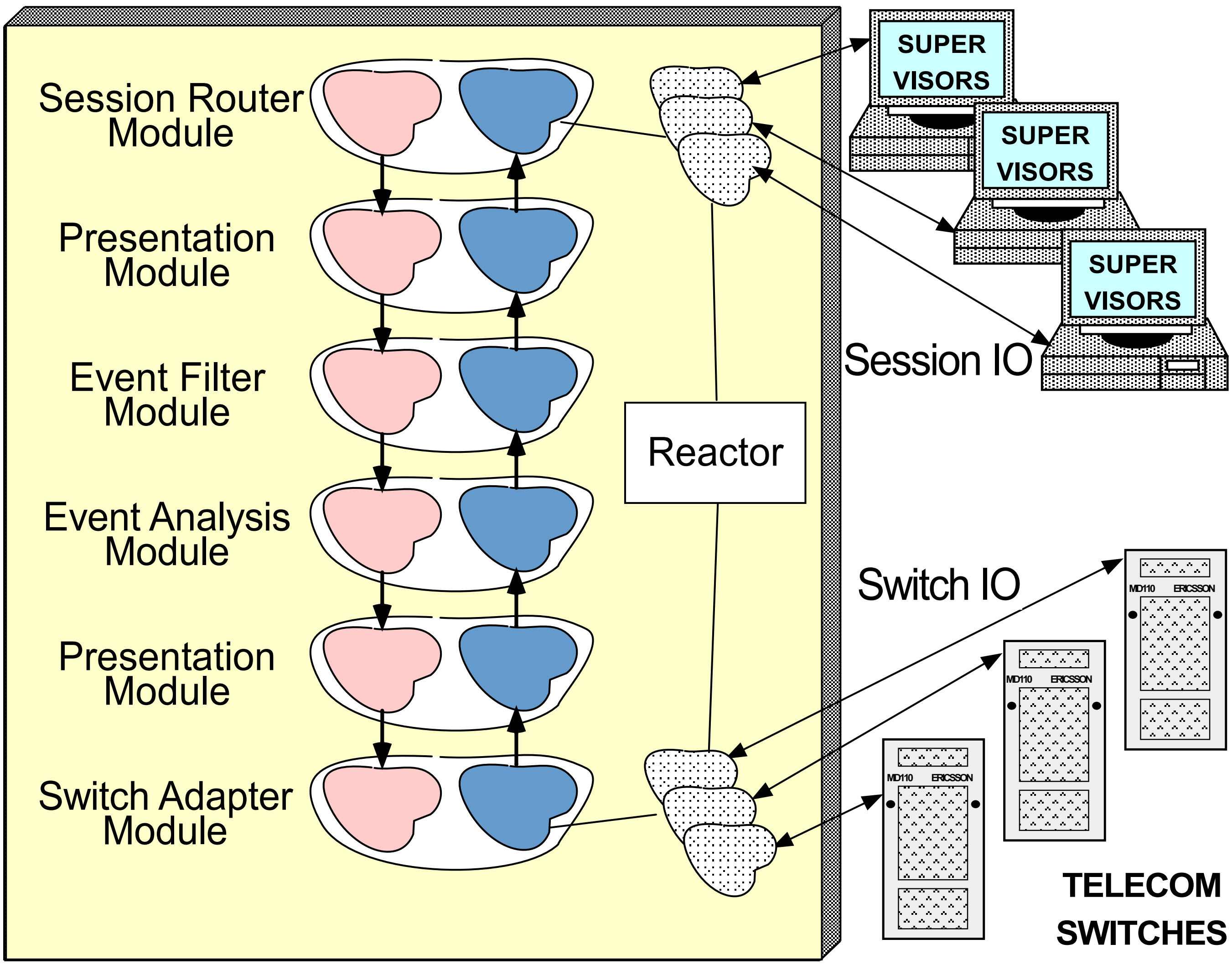
Note similarities to System V STREAMS

Alternative Concurrency Models for Message Processing



Task-based models are more intuitive but less efficient than Message-based models

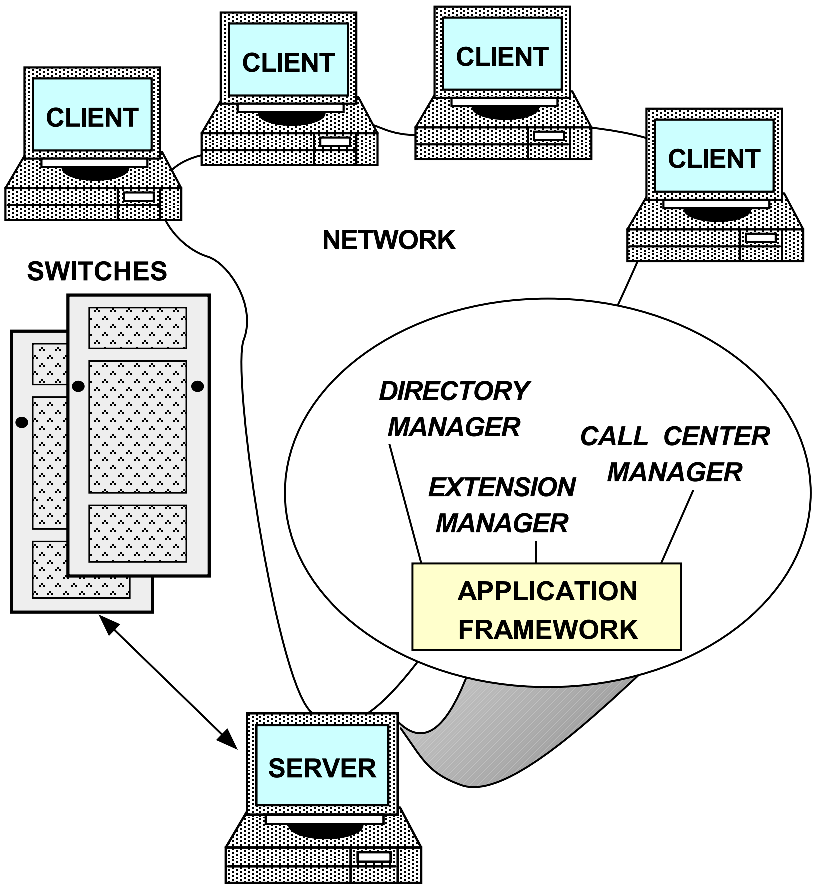
Using the ACE Streams Framework for the CCM Event Server



www.cs.wustl.edu/~schmidt/PDF/

DSEJ-94.pdf

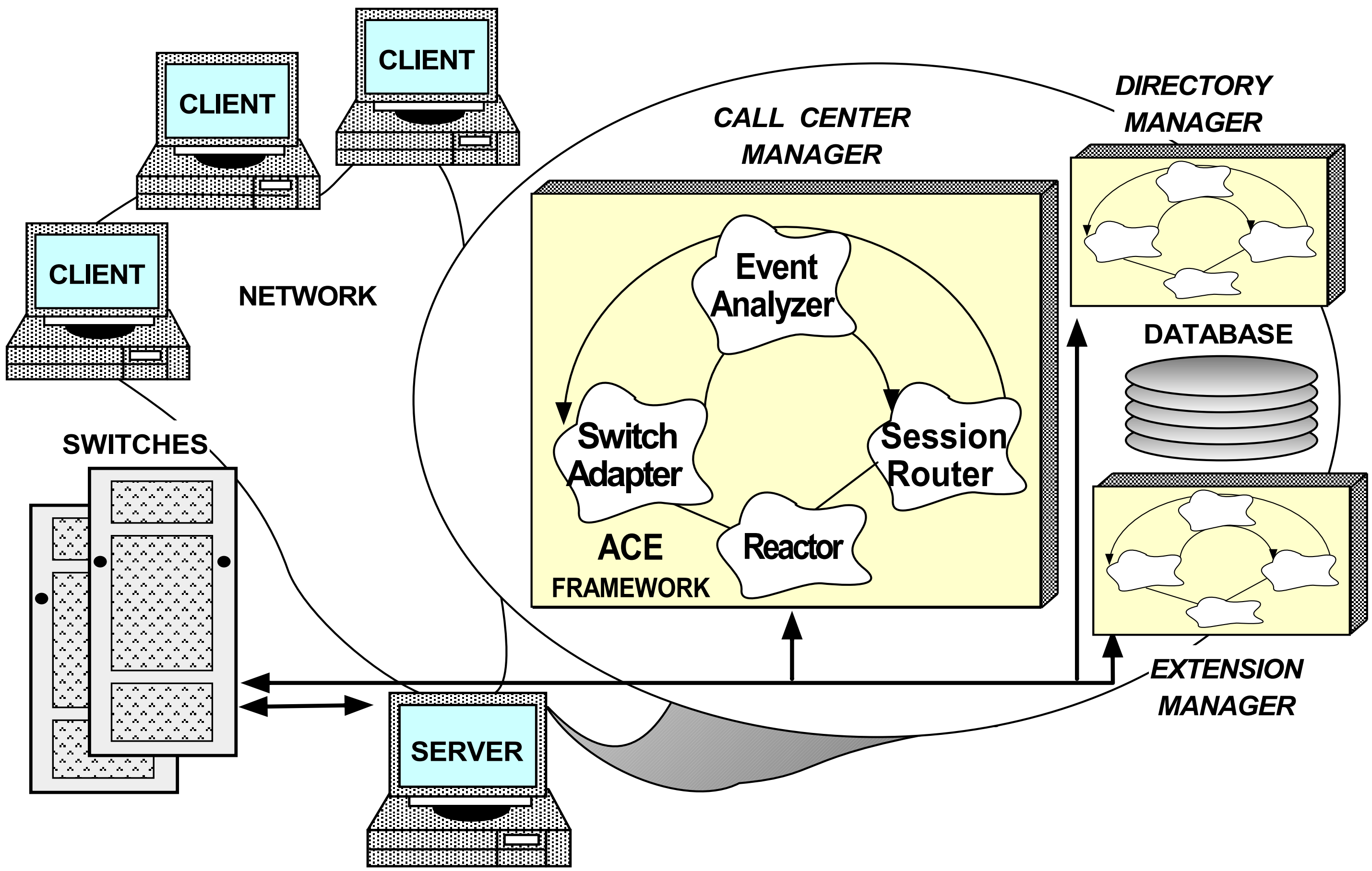
Broader Context: External OS for Telecom Switches



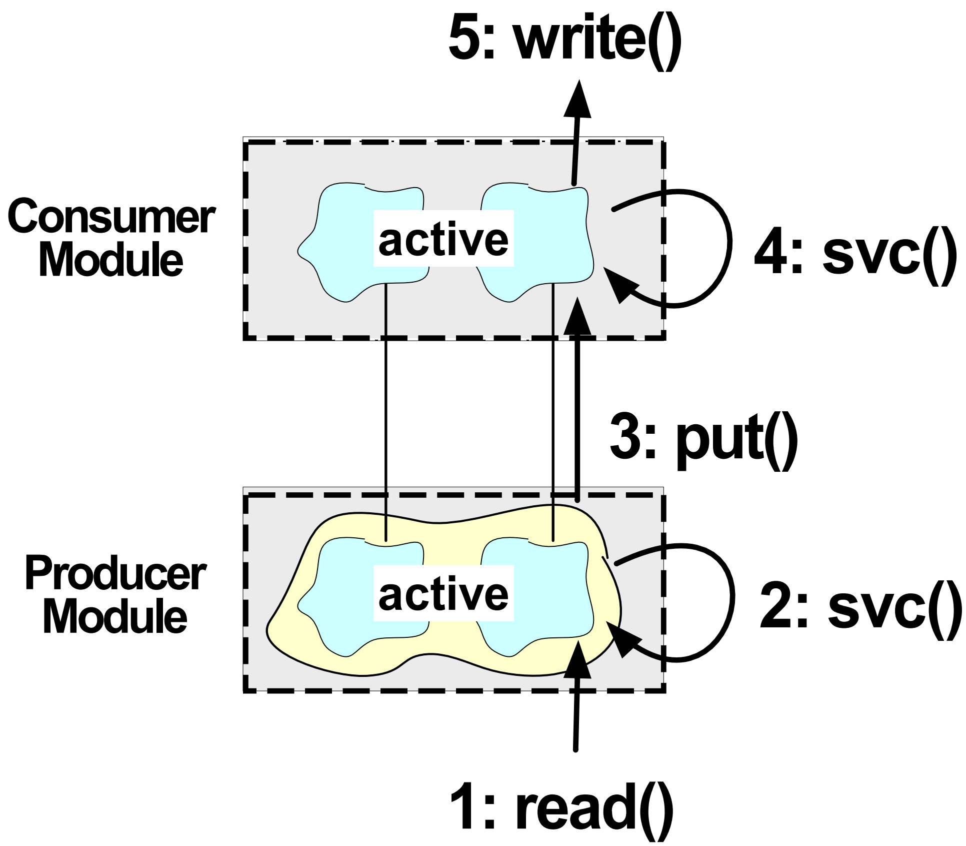
Features

- Allow clients to manage various aspects of telecom switches without modifying the switch software
- Support reuse of existing components based on a common architectural framework

Applying ACE Streams to External OS



ACE Stream Example: Parallel I/O Copy



- Program copies stdin to stdout via the use of a multi-threaded `ACE_Stream`
- Stream implements a “bounded buffer”
- Since the data flow is uni-directional the “read” `ACE_Task` is always ignored

Producer Class Interface

typedef short-hands for templates

```
typedef ACE_Stream<ACE_MT_SYNCH> MT_Stream;
typedef ACE_Module<ACE_MT_SYNCH> MT_Module;
typedef ACE_Task<ACE_MT_SYNCH> MT_Task;
```

Define the Producer interface

```
class Producer : public MT_Task
{
public:
  // Initialize Producer.
  virtual int open (void *)
  {
    // activate() is inherited from class Task.
    activate (THR_BOUND);
  }

  // Read data from stdin and pass to consumer.
  virtual int svc (void);
  // ...
};
```

Producer Class Implementation

Runs as an active object in a separate thread

```
int Producer::svc (void) {
  for (;;) {
    ACE_Message_Block *mb;
    // Allocate a new message.
    ACE_NEW_RETURN (mb,
                    ACE_Message_Block (BUFSIZ),
                    -1);
    // Keep reading stdin, until we reach EOF.
    ssize_t n = ACE_OS::read (ACE_STDIN,
                              mb->wr_ptr (),
                              mb->size ());
    if (n <= 0) {
      // Send shutdown message to other
      // thread and exit.
      mb->length (0);
      this->put_next (mb);
      break;
    } else {
      mb->wr_ptr (n); // Adjust write pointer.

      // Send the message to the other thread.
      this->put_next (mb);
    }
  }
}
```

Consumer Class Interface

Define the Consumer interface

```
class Consumer : public MT_Task
{
public:
  // Initialize Consumer.
  virtual int open (void *)
  {
    // <activate> is inherited from class Task.
    activate (THR_BOUND);
  }

  // Enqueue the message on the Message_Queue
  // for subsequent processing in <svc>.
  virtual int put (ACE_Message_Block *,
                   ACE_Time_Value * = 0)
  {
    // <putq> is inherited from class Task.
    return putq (mb, tv);
  }

  // Receive message from producer
  // and print to stdout.
  virtual int svc (void);
};
```

Consumer Class Implementation

Consumer dequeues a message from the ACE_Message_Queue, writes the message to the stderr stream, and deletes the message

```
int
Consumer::svc (void) {
  ACE_Message_Block *mb = 0;

  // Keep looping, reading a message from the queue,
  // until we get a 0 length message, then quit.
  for (;;) {
      int result = getq (mb);

      if (result == -1) break;
      int length = mb->length ();

      if (length > 0)
        ACE_OS::write (ACE_STDOUT, mb->rd_ptr (),
                       length);
      mb->release ();

      if (length == 0) break;
    }
}
```

The Producer sends a 0-sized message to inform the Consumer to stop reading and exit

Main Driver Function for the Stream

Create `Producer` and `Consumer` Modules and push them onto the Stream

```
int main (int argc, char *argv[])
{
  // Control hierarchically-related
  // active objects.
  MT_Stream stream;

  // All processing is performed in the
  // Stream after <push>'s complete.
  stream.push (new MT_Module
                ("Consumer", new Consumer);
  stream.push (new MT_Module
                ("Producer", new Producer));

  // Barrier synchronization: wait for
  // the threads, to exit, then exit
  // the main thread.
  ACE_Thread_Manager::instance ()->wait ();
}
```

Evaluation of the ACE Stream Framework

- Structuring active objects via an `ACE_Stream` allows "interpositioning"
  - *i.e.*, similar to adding a filter in a UNIX pipeline
- New functionality may be added by "pushing" a new processing `ACE_Module` onto an `ACE_Stream`, *e.g.*:

```
stream.push (new MT_Module ("Consumer", new Consumer))
stream.push (new MT_Module ("Filter", new Filter));
stream.push (new MT_Module ("Producer", new Producer));
```

- Communication between `ACE_Modules` is typically *anonymous*

Concurrency Strategies

- Developing correct, efficient, and robust concurrent applications is challenging
- Below, we examine a number of strategies that addresses challenges related to the following:
  - *Concurrency control*
  - *Library design*
  - *Thread creation*
  - *Deadlock and starvation avoidance*

General Threading Guidelines

- A threaded program should not arbitrarily enter non-threaded (*i.e.*, "unsafe") code
- Threaded code may refer to unsafe code only from the main thread
  - *e.g.*, beware of `errno` problems
- Use reentrant OS library routines ('_r') rather than non-reentrant routines
- Beware of thread global process operations, such as file I/O
- Make sure that `main()` terminates cleanly
  - *e.g.*, beware of `pthread_exit()`, `exit()`, and "falling off the end"

Thread Creation Strategies

- Use threads for independent jobs that must maintain state for the life of the job
- Don't spawn new threads for very short jobs
- Use threads to take advantage of CPU concurrency
- Only use "bound" threads when absolutely necessary
- If possible, tell the threads library how many threads are expected to be active simultaneously
  - *e.g.*, use `thr_setconcurrency()`

General Locking Guidelines

- Don't hold locks across long duration operations (*e.g.*, I/O) that can impact performance
  - Use `ACE_Token` instead...
- Beware of holding non-recursive mutexes when calling a method outside a class
  - The method may reenter the module and deadlock
- Don't lock at too small of a level of granularity
- Make sure that threads obey the global lock hierarchy
  - But this is easier said than done...

Locking Alternatives

- *Code locking*
  - Associate locks with body of functions
    * Typically performed using bracketed mutex locks
  - Often called a *Monitor Object*
- *Data locking*
  - Associate locks with data structures and/or objects
  - Permits a more fine-grained style of locking
- Data locking allows more concurrency than code locking, but may incur higher overhead

Single-lock Strategy

- One way to simplify locking is use a single, application-wide mutex lock
- Each thread must acquire the lock before running and release it upon completion
- The advantage is that most legacy code doesn't require changes
- The disadvantage is that parallelism is eliminated
  - Moreover, interactive response time may degrade if the lock isn't released periodically

Monitor Object Strategy

- A more OO locking strategy is to use a Monitor Object
  - `www.cs.wustl.edu/~schmidt/POSA/`
- Monitor Object synchronization mechanisms allow concurrent method invocations
  - Either eliminate access to shared data or use synchronization objects
  - Hide locking mechanisms behind method interfaces
    - Therefore, modules should not export data directly
- Advantage is transparency
- Disadvantages are increased overhead from excessive locking and lack of control over method invocation order

Active Object Strategy

- Each task is modeled as an active object that maintains its own thread of control
- Messages sent to an object are queued up and processed asynchronously with respect to the caller
  - *i.e.*, the order of execution may differ from the order of invocation
- This approach is more suitable to message passing-based concurrency
- The `ACE_Task` class can be used to implement active objects
  - `www.cs.wustl.edu/~schmidt/POSA/`

Invariants

- In general, an invariant is a condition that is always true
- For concurrent programs, an invariant is a condition that is always true when an associated lock is *not* held
  - However, when the lock is held the invariant may be false
  - When the code releases the lock, the invariant must be re-established
- *e.g.*, enqueueing and dequeueing messages in the `ACE_Message_Queue` class

Run-time Stack Problems

- Most threads libraries contain restrictions on stack usage
  - The initial thread gets the "real" process stack, whose size is only limited by the stacksize limit
  - All other threads get a fixed-size stack
    * Each thread stack is allocated off the heap and its size is fixed at startup time

- Therefore, be aware of "stack smashes" when debugging multi-threaded code
  - Overly small stacks lead to bizarre bugs, *e.g.*,
    * Functions that weren't called appear in backtraces
    * Functions have strange arguments

Deadlock

- Permanent blocking by a set of threads that are competing for a set of resources
- Caused by "circular waiting," *e.g.*,
  - A thread trying to reacquire a lock it already holds
  - Two threads trying to acquire resources held by the other
    - *e.g.*, T_1 and T_2 acquire locks L_1 and L_2 in opposite order
- One solution is to establish a global ordering of lock acquisition (*i.e.*, a *lock hierarchy*)
  - May be at odds with encapsulation...

Avoiding Deadlock in OO Frameworks

- Deadlock can occur due to properties of OO frameworks, *e.g.*,
  - *Callbacks*
  - *Inter-class method calls*
- There are several solutions
  - Release locks before performing callbacks
    - Every time locks are reacquired it may be necessary to reevaluate the state of the object
  - Make private “helper” methods that assume locks are held when called by methods at higher levels
  - Use an `ACE_Token` or `ACE_Recursive_Thread_Mutex`

ACE_Recursive_Thread_Mutex Implementation

Here is portable implementation of recursive thread mutexes available in ACE:

```
class ACE_Recursive_Thread_Mutex
{
public:
    // Initialize a recursive mutex.
  ACE_Recursive_Thread_Mutex (void);
    // Implicitly release a recursive mutex.
  ~ACE_Recursive_Thread_Mutex (void);
    // Acquire a recursive mutex.
  int acquire (void);
    // Conditionally acquire a recursive mutex.
  int tryacquire (void);
    // Releases a recursive mutex.
  int release (void);

private:
  ACE_Thread_Mutex nesting_mutex_;
  ACE_Condition_Thread_Mutex mutex_available_;
  ACE_thread_t owner_;
  int nesting_level_;
};
```

Acquiring an ACE_Recursive_Thread_Mutex

```
int ACE_Recursive_Thread_Mutex::acquire (void)
{
  ACE_thread_t t_id = ACE_Thread::self ();
  ACE_GUARD_RETURN (ACE_Thread_Mutex, guard,
                    nesting_mutex_, -1);
  // If there's no contention, grab mutex.
  if (nesting_level_ == 0) {
    owner_ = t_id;
    nesting_level_ = 1;
  }
  else if (t_id == owner_)
    // If we already own the mutex, then
    // increment nesting level and proceed.
    nesting_level_++;
  else {
    // Wait until nesting level drops
    // to zero, then acquire the mutex.
    while (nesting_level_ > 0)
      mutex_available_.wait ();

    // Note that at this point
    // the nesting_mutex_ is held...

    owner_ = t_id;
    nesting_level_ = 1;
  }
  return 0;
```

Releasing and Initializing an ACE_Recursive_Thread_Mutex

```
int ACE_Recursive_Thread_Mutex::release (void)
{
  ACE_thread_t t_id = ACE_Thread::self ();

  // Automatically acquire mutex.
  ACE_GUARD_RETURN (ACE_Thread_Mutex, guard,
                    nesting_mutex_, -1);
  nesting_level_--;

  if (nesting_level_ == 0) {
    // Put the mutex into a known state.
    owner_ = ACE_OS::NULL_thread;
    // Inform waiters that the mutex is free.
    mutex_available_.signal ();
  }
  return 0;
}

ACE_Recursive_Thread_Mutex::
  ACE_Recursive_Thread_Mutex (void)
  : nesting_level_ (0),
    owner_ (ACE_OS::NULL_thread),
    mutex_available_ (nesting_mutex_){}
```

Avoiding Starvation

- Starvation occurs when a thread never acquires a mutex even though another thread periodically releases it
- The order of scheduling is often undefined
- This problem may be solved via:
  - Use of “voluntary pre-emption” mechanisms
    * *e.g.*, `thr_yield()` or `Sleep()`
  - Using an ACE “Token” that strictly orders acquisition and release

Drawbacks to Multi-threading

- *Performance overhead*
  - Some applications do not benefit directly from threads
  - Synchronization is not free
  - Threads should be created for processing that lasts at least several 1,000 instructions
- *Correctness*
  - Threads are not well protected against interference
  - Concurrency control issues are often tricky
  - Many legacy libraries are not thread-safe
- *Development effort*
  - Developers often lack experience
  - Debugging is complicated (lack of tools)

Lessons Learned using OO Patterns

- ***Benefits of patterns***
  - Enable large-scale reuse of software architectures
  - Improve development team communication
  - Help transcend language-centric viewpoints
- ***Drawbacks of patterns***
  - Do not lead to direct code reuse
  - Can be deceptively simple
  - Teams may suffer from pattern overload

Lessons Learned using OO Frameworks

- ***Benefits of frameworks***
  - Enable direct reuse of code (*cf* patterns)
  - Facilitate larger amounts of reuse than stand-alone functions or individual classes
- ***Drawbacks of frameworks***
  - High initial learning curve
    - Many classes, many levels of abstraction
  - The flow of control for reactive dispatching is non-intuitive
  - Verification and validation of generic components is hard

Lessons Learned using C++

- ***Benefits of C++***
  - *Classes* and *namespaces* modularize the system architecture
  - *Inheritance* and *dynamic binding* decouple application *policies* from reusable *mechanisms*
  - *Parameterized types* decouple the reliance on particular types of synchronization methods or network IPC interfaces

- ***Drawbacks of C++***
  - Some language features are not implemented
  - Some development environments are primitive
  - Language has many dark corners and sharp edges
    - Purify helps alleviate many problems...

Lessons Learned using OOD

- Good designs can be boiled down to a few key principles:
  - Separate interface from implementation
  - Determine what is *common* and what is *variable* with an interface and an implementation
  - Allow substitution of *variable* implementations via a *common* interface
    * *i.e.*, the "open/closed" principle & Aspect-Oriented Programming (AOP)
  - Dividing *commonality* from *variability* should be goal-oriented rather than exhaustive
- Design is not simply drawing a picture using a CASE tool, using graphical UML notation, or applying patterns
  - Design is a fundamentally *creative* activity

Software Principles for Distributed Applications

- ***Use patterns/frameworks to decouple policies/mechanisms***
  - Enhance reuse of common concurrent programming components
- ***Decouple service functionality from configuration***
  - Improve flexibility and performance
- ***Use classes, inheritance, dynamic binding, and parameterized types***
  - Improve extensibility and modularity
- ***Enhance performance/functionality with OS features***
  - *e.g.*, implicit and explicit dynamic linking and multi-threading
- ***Perform commonality/variability analysis***
  - Identify uniform interfaces for *variable* components and support pluggability of variation

Conferences and Workshops on Patterns

- Pattern Language of Programs Conferences
  - PLoP, September, 2002, Monticello, Illinois, USA
  - OOPSLA, November, 2002, Seattle, USA
  - hillside.net/patterns/conferences/
- Distributed Objects and Applications Conference
  - Oct/Nov, 2002, UC Irvine
  - `www.cs.wustl.edu/~schmidt/activities-chair.html`

Patterns, Frameworks, and ACE Literature

- **Books**
  - Gamma et al., *Design Patterns: Elements of Reusable Object-Oriented Software* AW, '94
  - *Pattern Languages of Program Design* series by AW, '95-'99.
  - Siemens & Schmidt, *Pattern-Oriented Software Architecture*, Wiley, volumes '96 & '00 (`www.posa.uci.edu`)
  - Schmidt & Huston, *C++ Network Programming: Mastering Complexity with ACE and Patterns*, AW, '02 (`www.cs.wustl.edu/~schmidt/ACE/book1/`)
  - Schmidt & Huston, *C++ Network Programming: Systematic Reuse with ACE and Frameworks*, AW, '03 (`www.cs.wustl.edu/~schmidt/ACE/book2/`)

How to Obtain ACE Software and Technical Support

- All source code for ACE is freely available
  - `www.cs.wustl.edu/~schmidt/ACE.html`
- Mailing lists
  - `ace-users@cs.wustl.edu`
  - `ace-users-request@cs.wustl.edu`
  - `ace-announce@cs.wustl.edu`
  - `ace-announce-request@cs.wustl.edu`
- Newsgroup
  - `comp.soft-sys.ace`
- Commercial support from Riverace and OCI
  - `www.riverace.com`
  - `www.theaceorb.com`

Concluding Remarks

- Developers of networked application software confront recurring challenges that are largely application-independent
  - *e.g.*, service configuration and initialization, distribution, error handling, flow control, event demultiplexing, concurrency, synchronization, persistence, etc.
- Successful developers resolve these challenges by applying appropriate *patterns* to create communication *frameworks* containing *components*
- *Frameworks* and *components* are an effective way to achieve systematic reuse of software