Patterns and Frameworks for Concurrent Network Programming with ACE and C++

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Motivation for Concurrency

- Concurrent programming is increasing relevant to:
  - *Leverage hardware/software advances*
    - *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.*, synchronous vs. asynchronous network IPC

Motivation for Distribution

- Benefits of distributed computing:
  - Collaboration → *connectivity* and *interworking*
  - Performance → *multi-processing* and *locality*
  - Reliability and availability → *replication*
  - Scalability and portability → *modularity*
  - Extensibility → *dynamic configuration and reconfiguration*
  - Cost effectiveness → *open systems* and *resource sharing*

Challenges and Solutions

- However, 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
  - However, when used properly it helps minimize "accidental" complexity and improve software quality factors
- Advanced OS features provide additional functionality and performance, *e.g.*,
  - *Multi-threading*
  - *Multi-processing*
  - *Synchronization*
  - *Shared memory*
  - *Explicit dynamic linking*
  - *Communication protocols and IPC mechanisms*

Tutorial Outline

- Outline key OO networking and concurrency concepts and OS platform mechanisms
  - Emphasis is on *practical* solutions
- Examine several examples in detail
  1. *Distributed logger*
  2. *Concurrent WWW client/server*
  3. *Application-level Telecom Gateway*
  4. *OO framework for layered active objects*
- Discuss general concurrent programming strategies

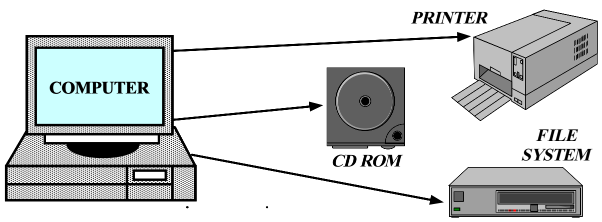
Software Development Environment

- The topics discussed here are largely independent of OS, network, and programming language
  - Currently used successfully on UNIX/POSIX, Win32, 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

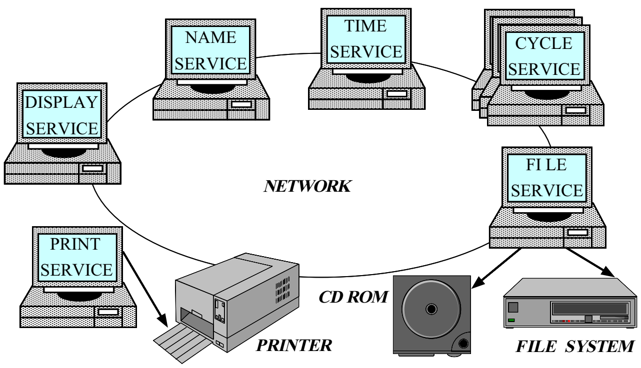
Definitions

- *Concurrency*
  - "Logically" simultaneous processing
  - Does *not* imply multiple processing elements
- *Parallelism*
  - "Physically" simultaneous processing
  - Involves multiple processing elements and/or independent device operations
- *Distribution*
  - Partition system/application into multiple components that can reside on different hosts
  - Implies message passing as primary IPC mechanism

Stand-alone vs. Distributed Application Architectures

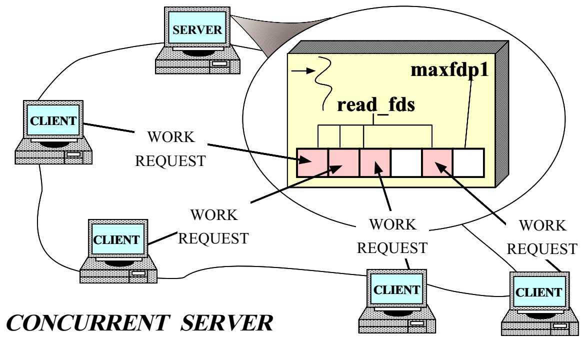


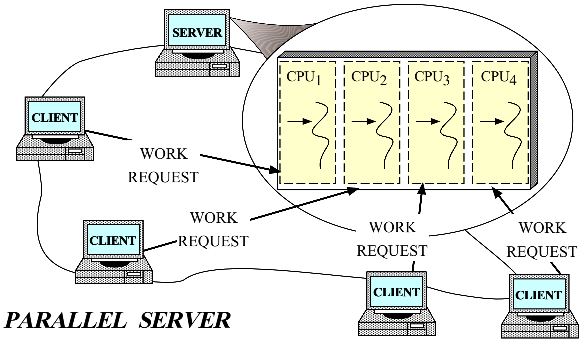
(1) STAND-ALONE APPLICATION ARCHITECTURE



(2) DISTRIBUTED APPLICATION ARCHITECTURE

Concurrency vs. Parallelism





Sources of Complexity

- Concurrent network application development exhibits both *inherent* and *accidental* complexity

- *Inherent complexity* results from fundamental challenges
  - *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 Complexity (cont'd)

- *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

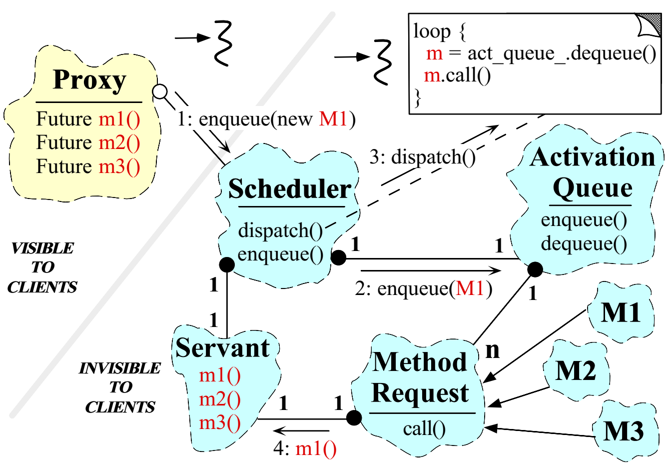
OO Contributions to Concurrent Applications

- Concurrent network programming has traditionally been performed using low-level OS mechanisms, *e.g.*,
  * *fork/exec*
  * *Shared memory, mmap, and SysV semaphores*
  * *Signals*
  * *sockets/select*
  * *POSIX pthreads, Solaris threads, Win32 threads*
- *Patterns* and *frameworks* elevate development to focus on application concerns, *e.g.*,
  - *Service functionality and policies*
  - *Service configuration*
  - *Concurrent event demultiplexing and event handler dispatching*
  - *Service concurrency and synchronization*

Patterns

- Patterns represent *solutions* to *problems* that arise when developing software within a particular *context*
  - *i.e.*, "Patterns == problem/solution pairs in 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

Active Object Pattern

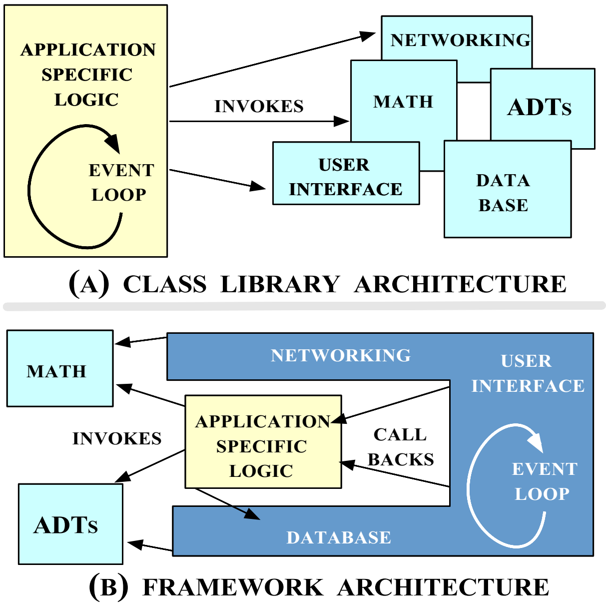


- *Intent*: decouples the thread of method execution from the thread of method invocation

Frameworks

- 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"
- Typically, applications are developed by *inheriting* from and *instantiating* framework components

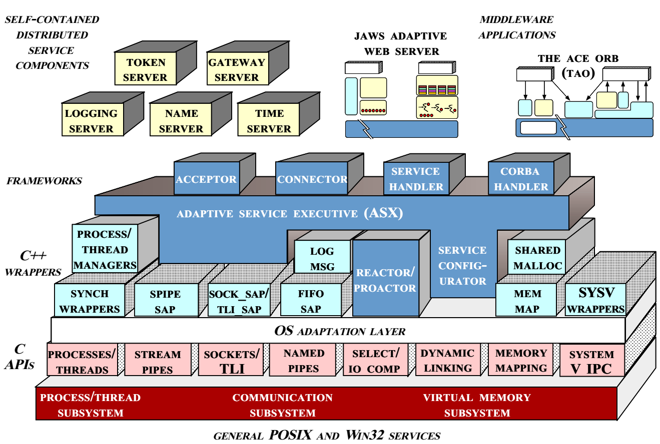
Differences Between Class Libraries and Frameworks



Why We Need Communication Middleware

- System call-level programming is wrong abstraction for application developers, *e.g.*,
  - *Too low-level* → error codes, endless reinvention
  - *Error-prone* → HANDLEs lack type-safety, thread cancellation woes
  - *Mechanisms do not scale* → Win32 TLS
  - *Steep learning curve* → Win32 Named Pipes
  - *Non-portable* → Win32 WinSock bugs
  - *Inefficient* → *i.e.*, tedious for humans
- GUI frameworks are inadequate for communication software, *e.g.*,
  - *Inefficient* → excessive use of virtual methods
  - *Lack of features* → minimal threading and synchronization mechanisms, no network services

The ADAPTIVE Communication Environment (ACE)

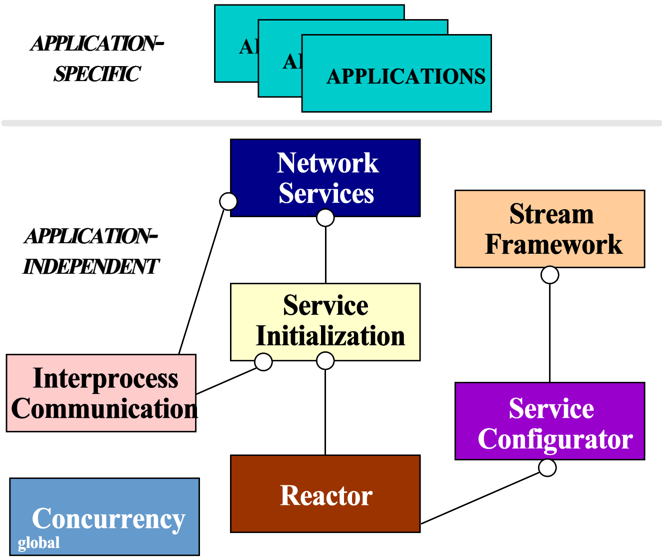


- A set of C++ wrappers, class categories, and frameworks based on patterns
  - www.cs.wustl.edu/~schmidt/ACE.html

ACE Statistics

- Core ACE frameworks and components contain 175,000 lines of C++
- > 20 person-years of effort
- Ported to UNIX, Win32, MVS, and embedded platforms
- Large user community (ACE-users.html)
- Currently used by dozens of companies
  - *e.g.*, Siemens, Motorola, Ericsson, Kodak, Bellcore, Boeing, SAIC, StorTek ,etc.
- Supported commercially by Riverace
  - www.riverace.com/

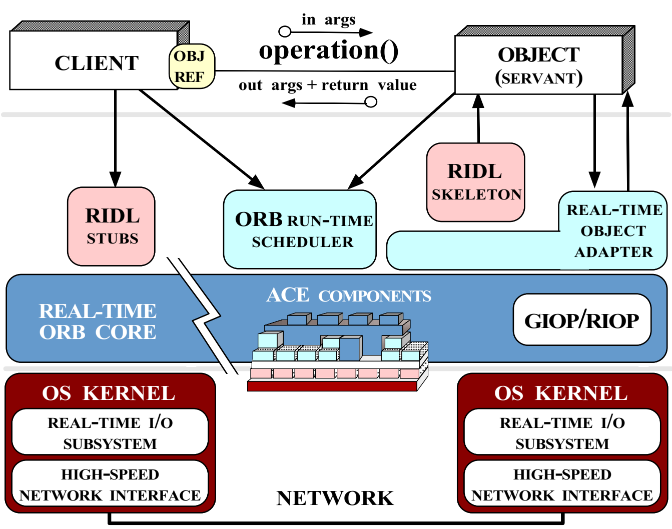
Class Categories in ACE



Class Categories in ACE (cont'd)

- Responsibilities of each class category
  - `IPC` encapsulates local and/or remote *IPC mechanisms*
  - `Service Initialization` encapsulates active/passive connection establishment mechanisms
  - `Concurrency` encapsulates and extends *multi-threading* and *synchronization* mechanisms
  - `Reactor` performs *event demultiplexing* and *event handler dispatching*
  - `Service Configurator` automates *configuration* and *reconfiguration* by encapsulating explicit dynamic linking mechanisms
  - `Stream Framework` models and implements *layers* and *partitions* of hierarchically-integrated communication software
  - `Network Services` provides distributed naming, logging, locking, and routing services

The ACE ORB (TAO)

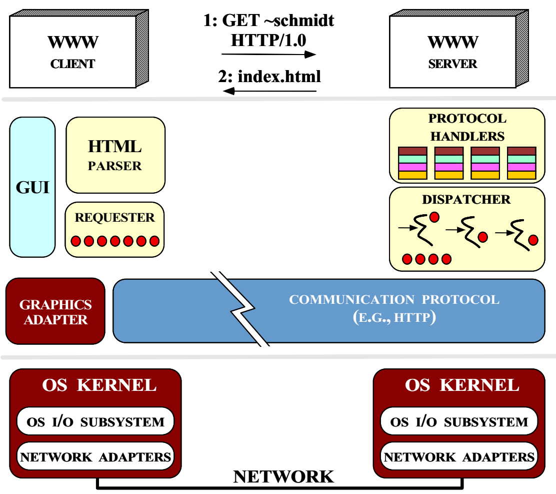


- A high-performance, real-time ORB built with ACE
- www.cs.wustl.edu/~schmidt/TAO.html

TAO Statistics

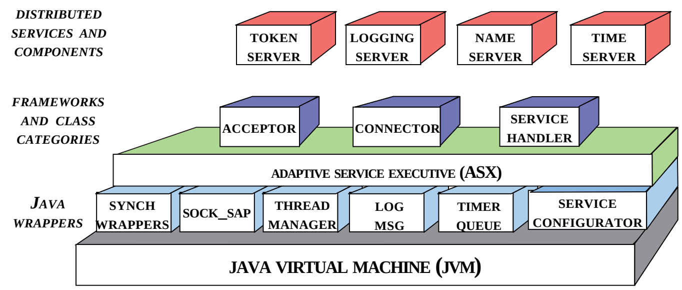
- Core TAO ORB contain ~50,000 lines of C++
  - Leverages ACE heavily
- > 10 person-years of effort
- Ported to UNIX, Win32, and embedded platforms
- Currently used by many companies
  - *e.g.*, Siemens, Boeing, SAIC, Raytheon, etc.
- Supported commercially by OCI
  - www.ociweb.com/

JAWS Adaptive Web Server



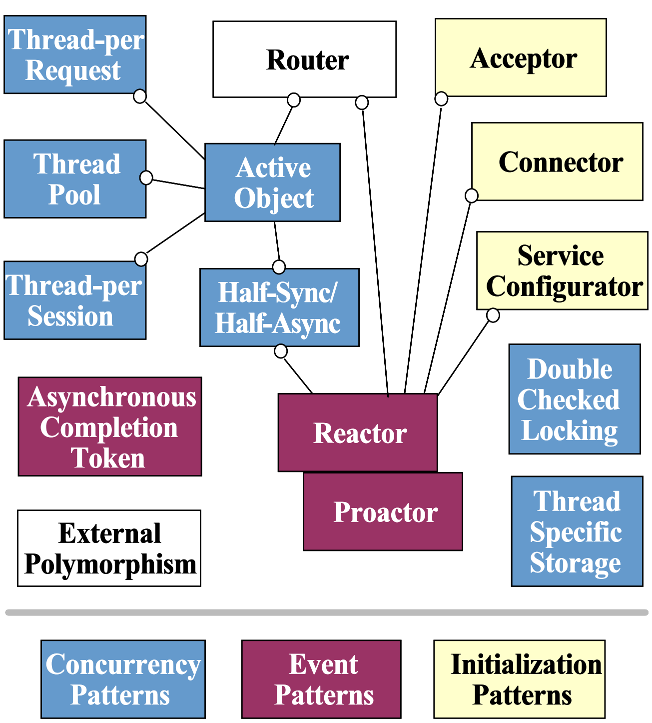
- A high-performance, cross-platform Web server built with ACE
  - Used commercially by Entera
- www.cs.wustl.edu/~jxh/research/

Java ACE



- A version of ACE written in Java
- Currently used for medical imaging prototype
- www.cs.wustl.edu/~schmidt/JACE.html
- www.cs.wustl.edu/~schmidt/C++2java.html
- www.cs.wustl.edu/~schmidt/MedJava.ps.gz

ACE-related Patterns



Concurrency Overview

- A thread of control is a single sequence of execution steps performed in one or more programs
  - *One program* → standalone systems
  - *More than one program* → 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
  1. *Complicated to program*, *e.g.*,
     - Signal handling may be tricky
     - Shared memory may be inconvenient
  2. *Inefficient*
     - The OS kernel is involved in synchronization and process management
     - Difficult to exert fine-grained control over scheduling and priorities

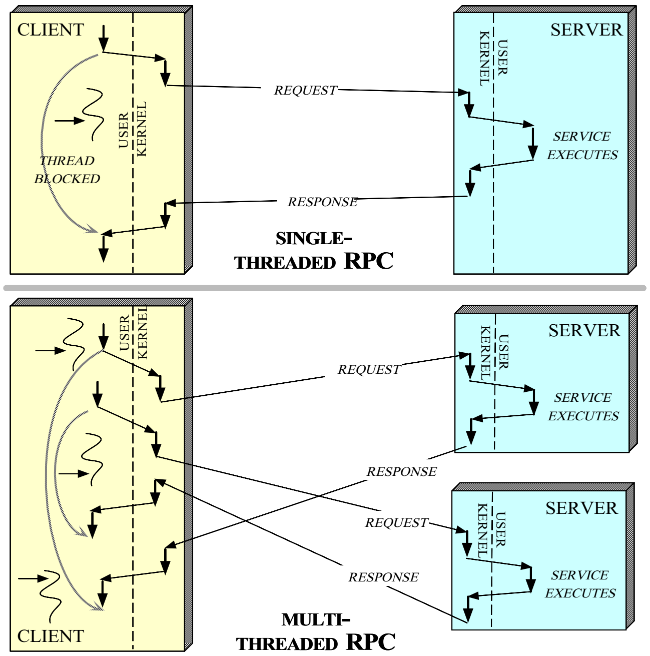
Modern OS Concurrency

- Modern OS platforms typically provide a standard set of APIs that handle
  1. Process/thread creation and destruction
  2. Various types of process/thread synchronization and mutual exclusion
  3. 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 OSs 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

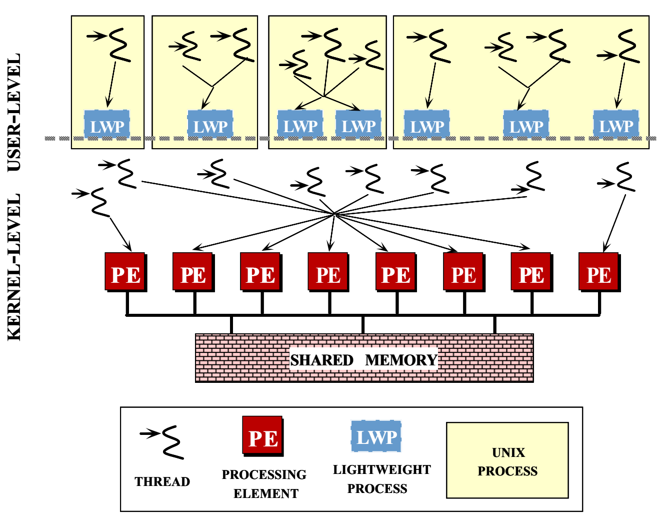
Single-threaded vs. Multi-threaded RPC



Hardware and OS Concurrency Support

- Most modern OS platforms provide kernel support for multi-threading
- *e.g.*, SunOS multi-processing (MP) model
  - There are 4 primary abstractions
    1. *Processing elements* (hardware)
    2. *Kernel threads* (kernel)
    3. *Lightweight processes* (user/kernel)
    4. *Application threads* (user)
  - Sun MP thread semantics work for both uni-processors and multi-processors...

Sun MP Model (cont'd)



- Application threads may be *bound* and/or *unbound*

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 generally no MMU protection for separate threads within 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

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 higher-level patterns and classes

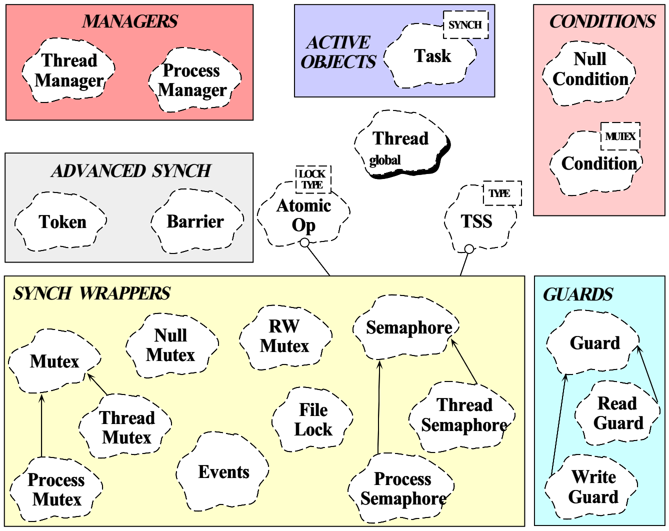
Common OS Synchronization Mechanisms

1. *Mutual exclusion* locks
   - Serialize thread access to a shared resource
2. *Counting semaphores*
   - Synchronize thread execution
3. *Readers/writer* locks
   - Serialize thread access to resources whose contents are searched more than changed
4. *Condition variables*
   - Used to block threads until shared data changes state
5. *File locks*
   - System-wide readers/write locks accessed by processes using filename

Additional ACE Synchronization Mechanism

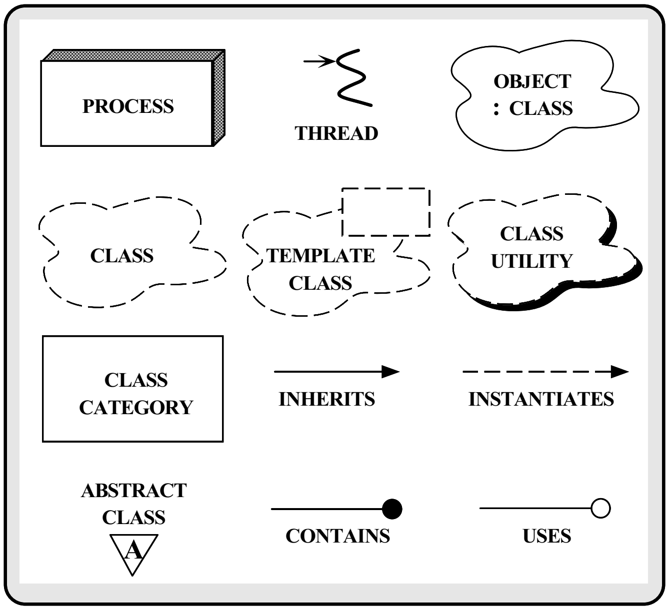
1. *Events*
   - *Gates* and *latches*
2. *Barriers*
   - Allows threads to synchronize their completion
3. *Token*
   - Provides FIFO scheduling order and simplifies multi-threaded event loop integration
4. *Task*
   - Provides higher-level "active object" semantics for concurrent applications
5. *Thread-specific storage*
   - Low-overhead, contention-free storage

Concurrency Mechanisms in ACE

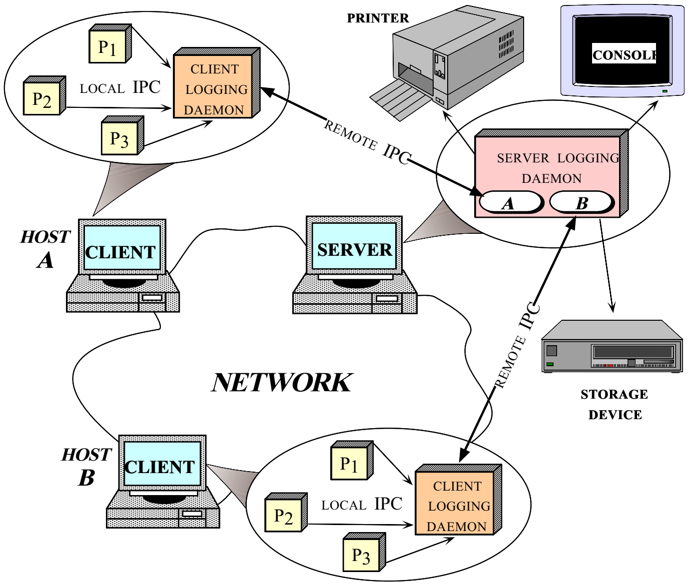


- www.cs.wustl.edu/~schmidt/Concurrency.ps.gz

Graphical Notation



Distributed Logging Service



- www.cs.wustl.edu/~schmidt/reactor-rules.ps.gz

Distributed Logging Service

- *Server logging daemon*
  - Collects, formats, and outputs logging records forwarded from *client logging daemons* residing throughout a network or internetwork

- The application interface is similar to `printf`

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

// generates on server host

Oct 29 14:50:13 1992@tango.ics.uci.edu@2766@LM_ERROR@client
::(4) fork failed


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

// generates on server host

Oct 29 14:50:28 1992@zola.ics.uci.edu@18352@LM_DEBUG@drwho
::(6) sending to server bastille
```

Conventional Logging Server Design

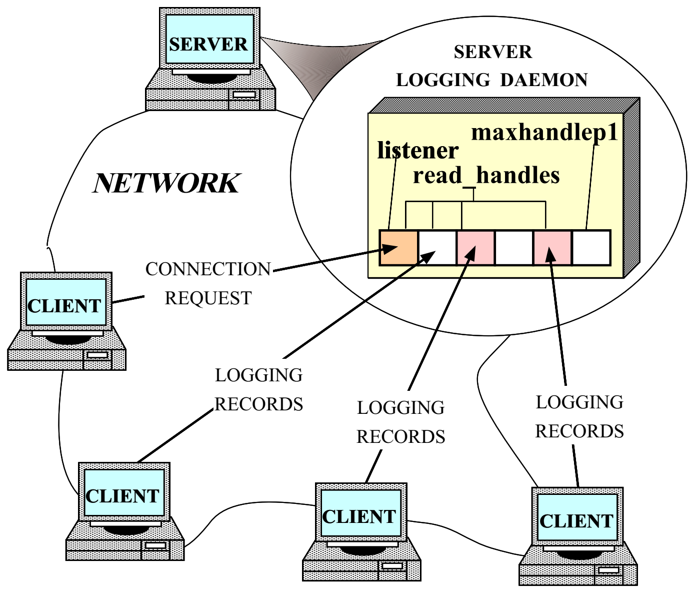
- Typical algorithmic pseudo-code for the server daemon portion of the distributed logging service:

void server_logging_daemon (**void**)
{
    initialize listener 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!

Select-based Logging Server Implementation



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;

// Passive-mode socket handle
static HANDLE listener;

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

// Set of currently active handles
static fd_set read_handles;

// Scratch copy of read_handles
static fd_set tmp_handles;
```



```
// Run main event loop of server logging daemon.

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

  // Loop forever performing logging server processing.

  for (;;) {
    tmp_handles = read_handles; // struct assignment.

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

    // First receive pending logging records
    handle_data ();

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

```
// Initialize the passive-mode socket handle

static void initialize_listener_endpoint (u_short port)
{
  struct sockaddr_in saddr;

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

  // Set up the address information to become a 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 (listener, (struct sockaddr *) &saddr, sizeof saddr);

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

  // Initialize handle sets
  FD_ZERO (&tmp_handles);
  FD_ZERO (&read_handles);
  FD_SET (listener, &read_handles);

  maxhp1 = listener + 1;
}
```



```
// Receive pending logging records

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

  for (HANDLE h = listener + 1; h < maxhp1; h++)
    if (FD_ISSET (h, &tmp_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, &read_handles);
        close (h);

        if (h + 1 == maxhp1) {

          // Skip past unused handles

          while (!FD_ISSET (--h, &read_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 log_record;

  // 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 *) &log_record) + nread,
                   len - nread, 0);

  // Decode and print record.
  decode_log_record (&log_record);
  write (out_h, log_record.buf, log_record.size);
  return n;
}
```



```
// Check if any connection requests have arrived

static void handle_connections (void)
{
  if (FD_ISSET (listener, &tmp_handles)) {
    static struct timeval poll_tv = {0, 0};
    HANDLE h;

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

    do {
      h = accept (listener, 0, 0);
      FD_SET (h, &read_handles);

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

Limitations with Algorithmic Decomposition Techniques

- Algorithmic decomposition tightly couples application-specific *functionality* and the following configuration-related characteristics:
  - **Structure**
    - The number of services per process
    - Time when services are configured into a process
  - **Communication Mechanisms**
    - The underlying IPC mechanisms that communicate with other participating clients and servers
    - Event demultiplexing and event handler dispatching mechanisms
  - **Concurrency Model**
    - The process and/or thread architecture that executes service(s) at run-time

Overcoming Limitations via OO

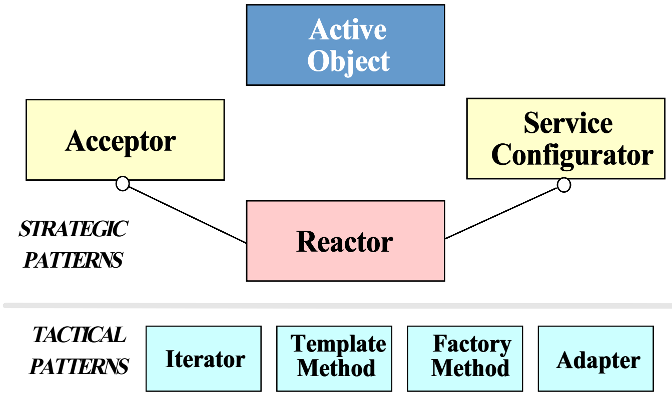
- The algorithmic decomposition illustrated above specifies *many* low-level details
  - Furthermore, the excessive coupling significantly complicates reusability, extensibility, and portability...
- In contrast, OO focuses on *application-specific* behavior, *e.g.*,

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

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


OO Contributions

- *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!
  - But objects are a useful abstraction mechanism

Patterns in the Distributed Logger



- Note that *strategic* and *tactical* are always relative to the *context* and *abstraction level*

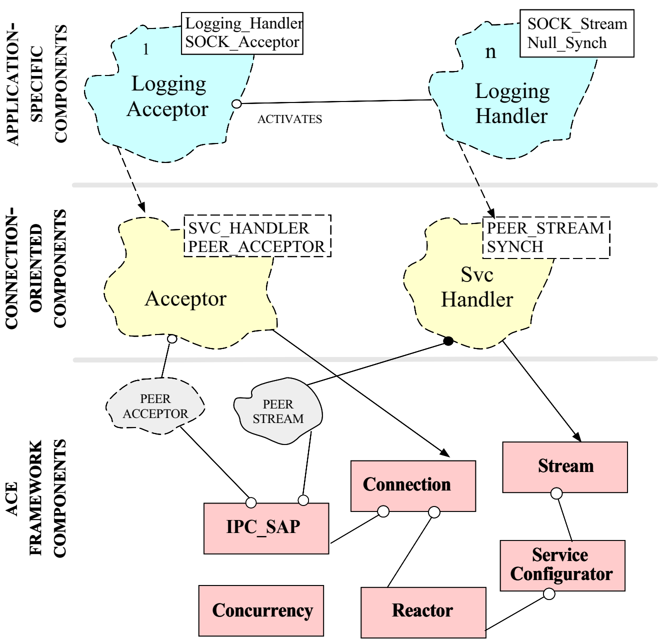
Pattern Intents

- *Reactor pattern*
  - Decouple event demultiplexing and event handler dispatching from application services performed in response to events
- *Acceptor pattern*
  - Decouple the passive initialization of a service from the tasks performed once the service is initialized
- *Service Configurator pattern*
  - Decouple the behavior of network services from point in time at which services are configured into an application
- *Active Object pattern*
  - Decouple method invocation from method execution and simplifies synchronized access to shared resources by concurrent threads

OO Logging Server

- OO server logging daemon decomposes into several modular components:
  1. *Application-specific components*
     - Process logging records received from clients
  2. *Connection-oriented application components*
     - `Svc_Handler`
       * Performs I/O-related tasks with clients
     - `Acceptor` factory
       * Passively accepts connection requests
       * Dynamically creates a `Svc_Handler` object for each client and "activates" it
  3. *Application-independent ACE framework components*
     - Perform IPC, explicit dynamic linking, event demultiplexing, event handler dispatching, multi-threading, etc.

Class Diagram for OO Logging Server



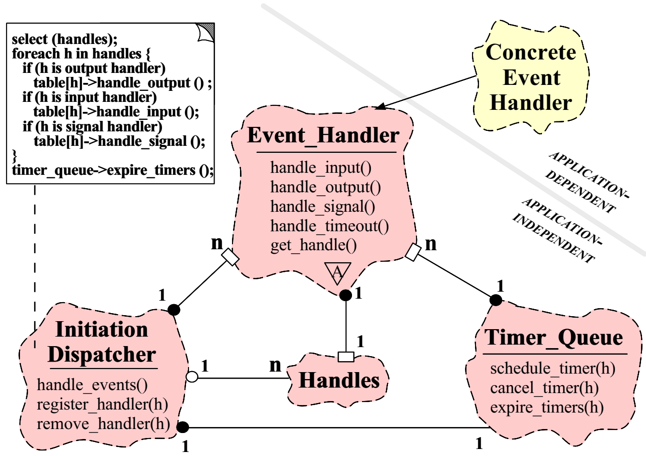
Demultiplexing and Dispatching Events

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

The Reactor Pattern

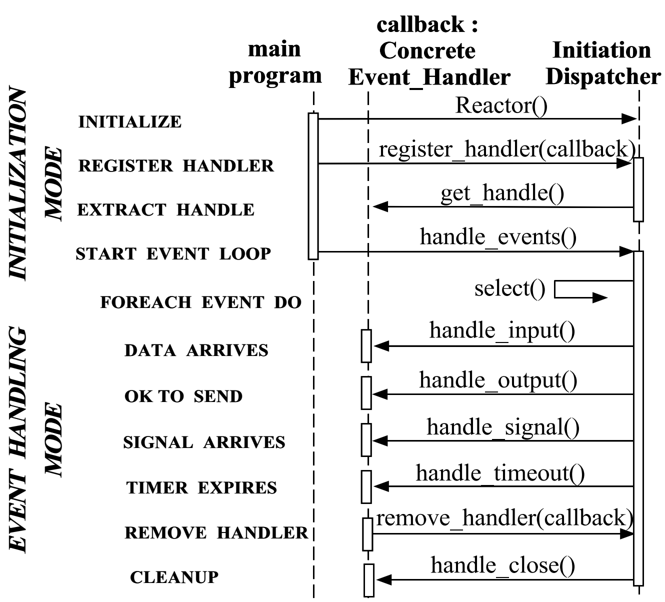
- *Intent*
  - "Decouple event demultiplexing and event handler dispatching from the services performed in response to events"
- This pattern resolves the following forces for event-driven software:
  - *How to demultiplex multiple types of events from multiple sources of events efficiently within a single thread of control*
  - *How to extend application behavior without requiring changes to the event dispatching framework*

Structure of the Reactor Pattern

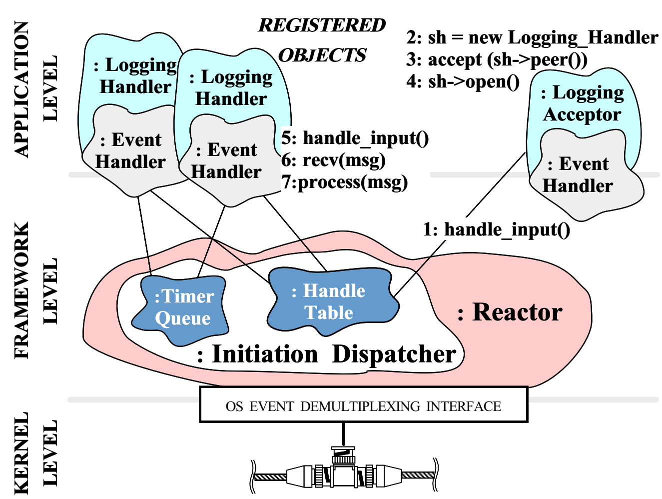


- www.cs.wustl.edu/~schmidt/Reactor.ps.gz

Collaboration in the Reactor Pattern



Using the Reactor Pattern in the Logging Server



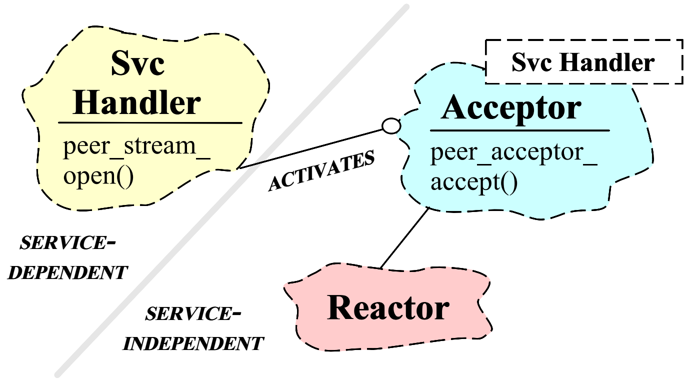
The Acceptor Pattern

- *Intent*
  - "Decouple the passive initialization of a service from the tasks performed once the service is initialized"

- This pattern resolves the following forces for network servers using interfaces like sockets or TLI:

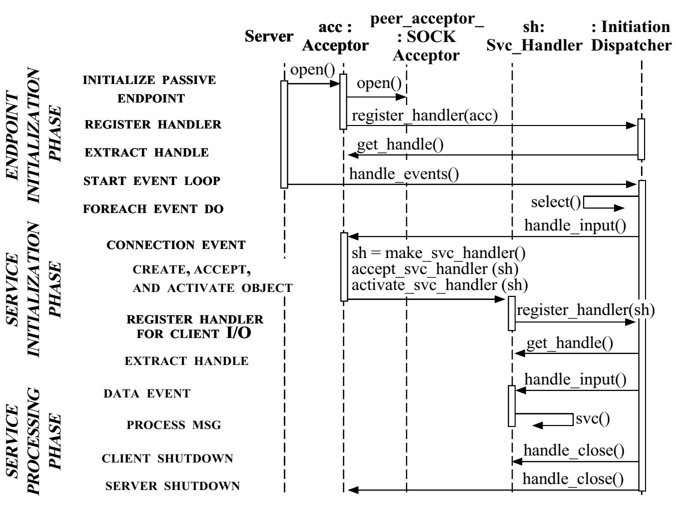
  1. *How to reuse passive connection establishment code for each new service*
  2. *How to make the connection establishment code portable across platforms that may contain sockets but not TLI, or vice versa*
  3. *How to enable flexible policies for creation, connection establishment, and concurrency*
  4. *How to ensure that a passive-mode handle is not accidentally used to read or write data*

Structure of the Acceptor Pattern



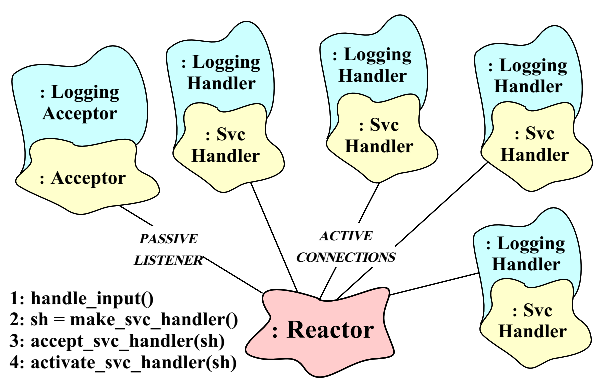
- www.cs.wustl.edu/~schmidt/Acc-Con.ps.gz

Collaboration in the Acceptor Pattern

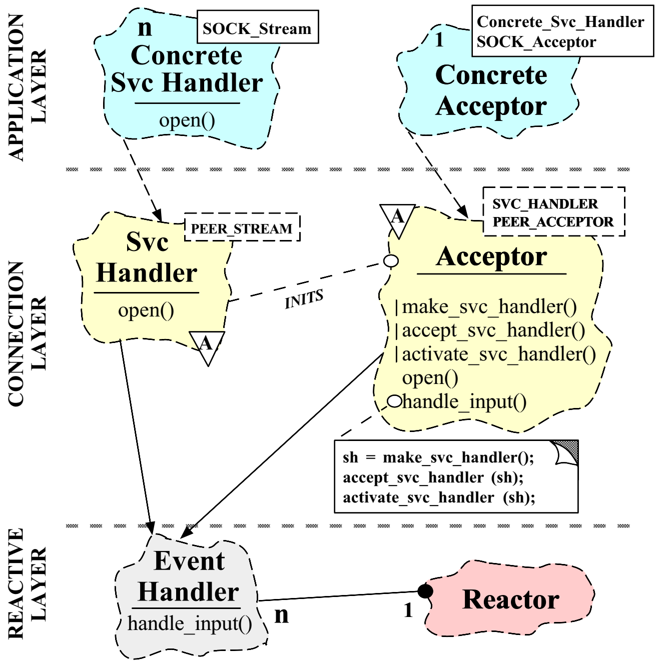


- `Acceptor` factory creates, connects, and activates a `Svc_Handler`

Using the Acceptor Pattern in the Logging Server



Structure of the Acceptor Pattern in ACE



Acceptor Class Public Interface

- A reusable template factory class that accepts connections from clients

```
template <class SVC_HANDLER, // Service aspect
          class PEER_ACCEPTOR>, // IPC aspect
class Acceptor : public Service_Object {
  // Service_Object inherits from Event_Handler
public:
    // Initialization.
  virtual int open (const PEER_ACCEPTOR::PEER_ADDR &,
                    Reactor * = Reactor::instance ());

    // Template Method or Strategy for creating,
    // connecting,  and activating SVC_HANDLER's.
  virtual int handle_input (HANDLE);
```

- Note how service and IPC *aspects* are strategized...

Acceptor Class Protected and Private Interfaces

- Only visible to the class and its subclasses

```
protected:
    // Factory method that creates a service handler.
  virtual SVC_HANDLER *make_svc_handler (void);

    // Factory method that accepts a new connection.
  virtual int accept_svc_handler (SVC_HANDLER *);

    // Factory method that activates a service handler.
  virtual int activate_svc_handler (SVC_HANDLER *);

private:
    // Passive connection mechanism.
  PEER_ACCEPTOR peer_acceptor_;
};
```


Acceptor Class Implementation

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

// Template Method Factory that creates, connects,
// and activates SVC_HANDLERs.

template <class SH, class PA> int
Acceptor<SH, PA>::handle_input (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);
}
```

```
// Factory method for creating a service handler.
// Can be overridden by subclasses to define new
// allocation policies (such as Singletons, etc.).

template <class SH, class PA> SH *
Acceptor<SH, PA>::make_svc_handler (HANDLE)
{
  return new SH; // Default behavior.
}

// Accept connections from clients (can be overridden).

template <class SH, class PA> int
Acceptor<SH, PA>::accept_svc_handler (SH *svc_handler)
{
  peer_acceptor_.accept (svc_handler->peer ());
}

// Activate the service handler (can be overridden).

template <class SH, class PA> int
Acceptor<SH, PA>::activate_svc_handler (SH *svc_handler)
{
  if (svc_handler->open () == -1)
    svc_handler->close ();
}
```



```
// Initialization.

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

  // Register with Reactor.

  reactor->register_handler
          (this, Event_Handler::ACCEPT_MASK);
}
```


Svc_Handler Class Public Interface

- Provides a generic interface for communication services that exchange data with a peer over a network connection

```
template <class PEER_STREAM, // IPC aspect
          class SYNCH_STRATEGY> // Synchronization aspect
class Svc_Handler : public Task<SYNCH_STRATEGY>
{
public:
    // Constructor.
  Svc_Handler (Reactor * = Reactor::instance ());

    // Activate the client handler.
  virtual int open (void *);

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

- Note how IPC and synchronization *aspects* are strategized...

Svc_Handler Class Protected Interface

- Contains the demultiplexing hooks and other implementation artifacts

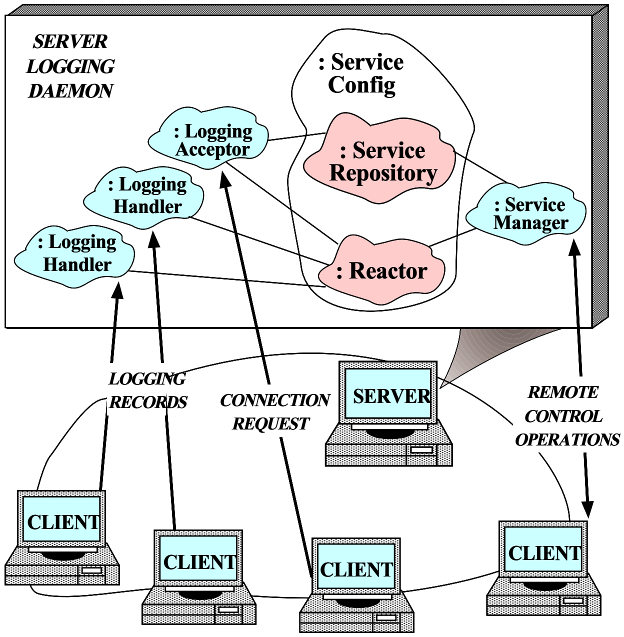
```
protected:
    // Demultiplexing hooks inherited from Task.
  virtual int handle_close (HANDLE, Reactor_Mask);
  virtual HANDLE get_handle (void) const;
  virtual void set_handle (HANDLE);

private:
    // Ensure dynamic initialization.
  virtual ~Svc_Handler (void);

  PEER_STREAM peer_; // IPC mechanism.
  Reactor *reactor_;
};
```

Svc_Handler implementation

- By default, a `Svc_Handler` object is registered with the `Reactor`
  - This makes the service singled-threaded and no other synchronization mechanisms are necessary

```
#define PS PEER_STREAM // Convenient short-hand.

template <class PS, class SYNCH_STRATEGY>
Svc_Handler<PS, SYNCH_STRATEGY>::Svc_Handler
  (Reactor *r): reactor_ (r) {}

template <class PS, class SYNCH_STRATEGY> int
Svc_Handler<PS, SYNCH_STRATEGY>::open (void *)
{
  // Enable non-blocking I/O.
  peer ().enable (ACE_NONBLOCK);

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


Object Diagram for OO Logging Server

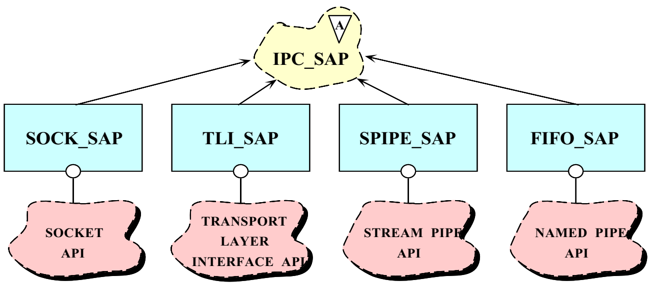


The Logging_Handler and Logging_Acceptor Classes

- Templates implement application-specific logging server

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

class Logging_Handler :
  public Svc_Handler<SOCK_Acceptor::PEER_STREAM,
                     NULL_SYNCH> {
public:
    // Recv and process remote logging records.
  virtual int handle_input (HANDLE);
};

// Logging_Handler factory.

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


OO Design Interlude

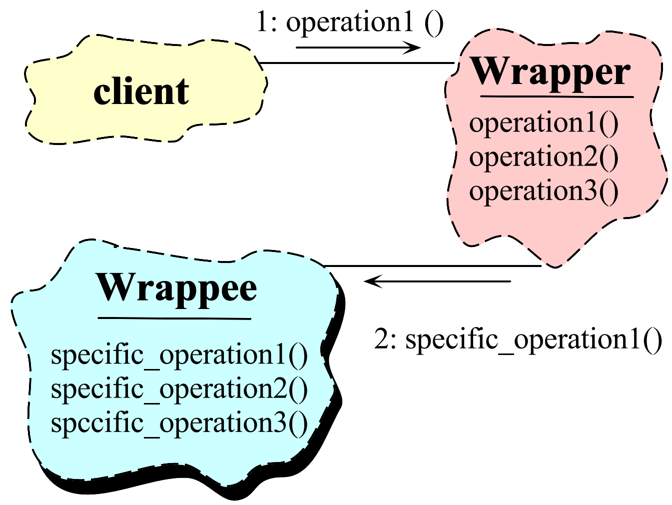


- Q: *What are the SOCK_* classes and why are they used rather than using sockets directly?*
- A: `SOCK_*` are "wrappers" that encapsulate network programming interfaces like sockets and TLI
  - This is an example of the "Wrapper pattern"

The Wrapper Facade Pattern

- *Intent*
  - "Encapsulate lower-level functions within type-safe, modular, and portable class interfaces"
- This pattern resolves the following forces that arise when using native C-level OS APIs
  1. *How to avoid tedious, error-prone, and non-portable programming of low-level IPC mechanisms*
  2. *How to combine multiple related, but independent, functions into a single cohesive abstraction*

Structure of the Wrapper Facade Pattern

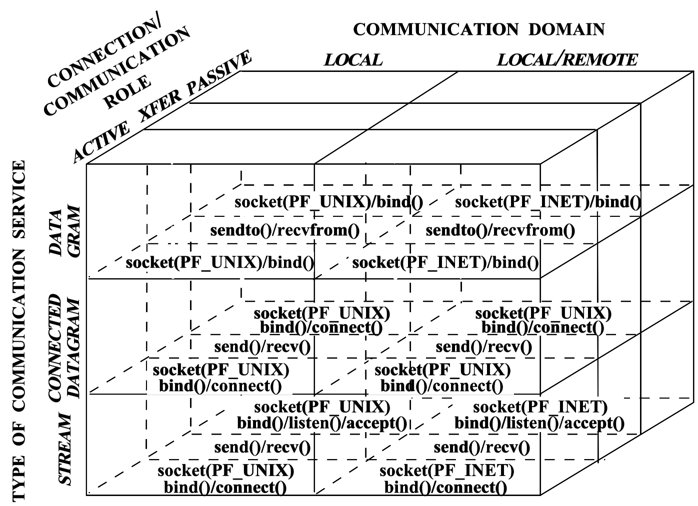


Socket Structure

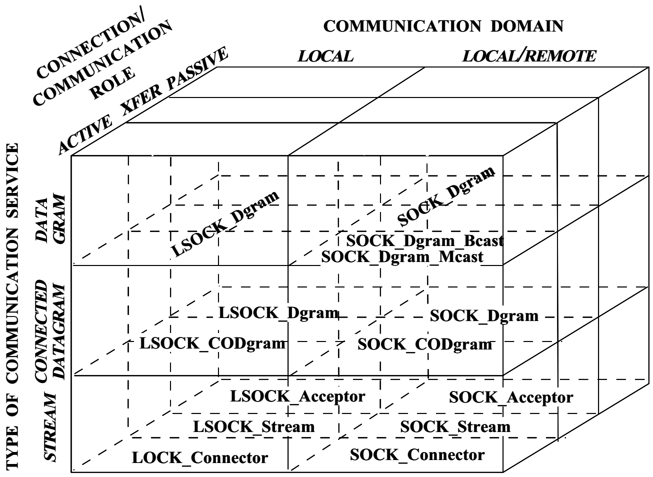
socket()
bind()
connect()
listen()
accept()
read()
write()
readv()
writev()
recv()
send()
recvfrom()
sendto()
recvmsg()
sendmsg()
setsockopt()
getsockopt()
getpeername()
getsockname()
gethostbyname()
getservbyname()

- Socket limitations
  1. API is *linear* rather than *hierarchical*
     - *i.e.*, it gives no hints on how to use it correctly
  2. There is no consistency among names
  3. Highly non-portable

Socket Taxonomy



SOCK_SAP Class Structure



SOCK_SAP Factory Class Interfaces

```
class SOCK_Connector
{
public:
  // Traits
  typedef INET_Addr PEER_ADDR;
  typedef SOCK_Stream PEER_STREAM;

  int connect (SOCK_Stream &new_sap,
               const Addr &remote_addr,
               Time_Value *timeout);
  // ...
};

class SOCK_Acceptor : public SOCK
{
public:
  // Traits
  typedef INET_Addr PEER_ADDR;
  typedef SOCK_Stream PEER_STREAM;

  SOCK_Acceptor (const Addr &local_addr);

  int accept (SOCK_Stream &, Addr *, Time_Value *) const;
  //...
};
```


SOCK_SAP Stream and Addressing Class Interfaces

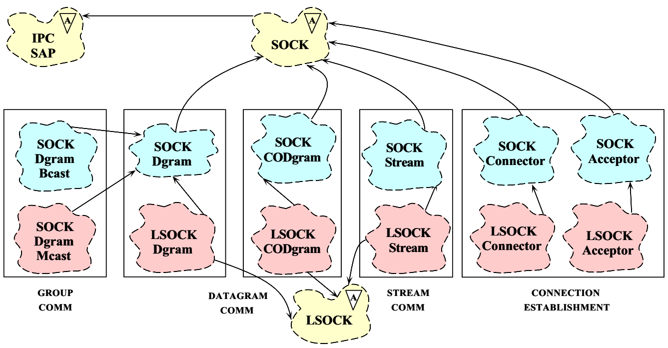
```
class SOCK_Stream : public SOCK
{
public:
  typedef INET_Addr PEER_ADDR; // Trait.

  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 recv_n (void *buf, int n);
  int close (void);
  // ...
};

class INET_Addr : public Addr
{
public:
  INET_Addr (u_short port_number, const char host[]);
  u_short get_port_number (void);
  int32 get_ip_addr (void);
  // ...
};
```


OO Design Interlude

- Q: *Why decouple the SOCK_Acceptor and the SOCK_Connector from SOCK_Stream?*

- A: For the same reasons that Acceptor and Connector are decoupled from Svc_Handler, *e.g.*,
  - A `SOCK_Stream` is only responsible for data transfer
    - * Regardless of whether the connection is established passively or actively
  - This ensures that the `SOCK*` components are never used incorrectly...
    - * *e.g.*, you can't accidentally **`read`** or **`write`** on `SOCK_Connectors` or `SOCK_Acceptors`, etc.

SOCK_SAP Hierarchy



- Shared behavior is isolated in base classes
- Derived classes implement different communication services, communication domains, and connection roles
- www.cs.wustl.edu/~schmidt/IPC_SAP−92.ps.gz

OO Design Interlude

- Q: "How can you switch between different IPC mechanisms?"
- A: By parameterizing IPC Mechanisms with C++ Templates!

```
#if defined (ACE_USE_SOCKETS)
typedef SOCK_Acceptor PEER_ACCEPTOR;
#elif defined (ACE_USE_TLI)
typedef TLI_Acceptor PEER_ACCEPTOR;
#endif /* ACE_USE_SOCKETS */

class Logging_Handler : public
  Svc_Handler<PEER_ACCEPTOR::PEER_STREAM,
              NULL_SYNCH>
    { /* ... /* };

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


Logging_Handler Implementation

- Implementation of the application-specific logging method

```
// Callback routine that receives logging records.
// This is the main code supplied by a developer!

int
Logging_Handler::handle_input (HANDLE)
{
  // Call existing function to recv
  // logging record and print to stdout.
  handle_log_record (peer ().get_handle (), STDOUT);
}
```



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

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

  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 Reactor
  open (addr, Reactor::instance ());
}

// Automatically called when object is dynamically unlinked.

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

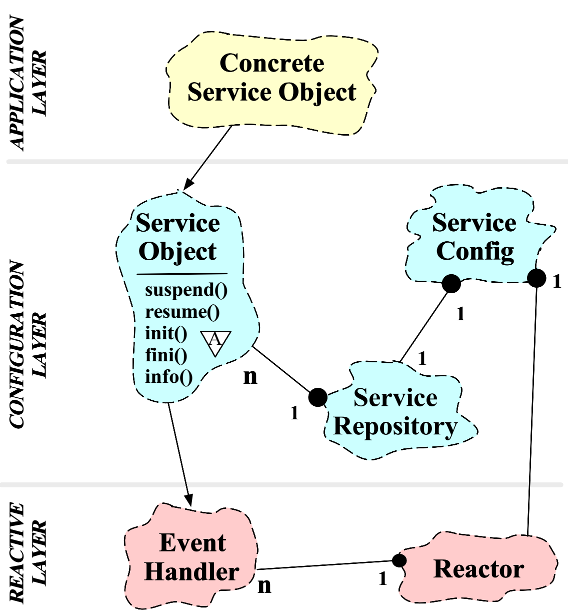
Putting the Pieces Together at Run-time

- *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 *Service Configurator* pattern to assemble the desired logging server components dynamically

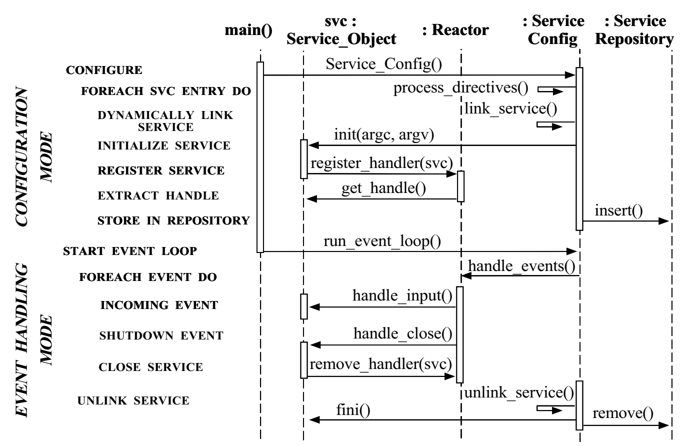
The Service Configurator Pattern

- *Intent*
  - "Decouple the behavior of services from the point in time at which these services are configured into an application"
- This pattern resolves the following forces for highly flexible communication software:
  - *How to defer the selection of a particular type, or a particular implementation, of a service until very late in the design cycle*
    - ∗ *i.e.*, at installation-time or run-time
  - *How to build complete applications by scripting multiple independently developed services*
  - *How to reconfigure and control the behavior of the service at run-time*

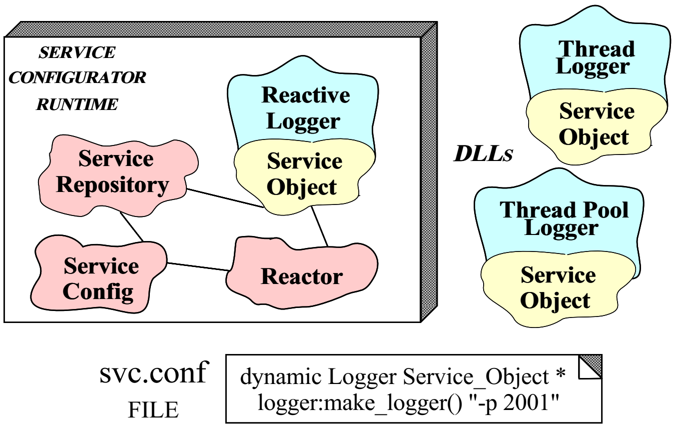
Structure of the Service Configurator Pattern



Collaboration in the Service Configurator Pattern



Using the Service Configurator Pattern for the Logging Server



- Existing service is single-threaded, other versions could be multi-threaded...

Dynamic Linking a Service

- Application-specific factory function used to dynamically create a service

```
// Dynamically linked factory function that allocates
// a new Logging_Acceptor object dynamically

extern "C" Service_Object *make_Logger (void);

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

- 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

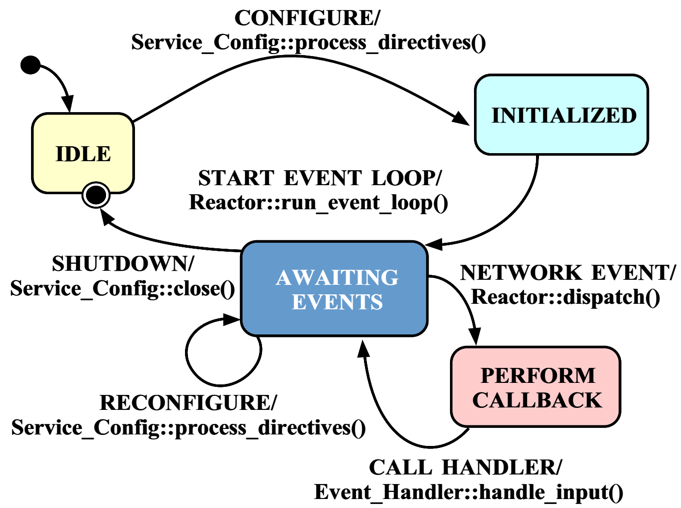
- The logging service is configured via scripting in a `svc.conf` file:

```
% cat ./svc.conf
# Dynamically configure the logging service
dynamic Logger Service_Object *
        logger:make_Logger() "-p 2010"
# Note, .dll or .so suffix added to "logger" automatically
```

- Generic event-loop to dynamically configure service daemons

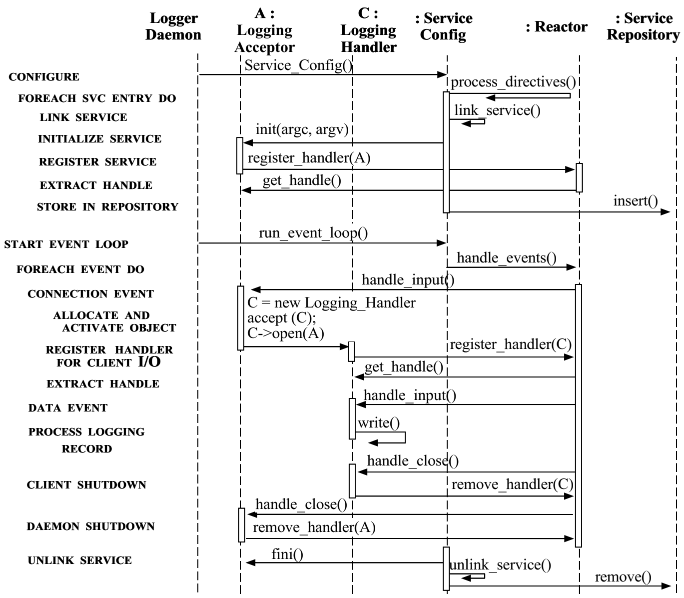
```
int
main (int argc, char *argv[])
{
  // Initialize the daemon and configure services
  Service_Config::open (argc, argv);

  // Run forever, performing configured services
  Reactor::run_event_loop ();
  /* NOTREACHED */
}
```


State-chart Diagram for the Service Configurator Pattern



- Note the separation of concerns between objects...

Collaboration of Patterns in the Server Logging Daemon



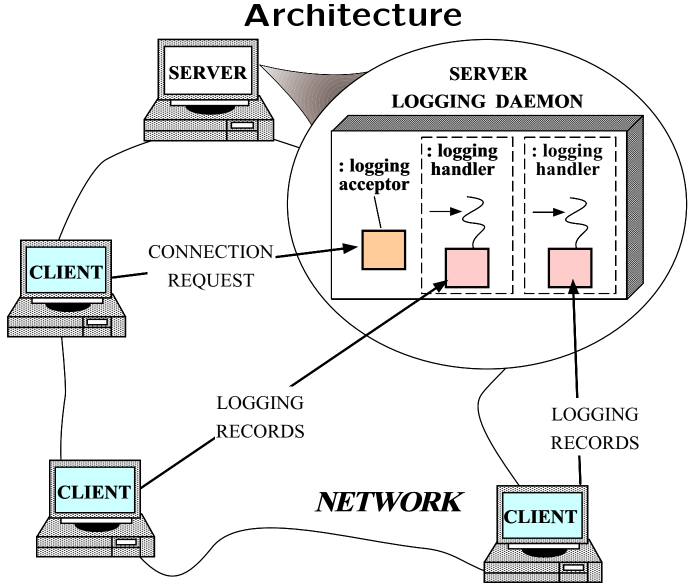
Advantages of OO Logging Server

- 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*:
  1. *Modifying*, *recompiling*, and *relinking* existing code
  2. *Terminating* and *restarting* executing daemons
- The remainder of the slides examine a set of techniques for decoupling functionality from *concurrency* mechanisms, as well

Concurrent OO Logging Server

- The structure of the server logging daemon 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



- Thread-per-connection implementation

Pseudo-code for Concurrent Server

- Pseudo-code for multi-threaded Logging_Handler factory server logging daemon

void handler_factory (**void**)
{
    initialize listener endpoint
    foreach (*pending connection event*) {
        accept connection
        spawn a thread to handle connection and
        run logger_handler() entry point
    }
}

- Pseudo-code for server logging daemon active object

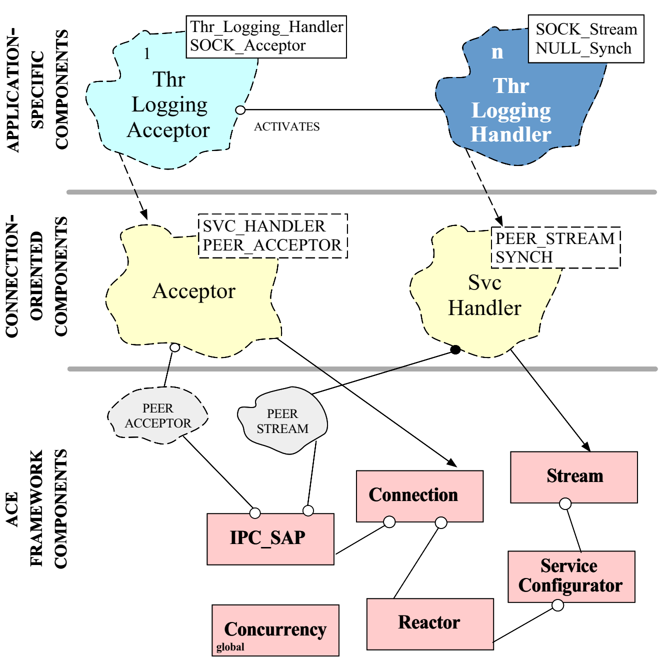
void logging_handler (**void**)
{
    foreach (*incoming logging records from client*)
        call handle_log_record()
    exit thread
}

Application-specific Logging Code

- The OO implementation localizes the application-specific part of the logging service in a single point, while leveraging off reusable ACE components

```
// Process remote logging records.  Loop until
// the client terminates the 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;
}
```


Class Diagram for Concurrent OO Logging Server



Thr_Logging_Acceptor and Thr_Logging_Handler

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

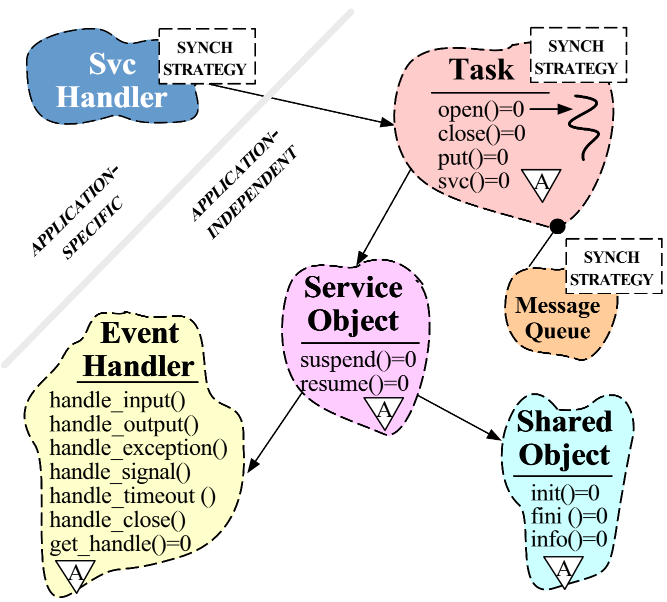
```
class Thr_Logging_Handler : public Logging_Handler
                            // Inherits <handle_input>
{
public:
    // Override definition in the Svc_Handler
    // class (spawns a new thread!).
  virtual int open (void *);

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

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

```
// Override definition in the Svc_Handler class
// (spawns a new thread in this case!).

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

// Process remote logging records.  Loop until
// the client terminates the 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;
}
```


ACE Tasks

- 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
- `Task` objects communicate by passing typed messages to other `Tasks`
  - Each `Task` maintains a queue of pending messages that it processes in *priority order*
- ACE `Task` are a low-level mechanism to support "active objects"

Task Inheritance Hierarchy



- Supports dynamically configured services

Task Class Public Interface

- C++ interface for message processing

  * `Tasks` can register with a `Reactor`
  * They can be dynamically linked
  * They can queue data
  * They can run as "active objects"

- *e.g.*,

```
template <class SYNCH_STRATEGY>
class Task : public Service_Object
{
public:
    // Initialization/termination hooks.
  virtual int open (void *args = 0) = 0;
  virtual int close (u_long flags = 0) = 0;

    // Hook to pass msg for immediate processing.
  virtual int put (Message_Block *,
                   Time_Value * = 0) = 0;

    // Hook run by daemon thread(s) for
    // deferred processing.
  virtual int svc (void) = 0;

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

Task Class Protected Interface

- The following methods are mostly used within put and svc

```
  // Accessors to internal queue.
Message_Queue<SYNCH_STRATEGY> *msg_queue (void);
void msg_queue (Message_Queue<SYNCH_STRATEGY> *);

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

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

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

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


OO Design Interlude

- Q: *What is the svc_run() function and why is it a static method?*

- A: OS thread spawn APIs require a C-style function as the entry point into a thread

- The Stream class category encapsulates the svc_run function within the Task::activate method:

```
template <class SYNCH_STRATEGY> int
Task<SYNCH_STRATEGY>::activate (long flags, int n_threads)
{
  if (thr_mgr () == NULL)
    thr_mgr (Thread_Manager::instance ());

  thr_mgr ()->spawn_n
    (n_threads, &Task<SYNCH_STRATEGY>::svc_run,
     (void *) this, flags);
}
```


OO Design Interlude (cont'd)

- 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_STRATEGY> void *
Task<SYNCH_STRATEGY>::svc_run (Task<SYNCH_STRATEGY> *t)
{
  // Thread added to thr_mgr()
  // automatically on entry...

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

  tc.status (status);
  t->close (u_long (status));

  // Status becomes ‘return’ value of thread...
  return status;

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


OO Design Interlude

- Q: “How can groups of collaborating threads be managed atomically?”

- A: Develop a “thread manager” class

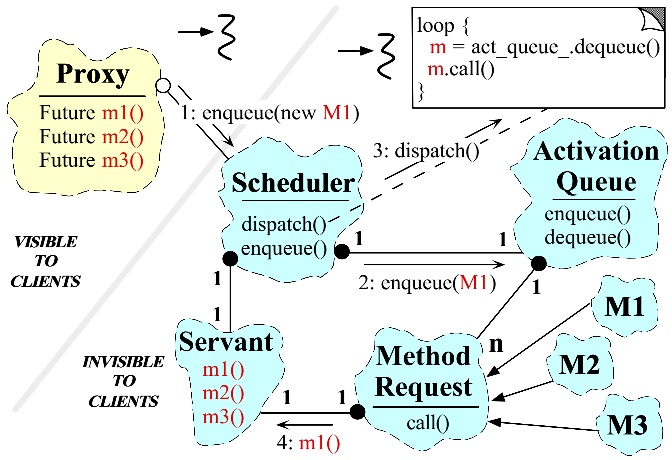
  - Thread_Manager is a collection class
    - It provides mechanisms for *suspending* and *resuming* groups of threads atomically
    - It implements *barrier synchronization* on thread exits
  - Thread_Manager also shields applications from incompabitilities between different OS thread libraries
    - It is integrated into ACE via the Task::activate method

The Active Object Pattern

- *Intent*
  - "Decouple method execution from method invocation and simplifies synchronized access to shared resources by concurrent threads"

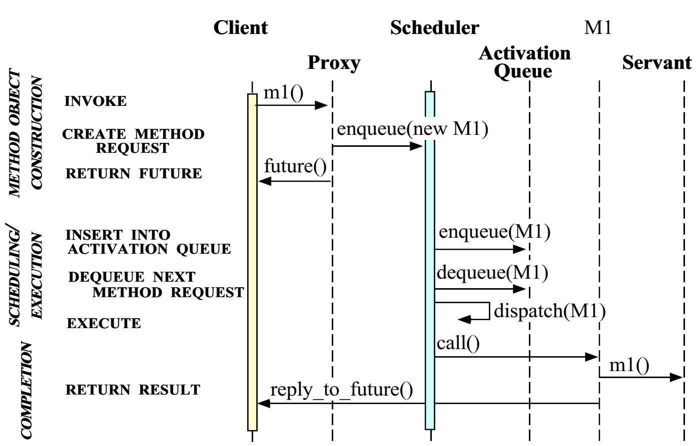
- This pattern resolves the following forces for concurrent communication software:
  - *How to allow blocking read and write operations on one endpoint that do not detract from the quality of service of other endpoints*
  - *How to serialize concurrent access to shared object state*
  - *How to simplify composition of independent services*

Structure of the Active Object Pattern

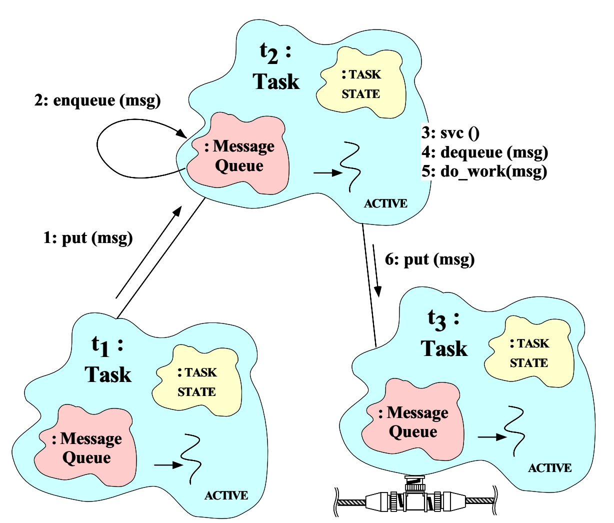


- www.cs.wustl.edu/~schmidt/Act-Obj.ps.gz

Collaboration in the Active Object Pattern

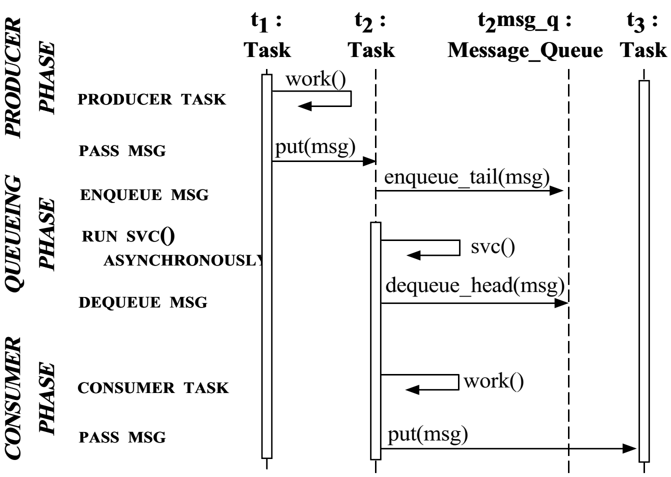


ACE Support for Active Objects



- Can implement complete Active Object pattern or lighterweight subsets

Collaboration in ACE Active Objects



Dynamically Reconfiguring the Logging Server

- The concurrent logger is reconfigured by changing the `svc.conf` file and sending SIGHUP signal to the server:

```
// Dynamically linked factory function that
// allocates a new threaded Logging Acceptor.

extern "C" Service_Object *make_Logger (void);

Service_Object *
make_Logger (void)
{
  return new Thr_Logging_Acceptor;
}

% cat ./svc.conf
# Dynamically configure the logging service
# dynamic Logger Service_Object *
#         /svcs/logger.dll:make_Logger() "-p 2010"
remove Logger
dynamic Logger Service_Object *
        thr_logger:make_Logger() "-p 2010"
# .dll or .so suffix added to "thr_logger" automatically
```


Caveats

- The concurrent server logging daemon has several problems
  1. Output in the **handle_log_record** function is not serialized
  2. 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 (HANDLE in_h, HANDLE out_h)
{
  // in method scope ...
  mutex_lock (&lock);
  write (out_h, log_record.buf, log_record.size);
  mutex_unlock (&lock);
  // ...
}
```

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

Problems Galore!

- Problems with explicit `mutex_*` calls:
  - *Inelegant*
    - "Impedance mismatch" with C/C++
  - *Obtrusive*
    - Must find and lock all uses of `write`
  - *Error-prone*
    - C++ exception handling and multiple method exit points cause subtle problems
    - Global mutexes may not be initialized correctly. . .
  - *Non-portable*
    - Hard-coded to Solaris 2.x
  - *Inefficient*
    - *e.g.*, expensive for certain platforms/designs

C++ Wrappers for Synchronization

- To address portability problems, define a C++ wrapper:

```
class Thread_Mutex
{
public:
  Thread_Mutex (void) {
    mutex_init (&lock_, USYNCH_THREAD, 0);
  }
  ~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:
  mutex_t lock_; // SunOS 5.x serialization mechanism.
  void operator= (const Thread_Mutex &);
  Thread_Mutex (const Thread_Mutex &);
};
```

- Note, this mutual exclusion class interface is portable to other OS platforms

Porting Mutex to Windows NT

- WIN32 version of `Mutex`

```
class Thread_Mutex
{
public:
  Thread_Mutex (void) {
    lock_ = CreateMutex (0, FALSE, 0);
  }
  ~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:
  HANDLE lock_; // Win32 locking mechanism.
  // ...
```


Using the C++ Mutex Wrapper

- Using C++ wrappers improves *portability* and *elegance*

```
// at file scope

Thread_Mutex lock; // Implicitly "unlocked".

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

  lock.acquire ();
  write (out_h, log_record.buf, log_record.size);
  lock.release ();

  // ...
}
```

- However, this doesn't really solve the *tedium* or *error-proneness* problems

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 Guard
{
public:
  Guard (LOCK &m): lock (m) { lock_.acquire (); }
  ~Guard (void) { lock_.release (); }

private:
  LOCK &lock_;
}
```

- `Guard` uses the C++ idiom whereby a *constructor acquires a resource* and the *destructor releases the resource*

OO Design Interlude

- Q: *Why is Guard parameterized by the type of LOCK?*

- A: since there are many different flavors of locking that benefit from the `Guard` functionality, *e.g.*,
  * *Non-recursive vs recursive mutexes*
  * *Intra-process vs inter-process mutexes*
  * *Readers/writer mutexes*
  * *Solaris and System V semaphores*
  * *File locks*
  * *Null mutex*

- In ACE, all synchronization wrappers use to Adapter pattern to provide identical interfaces whenever possible to facilitate parameterization

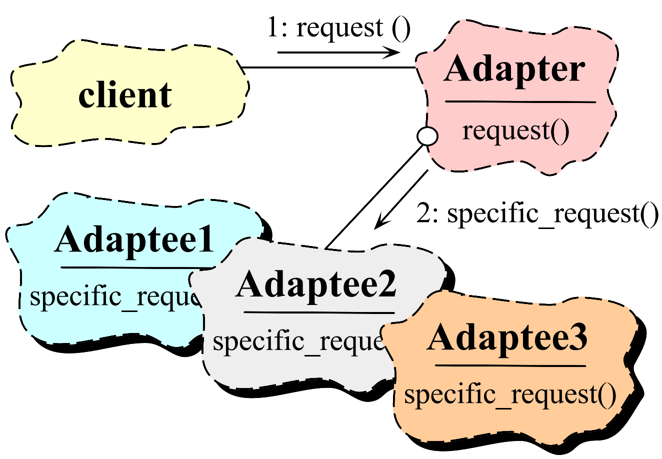
The Adapter Pattern

- *Intent*
  - "Convert the interface of a class into another interface client expects"
    * Adapter lets classes work together that couldn't otherwise because of incompatible interfaces

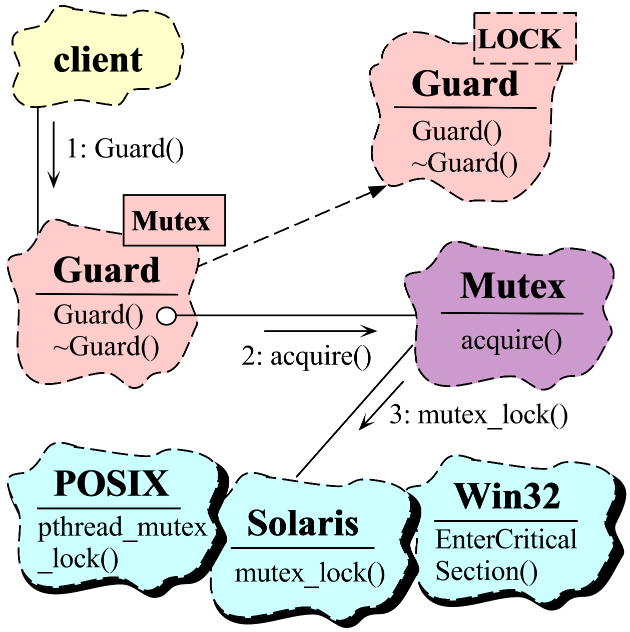
- This pattern resolves the following force that arises when using conventional OS interfaces

  1. *How to provide an interface that expresses the similarities of seemingly different OS mechanisms (such as locking or IPC)*

Structure of the Adapter Pattern



Using the Adapter Pattern for Locking



A thread-safe handle_log_record() Function

```
template <class LOCK = Thread_Mutex> ssize_t
handle_log_record (HANDLE in_h, HANDLE out_h)
{
  // new code (beware of static initialization...)
  static LOCK lock;
  ssize_t n;
  size_t len;
  Log_Record log_record;

  n = recv (h, (char *) &len, sizeof len, 0);

  if (n != sizeof len) return -1;
  len = ntohl (len); // Convert byte-ordering

  for (size_t nread = 0; nread < len; nread += n
    n = recv (in_h, ((char *) &log_record) + nread,
              len - nread, 0));
  // Perform presentation layer conversions.
  decode (&log_record);
  // Automatically acquire mutex lock.
  Guard<LOCK> monitor (lock);
  write (out_h, log_record.buf, log_record.size);
  // Automatically release mutex lock.
}
```


Remaining Caveats

- There is a race condition when incrementing the `request_count` variable

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

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

- Solving this problem using the `Mutex` or `Guard` classes is still *tedious*, *low-level*, and *error-prone*

- A more elegant solution incorporates parameterized types, overloading, and the Decorator pattern

Transparently Parameterizing Synchronization Using C++

- The following C++ template class uses the "Decorator" pattern to define a set of atomic operations on a type parameter

```
template <class LOCK = Thread_Mutex, class TYPE = u_long>
class Atomic_Op {
public:
  Atomic_Op (TYPE c = 0) { count_ = c; }
  TYPE operator++ (void) {
    Guard<LOCK> m (lock_); return ++count_;
  }
  void operator= (const Atomic_Op &ao) {
    if (this != &ao) {
      Guard<LOCK> m (lock_); count_ = ao.count_;
    }
  }
  operator TYPE () {
    Guard<LOCK> m (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 Atomic_Op<> COUNTER; // Note default parameters...
COUNTER request_count;
```

- request_count is now serialized automatically

```
  for (; ; ++request_count) // Atomic_Op::operator++
    handle_log_record (get_handle (), STDOUT);
```

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

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


Synchronization-aware Logging Classes

- A more sophisticated approach would add several new parameters to the Logging_Handler class

```
template <class PEER_STREAM,
          class SYNCH_STRATEGY, class COUNTER>
class Logging_Handler
  : public Svc_Handler<PEER_STREAM, SYNCH_STRATEGY>
{
public:
  Logging_Handler (void);
    // Process remote logging records.
  virtual int svc (void);

protected:
    // Receive the logging record from a client.
  ssize_t handle_log_record (HANDLE out_h);
    // Lock used to serialize access to std output.
  static SYNCH_STRATEGY::MUTEX lock_;
    // Count the number of logging records that arrive.
  static COUNTER request_count_;
};
```


Thread-safe handle_log_record Method

```
template <class PS, class LOCK, class COUNTER> ssize_t
Logging_Handler<PS, LOCK, COUNTER>::handle_log_record
     (HANDLE out_h)
{
  ssize_t n;
  size_t len;
  Log_Record log_record;

  ++request_count_; // Calls COUNTER::operator++().

  n = peer ().recv (&len, sizeof len);

  if (n != sizeof len) return -1;
  len = ntohl (len); // Convert byte-ordering

  peer ().recv_n (&log_record, len);

  // Perform presentation layer conversions
  log_record.decode ();
  // Automatically acquire mutex lock.
  Guard<LOCK> monitor (lock_);
  write (out_h, log_record.buf, log_record.size);
  // Automatically release mutex lock.
}
```


Using the Thread-safe handle_log_record() Method

- In order to use the thread-safe version, all we need to do is instantiate with Atomic_Op

```
typedef Logging_Handler<TLI_Stream,
                        NULL_SYNCH,
                        Atomic_Op<> >
        LOGGING_HANDLER;
```

- To obtain single-threaded behavior requires a simple change:

```
typedef Logging_Handler<TLI_Stream,
                        NULL_SYNCH,
                        Atomic_Op <Null_Mutex, u_long> >
        LOGGING_HANDLER;
```

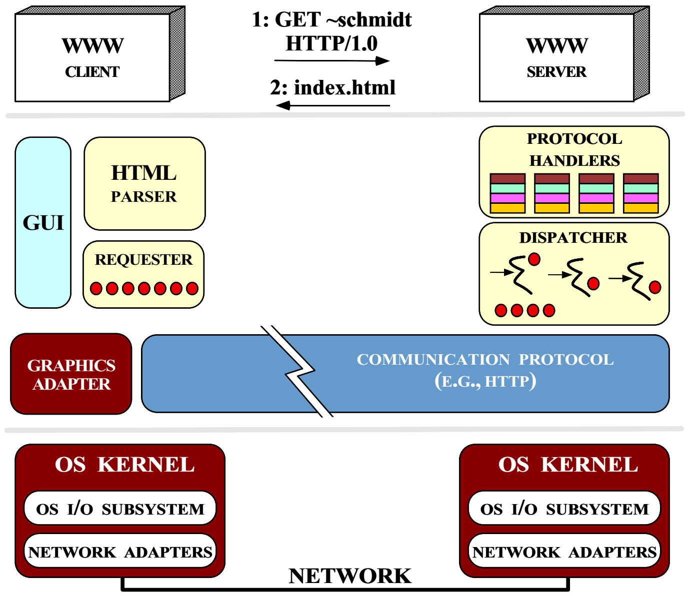
Concurrent WWW Client/Server Example

- The following example illustrates a concurrent OO architecture for a high-performance Web client/server

- Key system requirements are:

  1. Robust implementation of HTTP protocol
     - *i.e.*, resilient to incorrect or malicious Web clients/servers
  2. Extensible for use with other protocols
     - *e.g.*, DICOM, HTTP 1.1, SFP
  3. Leverage multi-processor hardware and OS software
     - *e.g.*, support various concurrency models

General Web Client/Server Interactions



Pseudo-code for Concurrent WWW Server

- Pseudo-code for master server

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

- Pseudo-code for thread pool workers

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


OO Design Interlude

- Q: *Why use a work queue to store messages, rather than directly reading from I/O handles?*

- A:
  - *Separation of concerns*
  - *Promotes more efficient use of multiple CPUs via load balancing*
  - *Enables transparent interpositioning and prioritization*
  - *Makes it easier to shut down the system correctly and portably*

- *Drawbacks*
  - Using a message queue may lead to greater *context switching* and *synchronization* overhead...
  - Single point for bottlenecks

Thread Entry Point

- Each thread executes a function that serves as the "entry point" into a separate thread of control
  - Note algorithmic design...

```
typedef u_long COUNTER;
// Track the number of requests
COUNTER request_count; // At file scope.

// Entry point into the WWW HTTP 1.0 protocol.
void *worker (Message_Queue *msg_queue)
{
  Message_Block *mb; // Message buffer.

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

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

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


Master Server Driver Function

- The master driver function in the WWW Server might be structured as follows:

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

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

  // 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_NEW_LWP, 0);

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

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


Pseudo-code for recv_requests()

- *e.g.*,

```
void recv_requests (Message_Queue *msg_queue)
{
    initialize socket listener endpoint 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);
        }
    }
}
```

- The "grand mistake:"
  - Avoid the temptation to "step-wise refine" this algorithmically decomposed pseudo-code directly into the detailed design and implementation of the WWW Server!

Limitations with the WWW 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
  - Furthermore, 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 concurrency control
- *Solution*
  - Utilize a "condition variables"

Condition Variable Overview

- Condition variables (CVs) are used to "sleep/wait" until a particular condition involving shared data is signaled
  - CVs may be 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 object allows a thread to make *itself* wait for a particular condition involving shared data

Condition Variable Usage

- A particular idiom is associated with acquiring resources via condition variables

```
// Global variables
static Thread_Mutex lock; // Initially unlocked.
// Initially unlocked.
static Condition_Thread_Mutex cond (lock);

void acquire_resources (void) {
    // Automatically acquire the lock.
    Guard<Thread_Mutex> monitor (lock);

    // Check condition (note the use of while)
    while (condition expression is not true)
        // Sleep if not expression is not true.
        cond.wait ();

    // Atomically modify shared information here...

    // monitor destructor automatically releases lock.
}
```

Condition Variable Usage (cont'd)

- Another idiom is associated with releasing resources via condition variables

```
void release_resources (void) {
    // Automatically acquire the lock.
    Guard<Thread_Mutex> monitor (lock);

    // Atomically modify shared information here...

    cond.signal (); // Could also use cond.broadcast()
    // monitor destructor automatically releases lock.
}
```

- Note how the use of the Guard idiom simplifies the solution
  - *e.g.*, now we can't forget to release the lock!

Condition Variable Interface

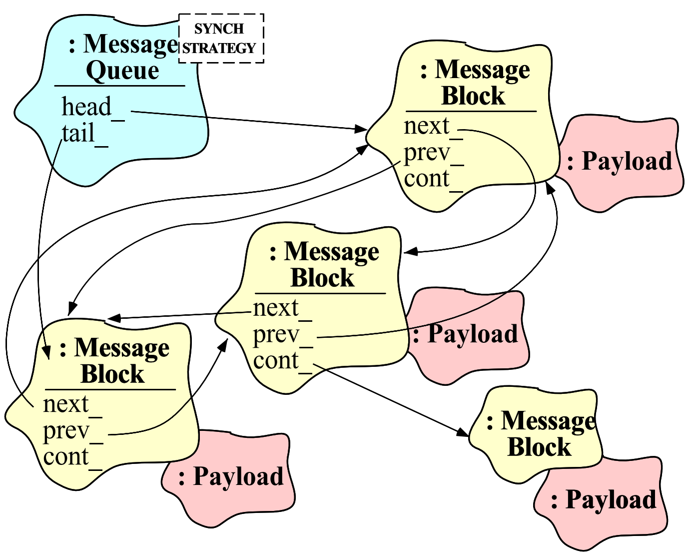
- In ACE, the `Condition_Thread_Mutex` class is a wrapper for the native OS condition variable abstraction
  - *e.g.*, `cond_t` on SunOS 5.x, `pthread_cond_t` for POSIX, and a custom implementation on Win32

```
class Condition_Thread_Mutex
public:
    // Initialize the condition variable.
  Condition_Thread_Mutex (const Thread_Mutex &);
    // Implicitly destroy the condition variable.
  ~Condition_Thread_Mutex (void);

    // Block on condition, or until time has
    // passed.  If time == 0 use blocking semantics.
  int wait (Time_Value *time = 0) const;
    // Signal one waiting thread.
  int signal (void) const;
    // Signal *all* waiting threads.
  int broadcast (void) const;
private:
  cond_t cond_; // Solaris condition variable.
  const Thread_Mutex &mutex_;
  // Reference to mutex lock.
};
```


Overview of Message_Queue and Message_Block Classes

- A `Message_Queue` is composed of one or more `Message_Blocks`
  - Similar to BSD `mbufs` or SVR4 STREAMS `m_blks`
  - Goal is to enable efficient manipulation of arbitrarily-large message payloads *without* incurring unnecessary memory copying overhead
- `Message_Blocks` are linked together by `prev_` and `next_` pointers
- A `Message_Block` may also be linked to a chain of other `Message_Blocks`

Message_Queue and Message_Block Object Diagram



The Message_Block Class

- The contents of a message are represented by a `Message_Block`

```
class Message_Block
{
friend class Message_Queue;
public:
  Message_Block (size_t size,
                 Message_Type type = MB_DATA,
                 Message_Block *cont = 0,
                 char *data = 0,
                 Allocator *alloc = 0);
  // ...

private:
  char *base_;
    // Pointer to beginning of payload.
  Message_Block *next_;
    // Pointer to next message in the queue.
  Message_Block *prev_;
    // Pointer to previous message in the queue.
  Message_Block *cont_;
    // Pointer to next fragment in this message.
    // ...
};
```


OO Design Interlude

- Q: *What is the Allocator object in the Message_Block constructor?*

- A: *It provides extensible mechanism to control how memory is allocated and deallocated*

  – This makes it possible to switch memory management policies *without* modifying `Message_Block`

  – By default, the policy is to use **`new`** and **`delete`**, but it's easy to use other schemes, *e.g.*,
    * Shared memory
    * Persistent memory
    * Thread-specific memory

  – A similar technique is also used in the C++ Standard Template Library

OO Design Interlude

- Here's an example of the interfaces used in ACE

  – Note the use of the Adapter pattern to integrate third-party memory allocators

```
class Allocator {
  // ...
  virtual void *malloc (size_t nbytes) = 0;
  virtual void free (void *ptr) = 0;
};

template <class ALLOCATOR>
class Allocator_Adapter : public Allocator {
  // ...
  virtual void *malloc (size_t nbytes) {
    return allocator_.malloc (nbytes);
  }

  ALLOCATOR allocator_;
};

Allocator_Adapter<Shared_Alloc> sh_malloc;
Allocator_Adapter<New_Alloc> new_malloc;
Allocator_Adapter<Persist_Alloc> p_malloc;
Allocator_Adapter<TSS_Alloc> p_malloc;
```


The Message_Queue Class Public Interface

- A `Message_Queue` is a thread-safe queueing facility for `Message_Blocks`

  – The bulk of the locking is performed in the public methods

```
template <class SYNCH_STRATEGY>
class 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 (Message_Block *, Time_Value *);
  int enqueue_tail (Message_Block *, Time_Value *);
  int dequeue_head (Message_Block *&, Time_Value *);
```

The Message_Queue Class Private Interface

- The bulk of the work is performed in the private methods

```
private:
    // Routines that actually do the enqueueing and
    // dequeueing (do not hold locks).
  int enqueue_prio_i (Message_Block *, Time_Value *);
  int enqueue_tail_i (Message_Block *new_item, Time_Value *
  int dequeue_head_i (Message_Block *&first_item);

    // Check the boundary conditions (do not hold locks).
  int is_empty_i (void) const;
  int is_full_i (void) const;

    // ...

    // Parameterized types for synchronization
    // primitives that control concurrent access.
    // Note use of C++ "traits"
  SYNCH_STRATEGY::MUTEX     lock_;
  SYNCH_STRATEGY::CONDITION not_empty_cond_;
  SYNCH_STRATEGY::CONDITION not_full_cond_;
};
```


The Message_Queue Class Implementation

- Uses ACE synchronization wrappers

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

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

template <class SYNCH_STRATEGY> int
Message_Queue<SYNCH_STRATEGY>::is_empty (void) const {
  Guard<SYNCH_STRATEGY::MUTEX> m (lock_);
  return is_empty_i ();
}

template <class SYNCH_STRATEGY> int
Message_Queue<SYNCH_STRATEGY>::is_full (void) const {
  Guard<SYNCH_STRATEGY::MUTEX> m (lock_);
  return is_full_i ();
}
```


OO Design Interlude

- Q: *How should locking be performed in an OO class?*
- A: In general, the following general pattern is useful:
  - "Public functions should lock, private functions should not lock"
    - This also 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...


```
// Queue new item at the end of the list.

template <class SYNCH_STRATEGY> int
Message_Queue<SYNCH_STRATEGY>::enqueue_tail
  (Message_Block *new_item, Time_Value *tv)
{
  Guard<SYNCH_STRATEGY::MUTEX> monitor (lock_);

  // Wait while the queue is full.

  while (is_full_i ())
    {
      // Release the lock_ and wait for timeout, signal,
      // or space becoming 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 (new_item);

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

```
// Dequeue the front item on the list and return it
// to the caller.

template <class SYNCH_STRATEGY> int
Message_Queue<SYNCH_STRATEGY>::dequeue_head
  (Message_Block *&first_item, Time_Value *tv)
{
  Guard<SYNCH_STRATEGY::MUTEX> monitor (lock_);

  // Wait while the queue is empty.

  while (is_empty_i ())
    {
      // Release the 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 (first_item);

  // Tell blocked threads that list is no longer full.
  not_full_cond_.signal ();
}
```


Overcoming Algorithmic Decomposition Limitations

- The previous slides illustrate *tactical* OO techniques, idioms, and patterns that:
  1. *Reduce accidental complexity e.g.,*
     - Automate synchronization acquisition and release (C++ constructor/destructor idiom)
     - Improve consistency of synchronization interface (Adapter and Wrapper patterns)
  2. *Eliminate race conditions*
- The next slides describe *strategic* patterns, frameworks, and components that:
  1. *Increase reuse and extensibility e.g.,*
     - Decoupling solution from particular service, IPC and demultiplexing mechanisms
  2. *Improve the flexibility of concurrency control*

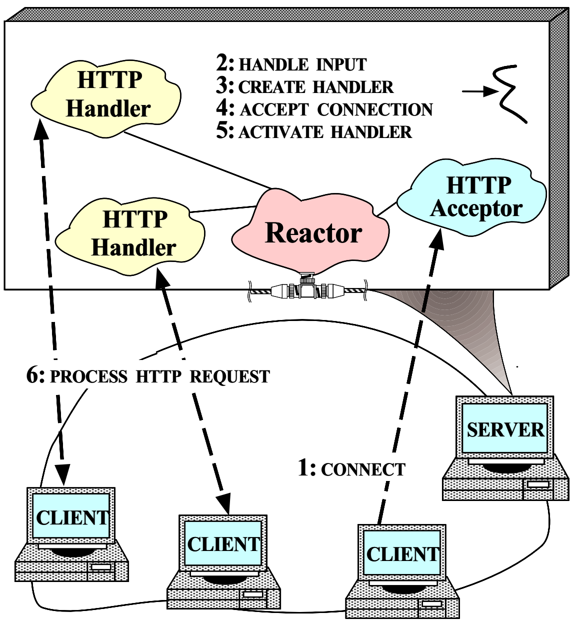
Selecting the Server's Concurrency Architecture

- *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

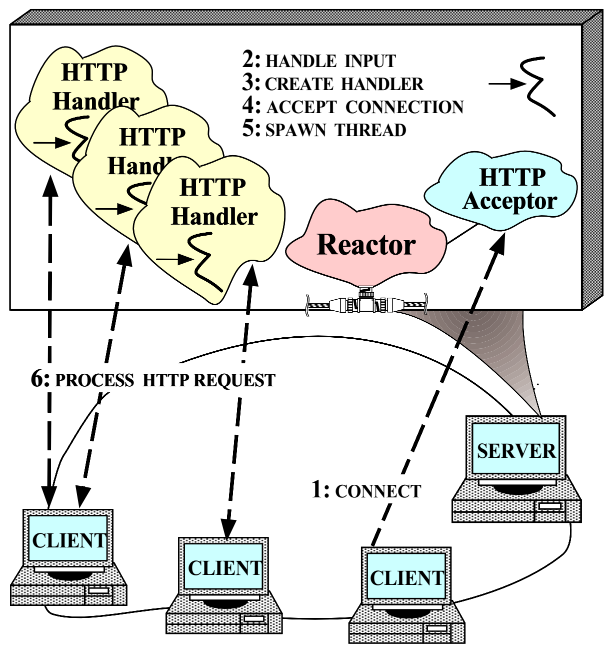
Concurrency Patterns in the Web Server

- 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
  1. *Reactive*
  2. *Thread-per-request*
  3. *Thread-per-connection*
  4. *Synchronous Thread Pool*
  5. *Asynchronous Thread Pool*

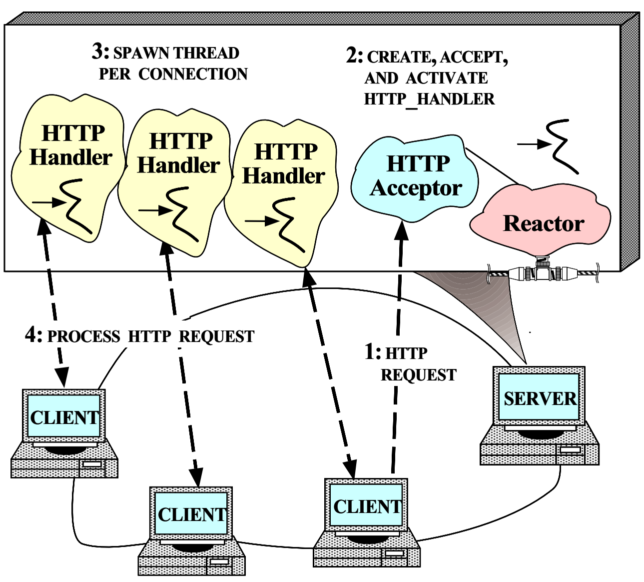
Reactive Web Server



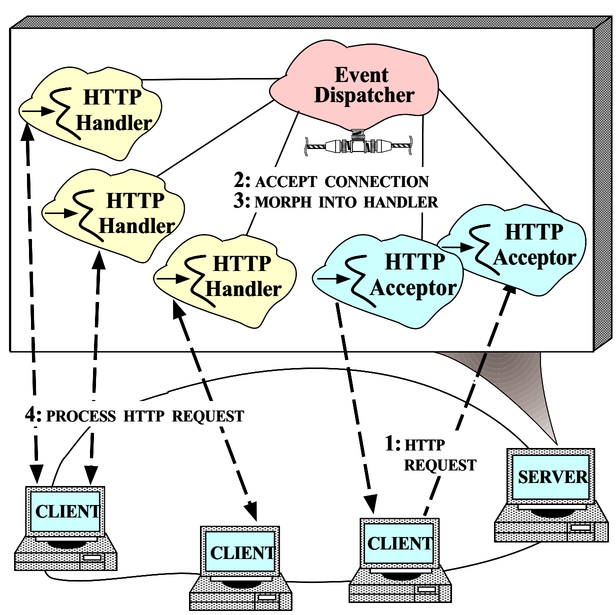
Thread-per-Request Web Server



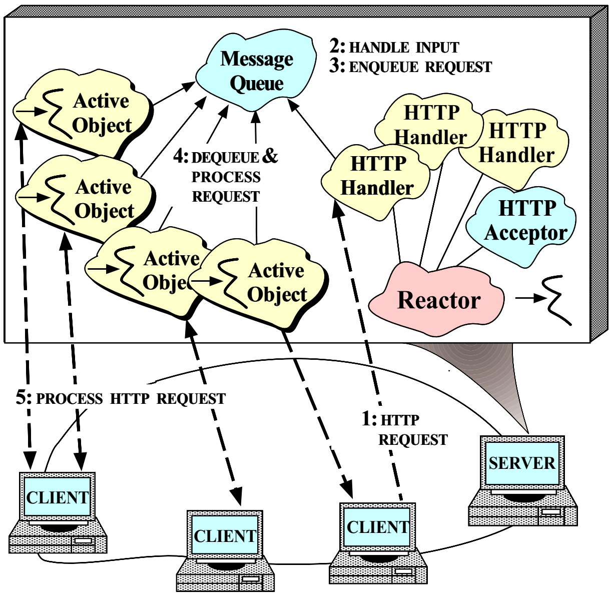
Thread-per-Connection Web Server



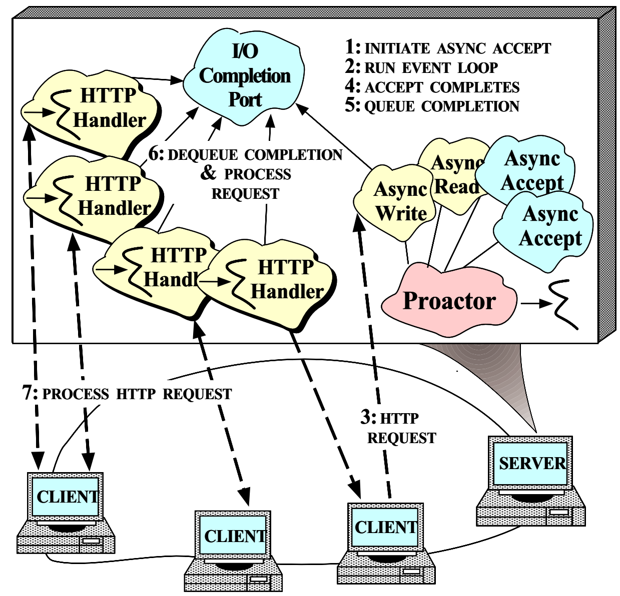
Handle-based Synchronous Thread Pool Web Server



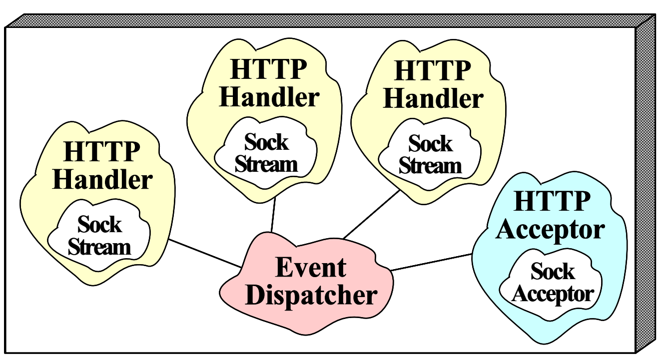
Queue-based Synchronous Thread Pool Web Server



Asynchronous Thread Pool Web Server

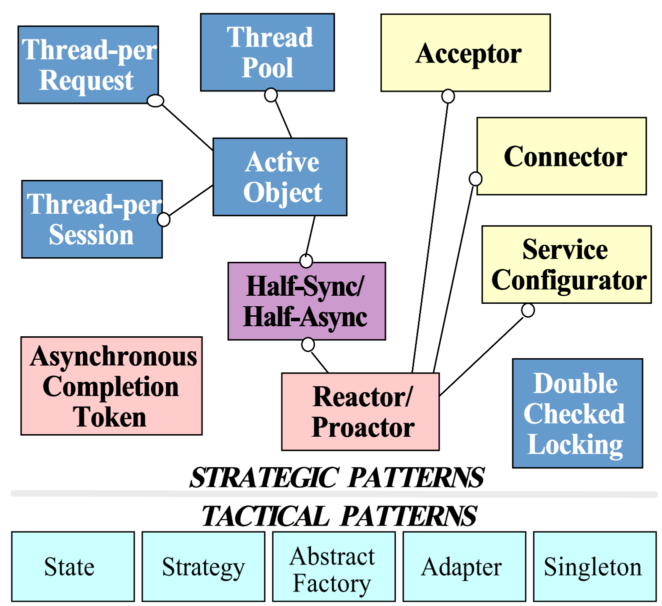


Web Server Software Architecture



- *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

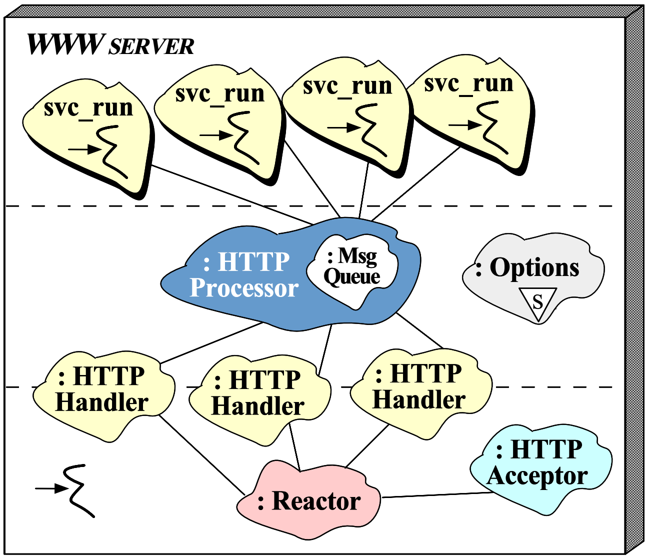
Patterns in the Web Server Implementation



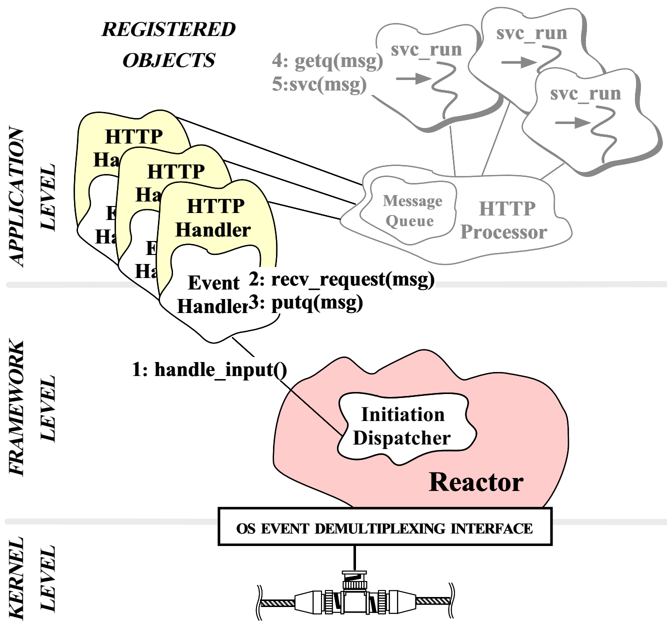
Patterns in the WWW Client/Server (cont'd)

- The WWW Client/Server uses same patterns as distributed logger
  - *i.e.*, Reactor, Service Configurator, Active Object, and Acceptor
- It also contains following patterns:
  - *Connector*
    - "Decouple the active initialization of a service from the tasks performed once the service is initialized"
  - *Double-Checked Locking Optimization*
    - "Ensures atomic initialization of objects and eliminates unnecessary locking overhead on each access"
  - *Half-Sync/Half-Async*
    - "Decouple synchronous I/O from asynchronous I/O in a system to simplify concurrent programming effort without degrading execution efficiency"

Architecture of Our WWW Server



An Integrated Reactive/Active Web Server



The HTTP_Handler Public Interface

- The `HTTP_Handler` is the Proxy for communicating with clients (e.g., WWW browsers like Netscape or IE)
  - It implements the asynchronous portion of Half-Sync/Half-Async pattern

```
template <class PEER_ACCEPTOR>
class HTTP_Handler :
  public Svc_Handler<PEER_ACCEPTOR::PEER_STREAM,
                     NULL_SYNCH> {
public:
    // Entry point into HTTP_Handler, called by
    // HTTP_Acceptor.
  virtual int open (void *)
  {
    // Register with Reactor to handle client input.
    Reactor::instance ()->register_handler
      (this, READ_MASK);

    // Register timeout in case client doesn't
    // send any HTTP requests.
    Reactor::instance ()->schedule_timer
      (this, 0, Time_Value (HTTP_CLIENT_TIMEOUT));
  }
```

The HTTP_Handler Protected Interface

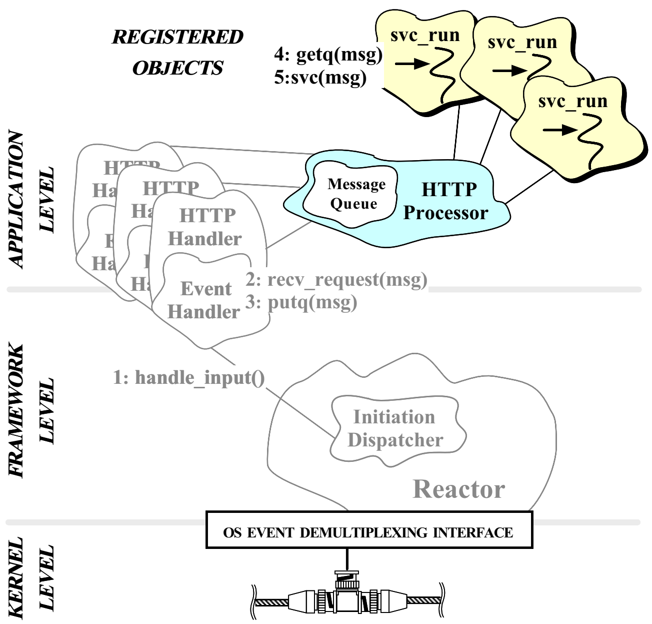
- The following methods are invoked by callbacks from the `Reactor`

```
protected:
    // Reactor notifies when client's timeout.
  virtual int handle_timeout (const Time_Value &,
                              const void *)
  {
    // Remove from the Reactor.
    Reactor::instance ()->remove_handler
      (this, READ_MASK);
  }

    // Reactor notifies when client
    // HTTP requests arrive.
  virtual int handle_input (HANDLE);

    // Receive/frame client HTTP requests (e.g., GET).
  int recv_request (Message_Block &*);
};
```


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 in the WWW Server



The HTTP_Processor Class

- Processes HTTP requests using the "Thread-Pool" concurrency model to implement the synchronous task portion of the Half-Sync/Half-Async pattern

```
class HTTP_Processor : public Task<MT_SYNCH> {
public:
    // Singleton access point.
  static HTTP_Processor *instance (void);

    // Pass a request to the thread pool.
  virtual int put (Message_Block *, Time_Value *);

    // Entry point into a pool thread.
  virtual int svc (int)
  {
    Message_Block *mb = 0; // Message buffer.

    // Wait for messages to arrive.
    for (;;)
    {
      getq (mb); // Inherited from class Task;
      // Identify and perform HTTP Server
      // request processing here...
```

Using the Singleton

- The `HTTP_Processor` is implemented as a Singleton that is created "on demand"

```
// Singleton access point.

HTTP_Processor *
HTTP_Processor::instance (void)
{
  // Beware of race conditions!
  if (instance_ == 0)
    instance_ = new HTTP_Processor;

  return instance_;
}

// Constructor creates the thread pool.

HTTP_Processor::HTTP_Processor (void)
{
  // Inherited from class Task.
  activate (THR_NEW_LWP, num_threads);
}
```

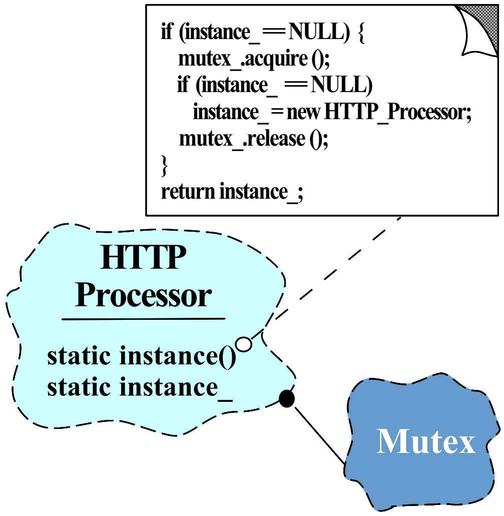

Subtle Concurrency Woes with the Singleton Pattern

- *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

- *Intent*
  - "Ensures atomic initialization of objects and eliminates unnecessary locking overhead on each access"
- This pattern resolves the following forces:
  1. *Ensures atomic initialization or access to objects, regardless of thread scheduling order*
  2. *Keeps locking overhead to a minimum*
     - *e.g.*, only lock on first access
- Note, this pattern assumes atomic memory access...

Using the Double-Checked Locking Optimization Pattern for the WWW Server



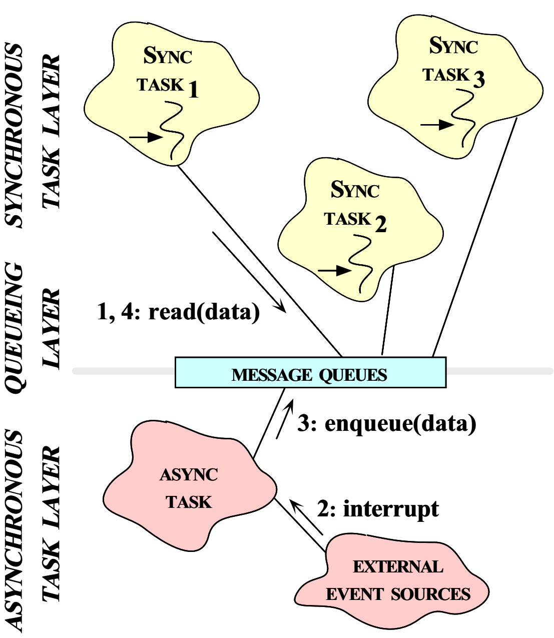
Integrating Reactive and Multi-threaded Layers

- *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

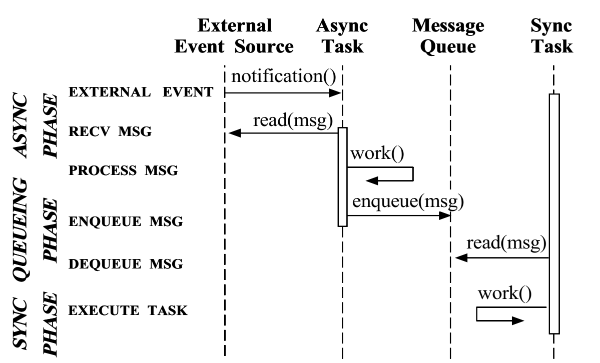
Half-Sync/Half-Async Pattern

- *Intent*
  - "An architectural pattern that decouples synchronous I/O from asynchronous I/O in a system to simplify programming effort without degrading execution efficiency"
- This pattern resolves the following forces for concurrent communication systems:
  - *How to simplify programming for higher-level communication tasks*
    - These are performed synchronously (via Active Objects)
  - *How to ensure efficient lower-level I/O communication tasks*
    - These are performed asynchronously (via the Reactor)

Structure of the Half-Sync/Half-Async Pattern

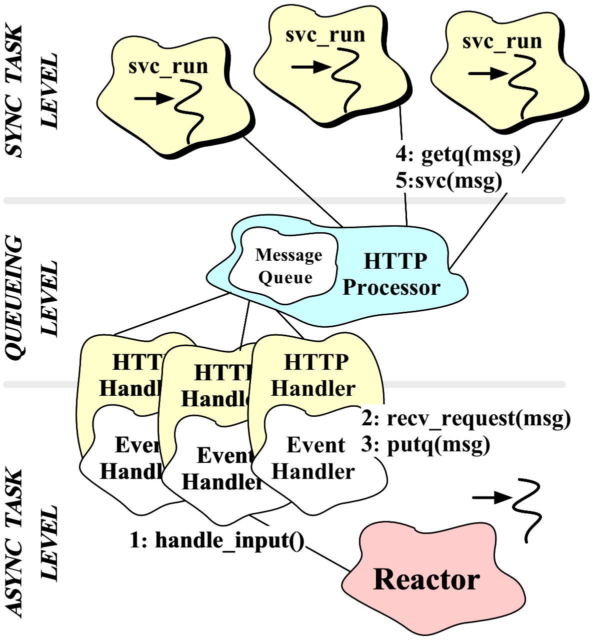


Collaboration in the Half-Sync/Half-Async Pattern



- This illustrates *input* processing (*output* processing is similar)

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



Joining Async and Sync Tasks in the WWW Server

- The following methods form the boundary between the Async and Sync layers

```
template <class PA> int
HTTP_Handler<PA>::handle_input (HANDLE h)
{
  Message_Block *mb = 0;

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

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

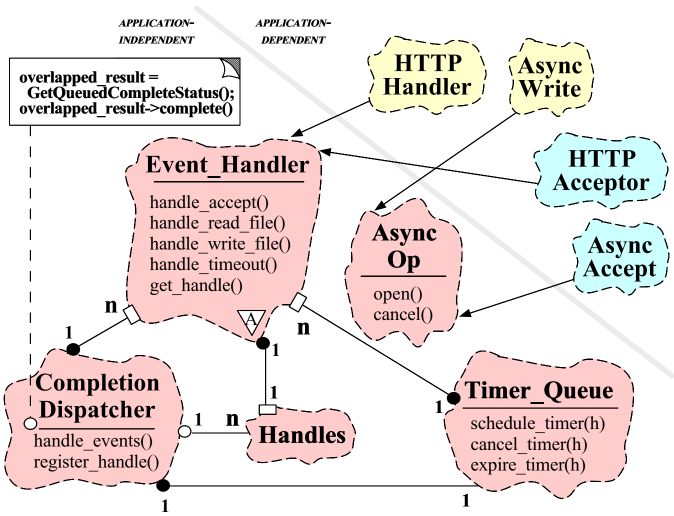

Optimizing Our Web Server for Asynchronous Operating Systems

- *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
  - Good designs should be adaptable to new contexts
- *Solution*
  - Use the *Proactor* pattern to maximize performance on Asynchronous OS platforms

The Proactor Pattern

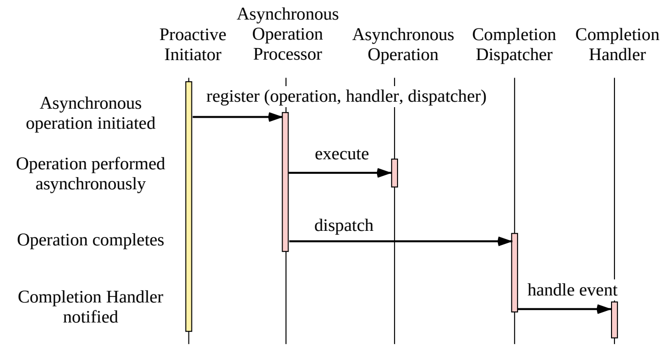
- *Intent*
  - "Decouples asynchronous event demultiplexing and event handler completion dispatching from service(s) performed in response to events"
- This pattern resolves the following forces for asynchronous event-driven software:
  - *How to demultiplex multiple types of events from multiple sources of events asynchronously and efficiently within a minimal number of threads*
  - *How to extend application behavior without requiring changes to the event dispatching framework*

Structure of the Proactor Pattern

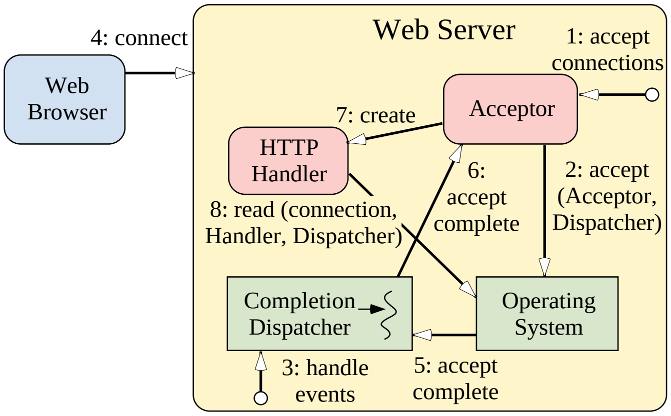


- www.cs.wustl.edu/~schmidt/proactor.ps.gz

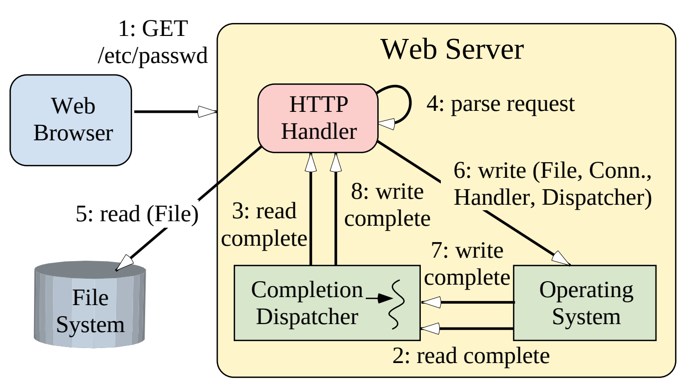
Collaboration in the Proactor Pattern



Client Connects to a Proactive Web Server



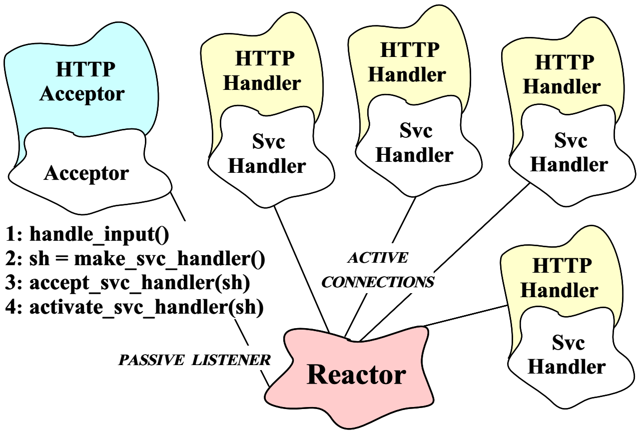
Client Sends Request to a Proactive Web Server



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 Acceptor Pattern in the WWW Server



The HTTP_Acceptor Class Interface

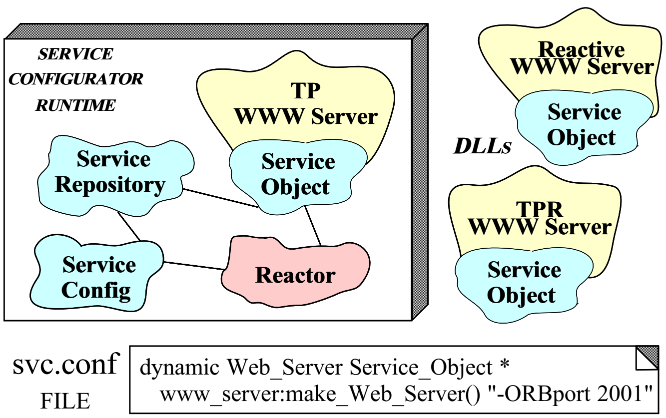
- The `HTTP_Acceptor` class implements the Acceptor pattern
  - *i.e.*, it accepts connections/initializes `HTTP_Handlers`

```
template <class PEER_ACCEPTOR>
class HTTP_Acceptor : public
                        // This is a ``trait.''
  Acceptor<HTTP_Handler<PEER_ACCEPTOR::PEER_STREAM>,
           PEER_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 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
    (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 Service Configurator Pattern in the WWW Server



- Existing service is based on Half-Sync/Half-Async “‘Thread pool”’ pattern
  - Other versions could be single-threaded, could use other concurrency strategies, and other protocols

Service Configurator Implementation in C++

- The concurrent WWW Server is configured and initialized via a configuration script

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

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

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

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


Main Program for WWW Server

- Dynamically configure and execute the WWW Server
  - Note that this is totally generic!

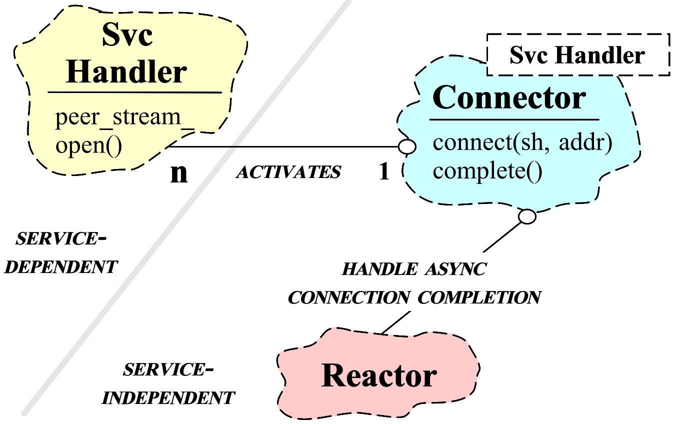
```
int main (int argc, char *argv[])
{
  // Initialize the daemon and dynamically
  // configure the service.
  Service_Config::open (argc, argv);

  // Loop forever, running services and handling
  // reconfigurations.

  Reactor::run_event_loop ();
  /* NOTREACHED */
}
```


The Connector Pattern

- *Intent*
  - “Decouple the active initialization of a service from the task performed once a service is initialized”

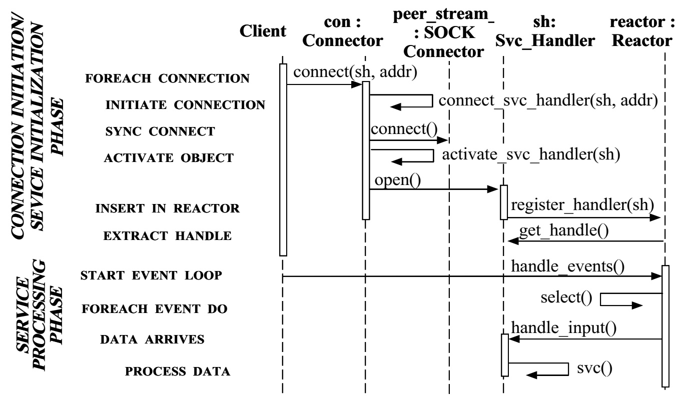
- This pattern resolves the following forces for network clients that use interfaces like sockets or TLI:
  1. *How to reuse active connection establishment code for each new service*
  2. *How to make the connection establishment code portable across platforms that may contain sockets but not TLI, or vice versa*
  3. *How to enable flexible policies for creation, connection establishment, and concurrency*
  4. *How to efficiently establish connections with large number of peers or over a long delay path*

Structure of the Connector Pattern



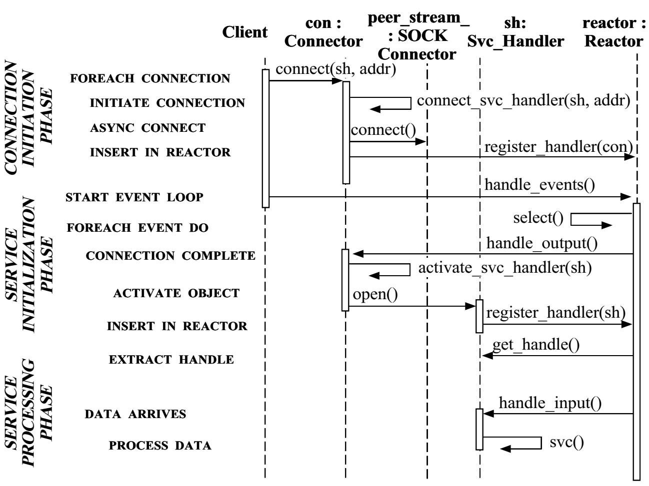
- www.cs.wustl.edu/~schmidt/Acc-Con.ps.gz

Collaboration in the Connector Pattern



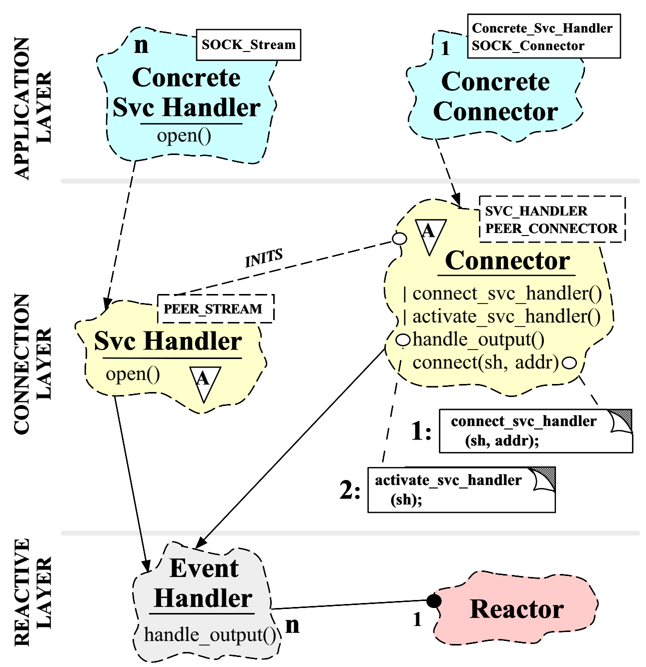
- Synchronous mode

Collaboration in the Connector Pattern

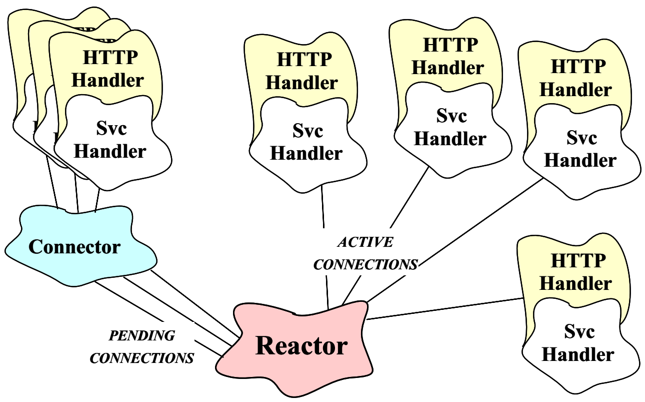


- Asynchronous mode

Structure of the Connector Pattern in ACE



Using the Connector Pattern in a WWW Client



- *e.g.*, in the Netscape HTML parser

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 Connector
  : public Service_Object
{
public:
    // Initiate connection to Peer.
  virtual int connect (SVC_HANDLER &*svc_handler,
                       const PEER_CONNECTOR::PEER_ADDR &,
                       Synch_Options &synch_options);

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


OO Design Interlude

- Q: *What is the Synch_Options class?*

- A: This allows callers to define the synchrony/asynchrony policies, *e.g.*,

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

  Synch_Options (u_long options = 0,
                 const Time_Value &timeout
                   = Time_Value::zero,
                 const void *arg = 0);

    // This is the default synchronous setting.
  static Synch_Options synch;
    // This is the default asynchronous setting.
  static Synch_Options asynch;
};
```


Connector Class Protected Interface

```
protected:
    // Demultiplexing hooks.
  virtual int handle_output (HANDLE); // Success.
  virtual int handle_input (HANDLE); // Failure.
  virtual int handle_timeout (Time_Value &, const void *);

    // Create and cleanup asynchronous connections...
  virtual int create_svc_tuple (SVC_HANDLER *,
                                Synch_Options &);
  virtual Svc_Tuple *cleanup_svc_tuple (HANDLE);

    // Table that maps an I/O handle to a Svc_Tuple *.
  Map_Manager<HANDLE, Svc_Tuple *, Null_Mutex>
    handler_map_;

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

OO Design Interlude

- Q: "What is a good technique to implementing a handler map?"
  - *e.g.*, to route messages or to map HANDLEs to SVC_HANDLERs
- A: Use a `Map_Manager` collection class
  - ACE provides a `Map_Manager` collection that associates *external ids* with *internal ids*, *e.g.*,
    - External ids → HANDLE
    - Internal ids → set of `Svc_Handlers`
  - `Map_Manager` uses templates to enhance reuse

Map_Manager Class

- Synchronization mechanisms are parameterized...

```
template <class EXT_ID, class INT_ID, class LOCK>
class Map_Manager
{
public:
  bool bind (EXT_ID, INT_ID *);
  bool unbind (EXT_ID);

  bool find (EXT_ID ex, INT_ID &in) {
    // Exception-safe code...
    Read_Guard<LOCK> monitor (lock_);
    // lock_.read_acquire ();
    if (find_i (ex, in))
      return true;
    else
      return false;
    // lock_.release ();
 }

private:
  LOCK lock_;
  bool locate_entry (EXT_ID, INT_ID &);
  // ...
};
```


Connector Class Implementation

```
// Shorthand names.
#define SH SVC_HANDLER
#define PC PEER_CONNECTOR

// Initiate connection using specified blocking semantics.
template <class SH, class PC> int
Connector<SH, PC>::connect
  (SH *sh,
   const PC::PEER_ADDR &r_addr,
   Synch_Options &options) {
  Time_Value *timeout = 0;
  int use_reactor = options[Synch_Options::USE_REACTOR];

  if (use_reactor) timeout = Time_Value::zerop;
  else
    timeout = options[Synch_Options::USE_TIMEOUT]
      ? (Time_Value *) &options.timeout () : 0;

  // Use Peer_Connector factory to initiate connection.
  if (connector_.connect (*sh, r_addr, timeout) == -1) {
    // If the connection hasn't completed, then
    // register with the Reactor to call us back.
    if (use_reactor && errno == EWOULDBLOCK)
      create_svc_tuple (sh, options);
  } else
    // Activate immediately if we are connected.
    sh->open ((void *) this);
}
```



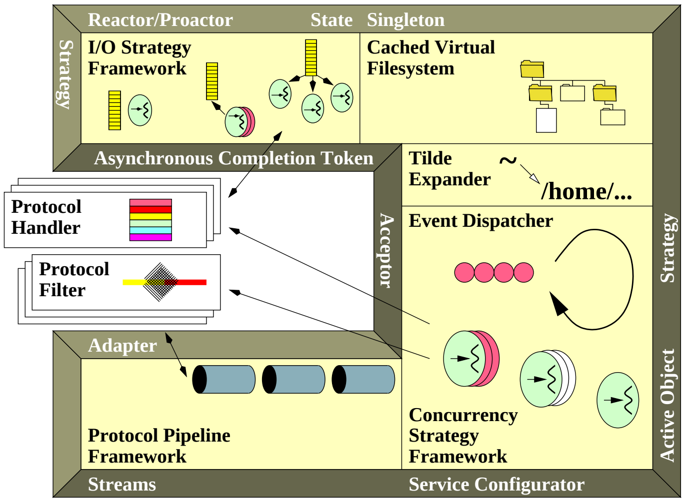
```
// Register a Svc_Handler that is in the
// process of connecting.

template <class SH, class PC> int
Connector<SH, PC>::create_svc_tuple
  (SH *sh, Synch_Options &options)
{
  // Register for both "read" and "write" events.
  Reactor::instance ()->register_handler
      (sh->get_handle (),
       Event_Handler::READ_MASK |
       Event_Handler::WRITE_MASK);

  Svc_Tuple *st = new Svc_Tuple (sh, options.arg ());

  if (options[Synch_Options::USE_TIMEOUT])
    // Register timeout with Reactor.
    int id = Reactor::instance ()->schedule_timer
               (this, (const void *) st,
                options.timeout ());
    st->id (id);

  // Map the HANDLE to the Svc_Handler.
  handler_map_.bind (sh->get_handle (), st);
}
```

```
// Cleanup asynchronous connections...

template <class SH, class PC> Svc_Tuple *
Connector<SH, PC>::cleanup_svc_tuple (HANDLE h)
{
  Svc_Tuple *st;

  // Locate the Svc_Tuple based on the handle;
  handler_map_.find (h, st);

  // Remove SH from Reactor's Timer_Queue.
  Reactor::instance ()->cancel_timer (st->id ());

  // Remove HANDLE from Reactor.
  Reactor::instance ()->remove_handler (h,
    Event_Handler::RWE_MASK | Event_Handler::DONT_CALL);

  // Remove HANDLE from the map.
  handler_map_.unbind (h);
  return st;
}
```



```
// Finalize a successful connection (called by Reactor).

template <class SH, class PC> int
Connector<SH, PC>::handle_output (HANDLE h) {
  Svc_Tuple *st = cleanup_svc_tuple (h);

  // Transfer I/O handle to SVC_HANDLE *.
  st->svc_handler ()->set_handle (h);

  // Delegate control to the service handler.
  sh->open ((void *) this);
}

// Handle connection errors.

template <class SH, class PC> int
Connector<SH, PC>::handle_input (HANDLE h) {
  Svc_Tuple *st = cleanup_svc_tuple (h);
}

// Handle connection timeouts.

template <class SH, class PC> int
Connector<SH, PC>::handle_timeout
  (Time_Value &time, const void *arg) {
  Svc_Tuple *st = (Svc_Tuple *) arg;
  st = cleanup_svc_tuple
         (st->svc_handler ()->get_handle ());
  // Forward "magic cookie"...
  st->svc_handler ()->handle_timeout (tv, st->arg ());
}
```


The OO Architecture of the JAWS Framework



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

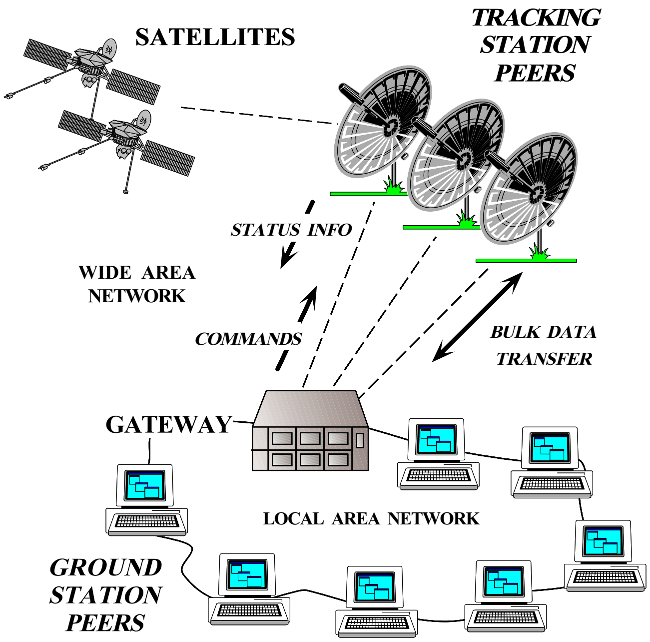
Web Server Optimization Techniques

- 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

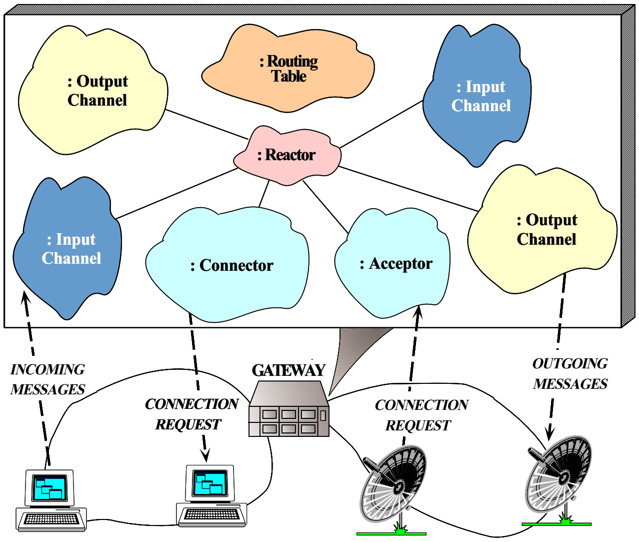
Application-level Gateway Example

- The next example explores the *patterns* and *reusable framework* components used in an OO architecture for *application-level Gateways*
- Gateways route messages between Peers in a large-scale telecommunication system
- Peers and Gateways are connected via TCP/IP

Physical Architecture of the Gateway



OO Software Architecture of the Gateway

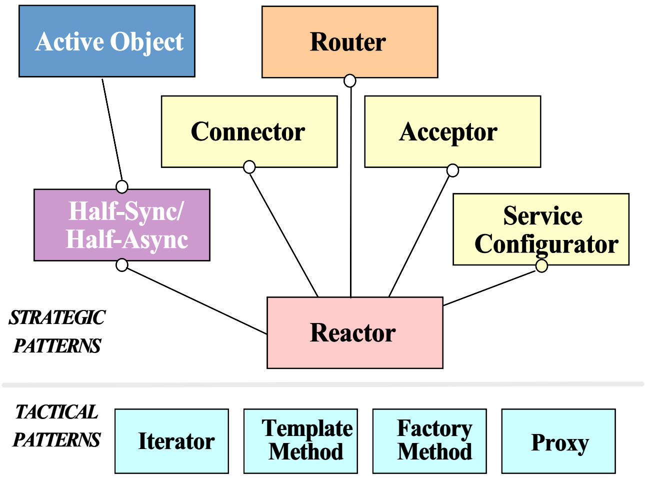


Gateway Behavior

- Components in the Gateway behave as follows:

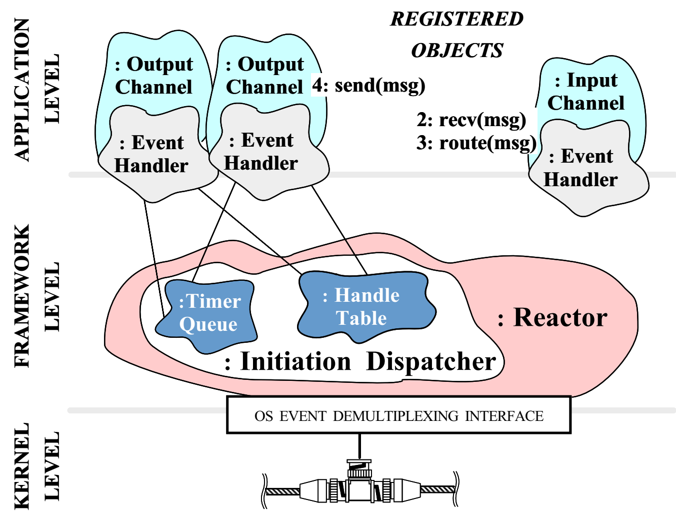
1. `Gateway` parses configuration files that specify which Peers to connect with and which routes to use
2. `Channel_Connector` connects to Peers, then creates and activates `Channel` subclasses (`Input_Channel` or `Output_Channel`)
3. Once connected, Peers send messages to the Gateway
   - Messages are handled by an `Input_Channel`
   - `Input_Channels` work as follows:
     (a) Receive and validate messages
     (b) Consult a `Routing_Table`
     (c) Forward messages to the appropriate Peer(s) via `Output_Channels`

Patterns in the Gateway

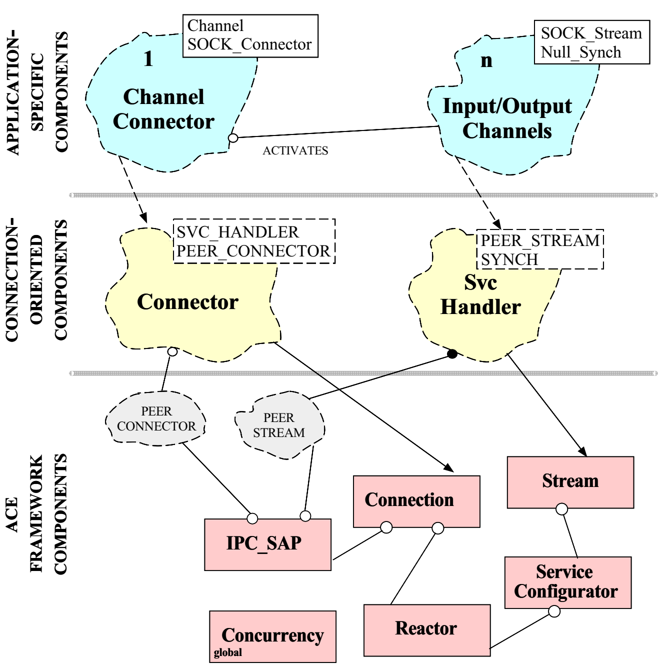


- The Gateway components are based upon a system of patterns

Using the Reactor Pattern for the Gateway



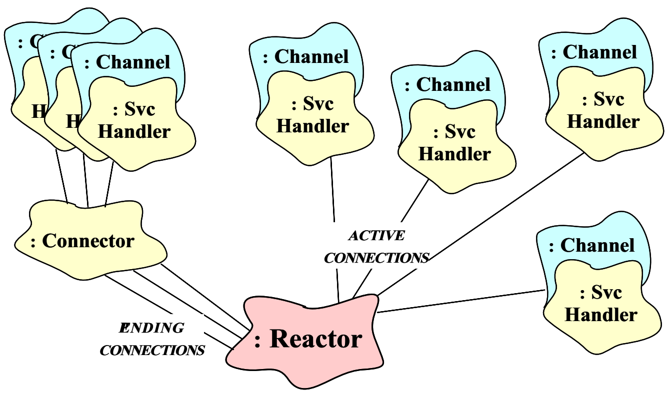
Class Diagram for Single-Threaded Gateway



OO Gateway Architecture

- The Gateway is decomposed into components that are layered as follows:
  1. *Application-specific components*
     - `Channels` route messages among Peers
  2. *Connection-oriented application components*
     - `Svc_Handler`
       * Performs I/O-related tasks with connected clients
     - `Connector` factory
       * Establishes new connections with clients
       * Dynamically creates a `Svc_Handler` object for each client and "activates" it
  3. *Application-independent ACE framework components*
     - Perform IPC, explicit dynamic linking, event demultiplexing, event handler dispatching, multi-threading, etc.

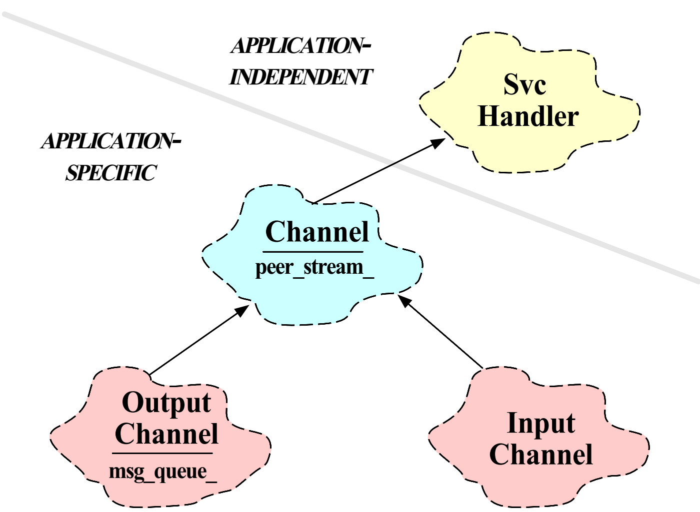
Using the Connector Pattern for the Gateway



Specializing Connector and Svc_Handler

- Producing an application that meets Gateway requirements involves *specializing* ACE components
  - `Connector` → `Channel_Connector`
  - `Svc_Handler` → `Channel` → `Input_Channel` and `Output_Channel`
- Note that these new classes selectively override methods defined in the base classes
  - The Reactor automatically invokes these methods in response to I/O, signal, and timer events

Channel Inheritance Hierarchy



Channel Class Public Interface

- Common methods and data for I/O Channels

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

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

class Channel
  : public Svc_Handler<SOCK_Stream, SYNCH>
{
public:
    // Initialize the handler (called by Connector).
  virtual int open (void * = 0);

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

OO Design Interlude

- Q: *What is the MT_SYNCH class and how does it work?*
- A: *MT_SYNCH provides a thread-safe synchronization policy for a particular instantiation of a Svc_Handler*
  - e.g., it ensures that any use of a `Svc_Handler`'s `Message_Queue` will be thread-safe
  - Any `Task` that accesses shared state can use the "traits" in the `MT_SYNCH`

```
class MT_SYNCH { public:
  typedef Thread_Mutex MUTEX;
  typedef Condition_Thread_Mutex CONDITION;
};
```

  - Contrast with `NULL_SYNCH`

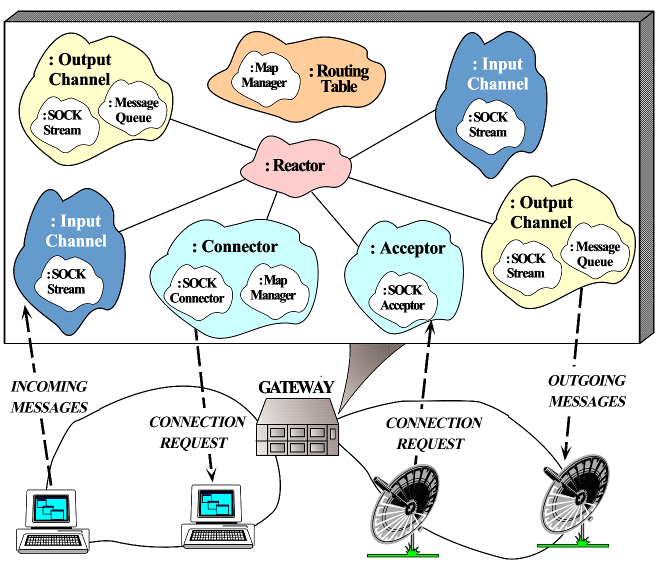
```
class NULL_SYNCH { public:
  typedef Null_Mutex MUTEX;
  typedef Null_Condition_Thread_Mutex CONDITION;
};
```


Channel Class Protected Interface

- Common data for I/O Channels

```
protected:
    // Reconnect Channel if connection terminates.
  virtual int handle_close (HANDLE, Reactor_Mask);

    // Address of peer.
  INET_Addr addr_;

    // The assigned connection ID of this Channel.
  CONN_ID id_;
};
```


Detailed OO Architecture of the Gateway



Input_Channel Interface

- Handle input processing and routing of messages from Peers

```
class Input_Channel : public Channel
{
public:
  Input_Channel (void);

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

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

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

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

Output_Channel Interface

- Handle output processing of messages sent to Peers

```
class Output_Channel : public Channel
{
public:
  Output_Channel (void);

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

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

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

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


Channel_Connector Class Interface

- A Concrete factory class that behaves as follows:

  1. Establishes connections with Peers to produce `Channels`
  2. Activates `Channels`, which then do the work

```
class Channel_Connector : public
  Connector <Channel, // Type of service
             SOCK_Connector> // Connection factory
{
public:
  // Initiate (or reinitiate) a connection on Channel.
  int initiate_connection (Channel *);
}
```

- `Channel_Connector` also ensures reliability by restarting failed connections

Channel_Connector Implementation

- Initiate (or reinitiate) a connection to the Channel

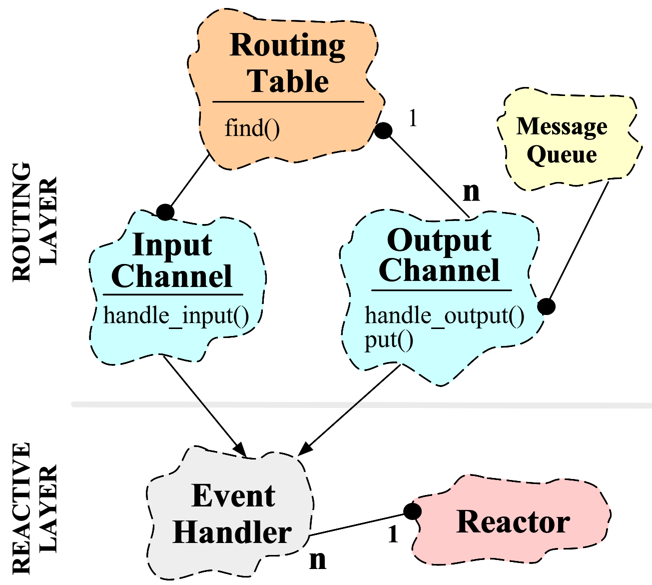
```
int
Channel_Connector::initiate_connection (Channel *channel)
{
  // Use asynchronous connections...
  if (connect (channel, channel->addr (),
                   Synch_Options::asynch) == -1) {
    if (errno != EWOULDBLOCK)
      // Reschedule ourselves to try to connect again.
      Reactor::instance ()->schedule_timer
        (channel, 0, channel->timeout ());
    else
      return -1; // Failure.
  }
  else
    // We're connected.
    return 0;
}
```


The Router Pattern

- *Intent*
  - "Decouple multiple sources of input from multiple sources of output to prevent blocking"

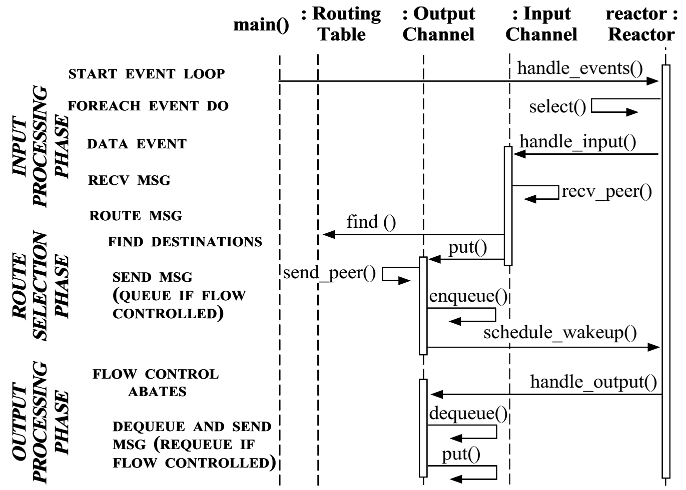
- The Router pattern resolves the following forces for connection-oriented routers:
  - *How to prevent misbehaving connections from disrupting the quality of service for well-behaved connections*
  - *How to allow different concurrency strategies for Input and Output Channels*

Structure of the Router Pattern

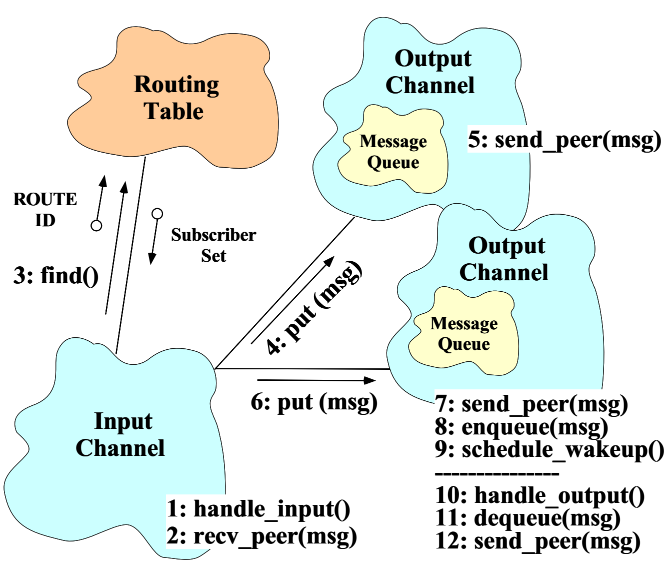


- www.cs.wustl.edu/~schmidt/TAPOS−95.ps.gz

Collaboration in the Router Pattern



Collaboration in Single-threaded Gateway Routing




```
// Receive input message from Peer and route
// the message.

int
Input_Channel::handle_input (HANDLE)
{
  Message_Block *route_addr = 0;

  // Try to get the next message.
  if ((n = recv_peer (route_addr)) <= 0) {
    if (errno == EWOULDBLOCK) return 0;
    else return n;
  }
  else
    route_message (route_addr);
}

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

int
Output_Channel::put (Message_Block *mb, 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, Time_Value::zerop);
}
```

```
// Route message from a Peer.

int
Input_Channel::route_messages (Message_Block *route_addr)
{
  // Determine destination address.
  CONN_ID route_id = *(CONN_ID *) route_addr->rd_ptr ();

  const 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<Channel *> si (re->destinations ());

  // Multicast message.
  for (Channel *out_ch;
       si.next (out_ch) != -1;
       si.advance ()) {
    Message_Block *newmsg = data->duplicate ();
    if (out_ch->put (newmsg) == -1) // Drop message.
      newmsg->release (); // Decrement reference count.
  }
  delete route_addr;
}
```


Peer_Message

```
// unique connection id that denotes a Channel.
typedef short CONN_ID;

// 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 portion.
  char sdu_[MAX_PAYLOAD_SIZE]; // Message payload.
};
```


OO Design Interlude

- 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


```
// Pseudo-code for receiving framed message
// (using non-blocking I/O).

int
Input_Channel::recv_peer (Message_Block *&route_addr)
{
  if (msg_frag_ is empty) {
    msg_frag_ = new 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

  perform 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
}
```

OO Design Interlude

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


```
// Perform a non-blocking put() of message MB.

int Output_Channel::nonblk_put (Message_Block *mb)
{
  // Try to send the message using 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, Time_Value::zerop);

    // Tell Reactor to call us back when we can send again.

    Reactor::instance ()->schedule_wakeup
      (this, Event_Handler::WRITE_MASK);
  }
}
```

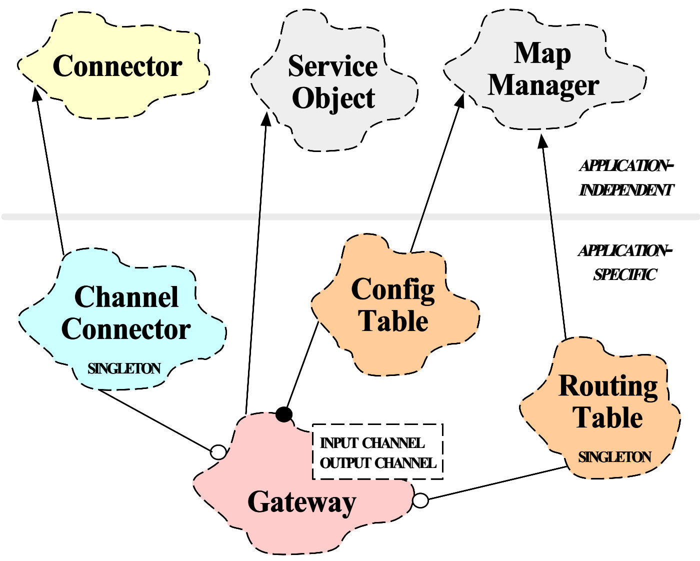


```
// Simple implementation...

int
Output_Channel::send_peer (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) */ {
    delete mb; // Decrement reference count.
    errno = 0;
  }
  return n;
}
```



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

int
Output_Channel::handle_output (HANDLE)
{
  Message_Block *mb = 0;

  // Take the first message off the queue.
  msg_queue_->dequeue_head
                  (mb, Time_Value::zerop);
  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 Message_Queue), then tell the Reactor
    // not to notify us anymore.

    if (msg_queue_->is_empty ()
      Reactor::instance ()->cancel_wakeup
        (this, Event_Handler::WRITE_MASK);
  }
}
```

The Gateway Class



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

Gateway Class Public Interface

- Since `Gateway` inherits from `Service_Object` it may be dynamically (re)configured into a process at run-time

```
// Parameterized by the type of I/O channels.
template <class INPUT_CHANNEL, // Input policies
          class OUTPUT_CHANNEL> // Output policies
class Gateway
  : public Service_Object
{
public:

    // Perform initialization.
  virtual int init (int argc, char *argv[]);

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

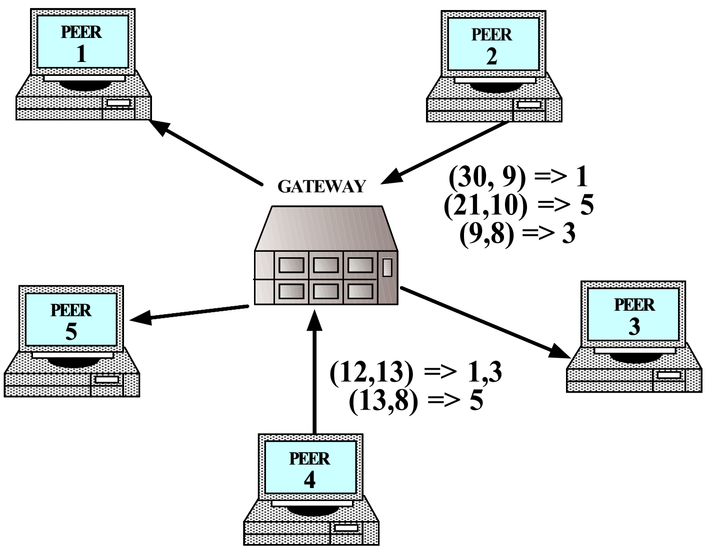

Gateway Class Private Interface

```
protected:
    // Parse the channel table configuration file.
  int parse_cc_config_file (void);

    // Parse the routing table configuration file.
  int parse_rt_config_file (void);

    // Initiate connections to the Peers.
  int initiate_connections (void);

  // Table that maps Connection IDs to Channel *'s.
  Map_Manager<CONN_ID, Channel *, Null_Mutex>
    config_table_;
};
```



```
// Convenient short-hands.
#define IC INPUT_CHANNEL
#define OC OUTPUT_CHANNEL

// Pseudo-code for initializing the Gateway (called
// automatically on startup).

template <class IC, class OC>
Gateway<IC, OC>::init (int argc, char *argv[])
{
  // Parse command-line arguments.
  parse_args (argc, argv);

  // Parse and build the connection configuration.
  parse_cc_config_file ();

  // Parse and build the routing table.
  parse_rt_config_file ();

  // Initiate connections with the Peers.
  initiate_connections ();
  return 0;
}
```

Configuration and Gateway Routing



Configuration Files

- The Gateway decouples the connection topology from the peer routing topology
  - The following config file specifies the connection topology among the Gateway and its Peers

```
# Conn ID   Hostname   Port    Direction   Max Retry
# -------   --------   ----    ---------   ---------
   1        peer1      10002   O           32
   2        peer2      10002   I           32
   3        peer3      10002   O           32
   4        peer4      10002   I           32
   5        peer5      10002   O           32
```

  - The following config file specifies the routing topology among the Gateway and its Peers

```
# Conn ID   Logical ID   Payload   Destinations
# -------   ----------   -------   ------------
  2         30           9         1
  2         21           10        5
  2         09           8         3
  4         12           13        1,3
  4         13           8         5
```



```
// Parse the cc_config_file and
// build the connection table.

template <class IC, class OC>
Gateway<IC, OC>::parse_cc_config_file (void)
{
  CC_Entry entry;
  cc_file.open (cc_filename);

  // Example of the Builder Pattern.

  while (cc_file.read_line (entry) {
    Channel *ch;

    // Locate/create routing table entry.
    if (entry.direction_ == 'O')
      ch = new OC;
    else
      ch = new IC;

    // Set up the peer address.
    INET_Addr addr (entry.port_, entry.host_);
    ch->bind (addr, entry.conn_id_);
    ch->max_timeout (entry.max_retry_delay_);
    config_table_.bind (entry.conn_id_, ch);
  }
}
```



```
// Parse the rt_config_file and
// build the routing table.

template <class IC, class OC>
Gateway<IC, OC>::parse_rt_config_file (void)
{
  RT_Entry entry;
  rt_file.open (cc_filename);

  // Example of the Builder Pattern.

  while (cc_file.read_line (entry) {
    Routing_Entry *re = new Routing_Entry;
    Peer_Addr peer_addr (entry.conn_id, entry.logical_id_);
    Set<Channel *> *channel_set = new Set<Channel *>;

    // Example of the Iterator pattern.
    foreach destination_id in entry.total_destinations_ {
      Channel *ch;
      if (config_table_.find (destination_id, ch);
        channel_set->insert (ch);
    }

    // Attach set of destination channels to routing entry.
    re->destinations (channel_set);

    // Bind with routing table, keyed by peer address.
    routing_table.bind (peer_addr, re);
  }
}
```

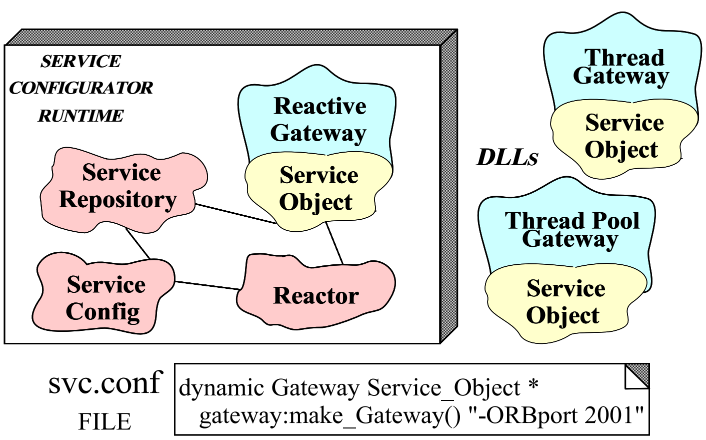
```
// Initiate connections with the Peers.

int Gateway<IC, OC>::initiate_connections (void)
{
  // Example of the Iterator pattern.
  Map_Iterator<CONN_ID, Channel *, Null_Mutex>
    cti (connection_table_);

  // Iterate through connection table
  // and initiate all channels.

  for (const Map_Entry <CONN_ID, Channel *> *me = 0;
       cti.next (me) != 0;
       cti.advance ()) {
    Channel *channel = me->int_id_;

    // Initiate non-blocking connect.
    Channel_Connector::instance ()->
      initiate_connection (channel);
  }
  return 0;
}
```


Dynamically Configuring Services into an Application

- Main program is generic

```
// Example of the Service Configurator pattern.

int main (int argc, char *argv[])
{
  // Initialize the daemon and
  // dynamically configure services.
  Service_Config::open (argc, argv);

  // Run forever, performing configured services.

  Reactor::run_event_loop ();

  /* NOTREACHED */
}
```


Using the Service Configurator Pattern for the Gateway



- Replace the single-threaded Gateway with a multi-threaded Gateway

Dynamic Linking a Gateway Service

- Service configuration file

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

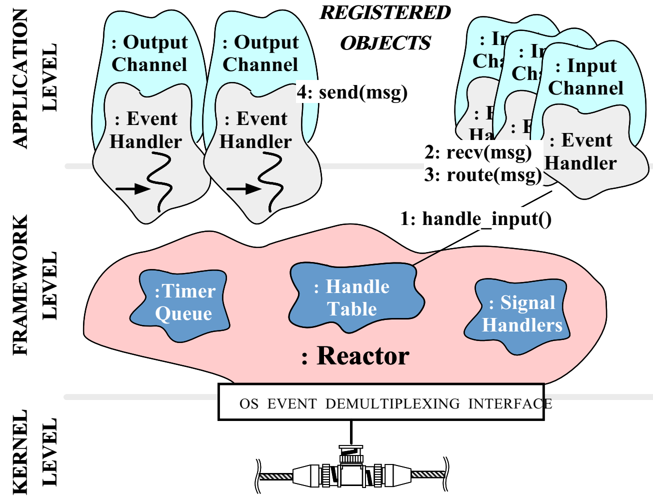
- Application-specific factory function used to dynamically link a service

```
// Dynamically linked factory function that allocates
// a new single-threaded Gateway object.

extern "C" Service_Object *make_Gateway (void);

Service_Object *
make_Gateway (void)
{
  return new Gateway<Input_Channel, Output_Channel>;
  // ACE automatically deletes memory.
}
```

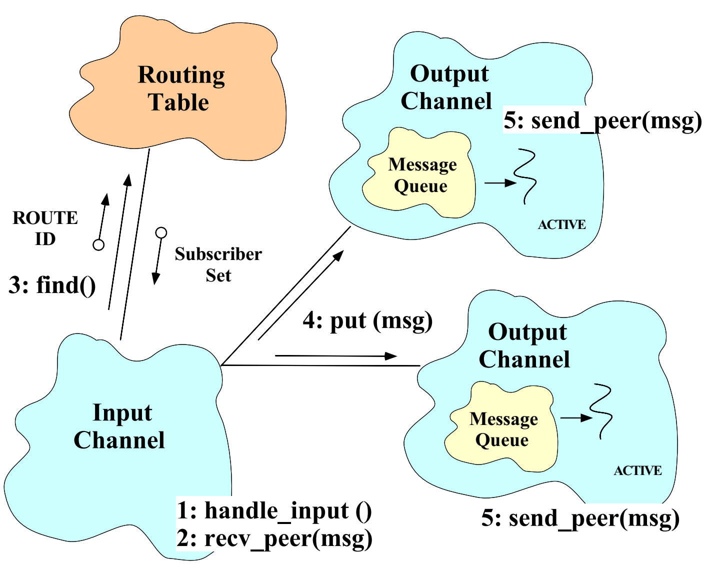
Concurrency Strategies for Patterns

- The Acceptor and Connector patterns do not constrain the concurrency strategies of a `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 OO techniques push this decision to the "edges" of the design
  - This greatly increases reuse, flexibility, and performance tuning

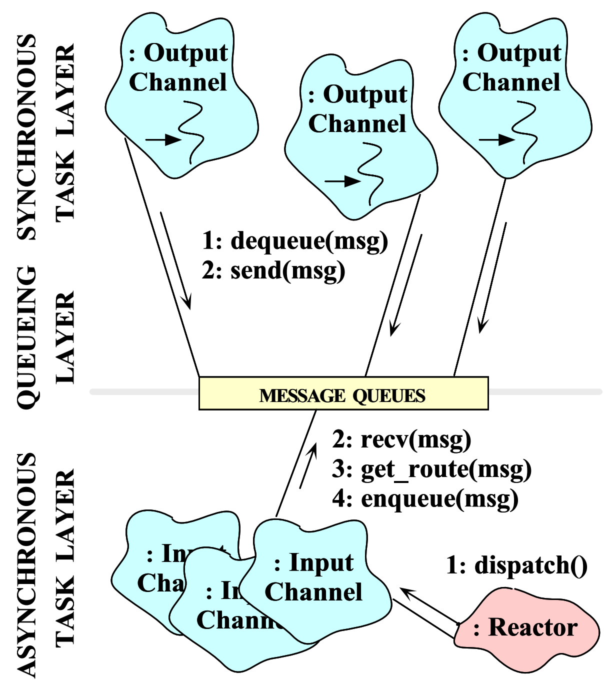
Using the Active Object Pattern for the Gateway



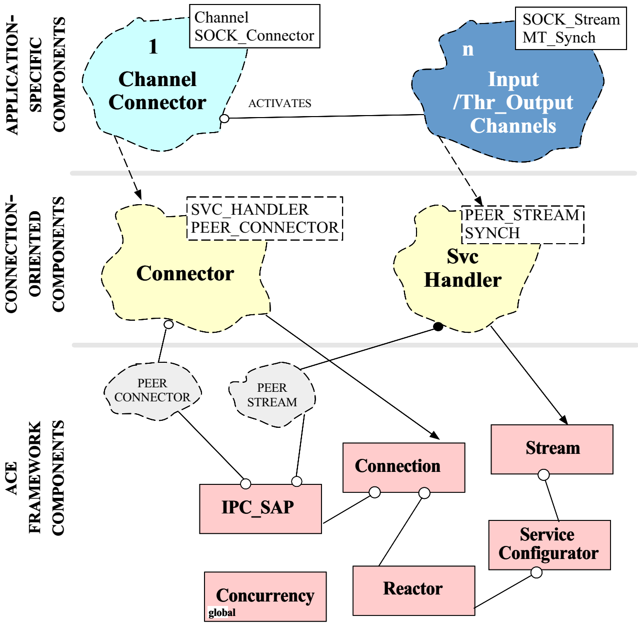
Collaboration in the Active Object-based Gateway Routing



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



Class Diagram for Multi-Threaded Gateway



Thr_Output_Channel Class Interface

- New subclass of `Channel` uses the Active Object pattern for the `Output_Channel`
  - 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

```
#define ACE_USE_MT
#include "Channel.h"

class Thr_Output_Channel : public Output_Channel
{
public:
    // Initialize the object and spawn a new thread.
  virtual int open (void *);

    // Send a message to a peer.
  virtual int put (Message_Block *, Time_Value * = 0);

    // Transmit peer messages within separate thread.
  virtual int svc (void);
};
```


Thr_Output_Channel Class Implementation

- The multi-threaded version of `open` is slightly different since it spawns a new thread to become an active object!

```
// Override definition in the Output_Channel class.

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

  activate (THR_NEW_LWP | THR_DETACHED);
}
```

- `activate` is a pre-defined method on class `Task`


```
// Queue up a message for transmission (must not block
// since all Input_Channels are single-threaded).

int
Thr_Output_Channel::put (Message_Block *mb, Time_Value *)
{
  // Perform non-blocking enqueue.
  msg_queue_->enqueue_tail (mb, Time_Value::zerop);
}

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

int
Thr_Output_Channel::svc (void)
{
  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);

  return 0;
}
```

Dynamic Linking a Gateway Service

- Service configuration file

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

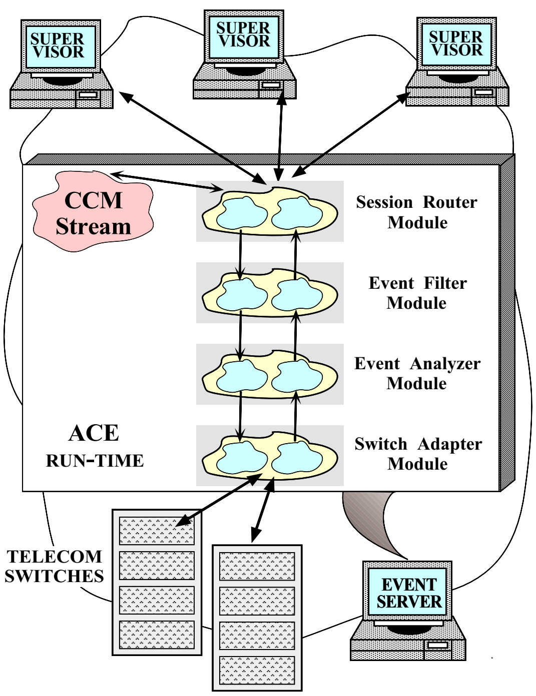
- Application-specific factory function used to dynamically link a service

```
// Dynamically linked factory function that allocates
// a new multi-threaded Gateway object.

extern "C" Service_Object *make_Gateway (void);

Service_Object *
make_Gateway (void)
{
  return new Gateway<Input_Channel, Thr_Output_Channel>;
  // ACE automatically deletes memory.
}
```


ACE Streams

- An ACE `Stream` allows flexible configuration of layered processing modules
- It is an implementation of the *Pipes and Filters* architectural pattern
  - This pattern provides a structure for systems that process a stream of data
  - Each processing step is encapsulated in a filter component
  - Data is passed through pipes between adjacent filters, which can be re-combined

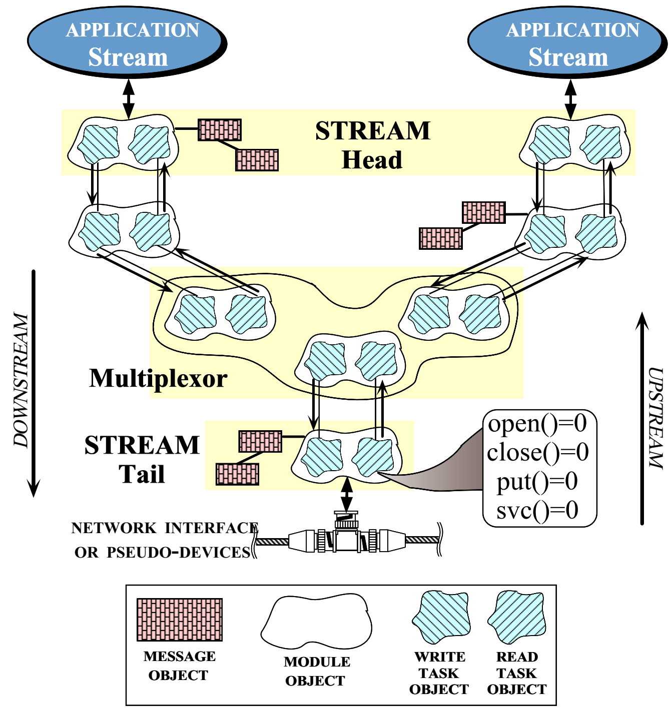
Call Center Manager Example



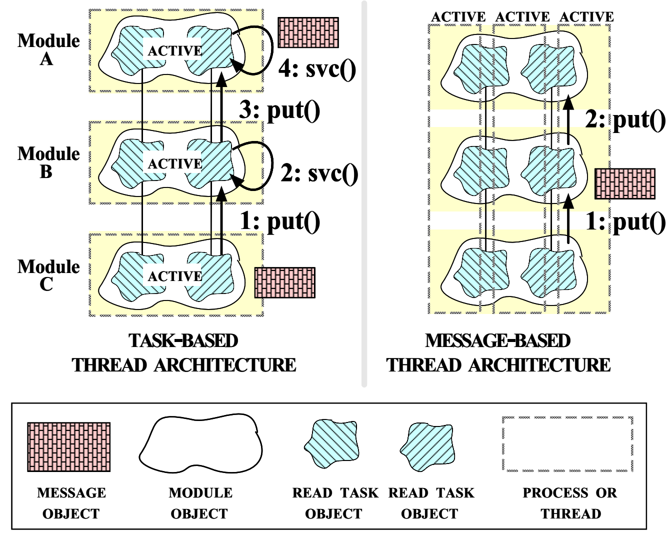
Implementing a Stream in ACE

- A `Stream` contains a stack of `Modules`
- Each `Module` contains two `Tasks`
  - *i.e.*, a *read* `Task` and a *write* `Task`
- Each `Task` contains a `Message_Queue` and a pointer to a `Thread_Manager`

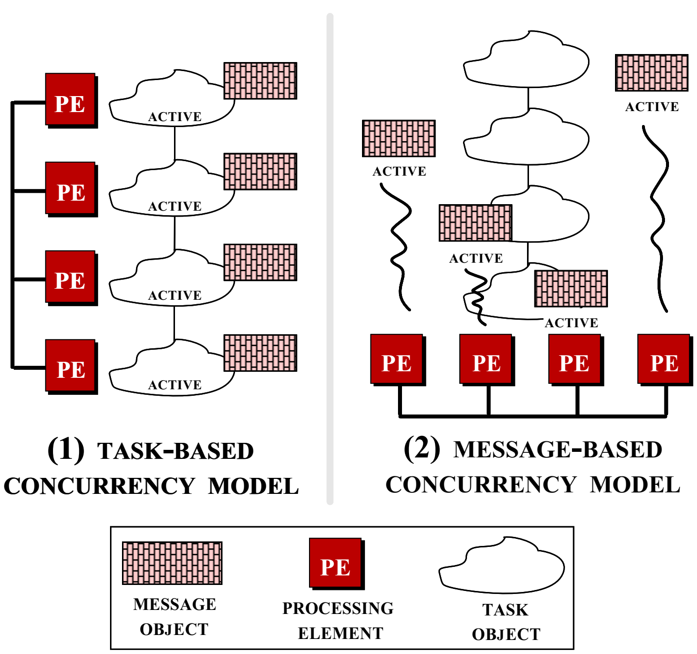
Stream Class Category



Alternative Invocation Methods



Alternative Concurrency Models



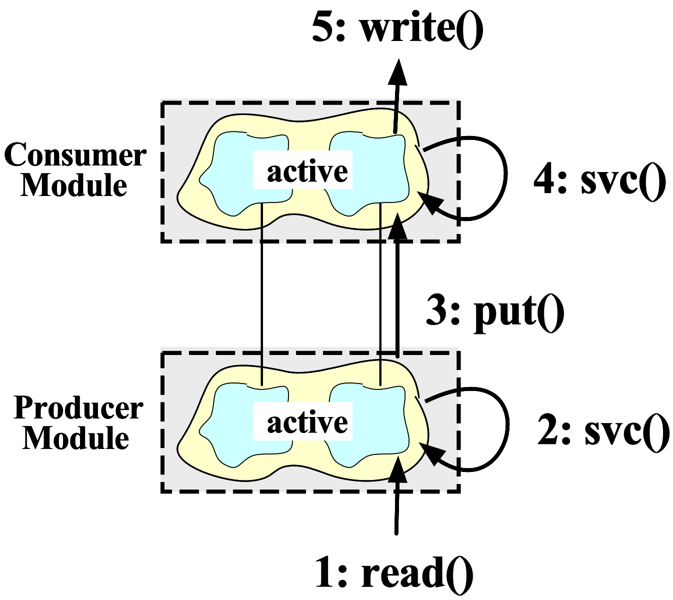
ACE Stream Example: Parallel I/O Copy

- Illustrates an implementation of the classic "bounded buffer" problem

- The program copies stdin to stdout via the use of a multi-threaded `Stream`

- In this example, the "read" `Task` is always ignored since the data flow is uni-directional

Producer and Consumer Object Interactions



Producer Interface

- *e.g.*,

```
// typedef short-hands for the templates.
typedef Stream<MT_SYNCH> MT_Stream;
typedef Module<MT_SYNCH> MT_Module;
typedef Task<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_NEW_LWP);
  }

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



```
// Run in a separate thread.

int
Producer::svc (void)
{
  for (int n; ; ) {
    // Allocate a new message.
    Message_Block *mb = new Message_Block (BUFSIZ);

    // Keep reading stdin, until we reach EOF.

    if ((n = read (STDIN, mb->rd_ptr (), mb->size ())) <= 0)
    {
      // Send a 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);
    }
  }
  return 0;
}
```


Consumer Class Interface

- *e.g.*,

```
// Define the Consumer interface.

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

    // Enqueue the message on the Message_Queue for
    // subsequent processing in svc().
  virtual int put (Message_Block*, 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);
};
```

```
// The consumer dequeues a message from the Message_Queue,
// writes the message to the stderr stream, and deletes
// the message.  The Consumer sends a 0-sized message to
// inform the consumer to stop reading and exit.

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

  // Keep looping, reading a message out of the queue,
  // until we get a message with a length == 0,
  // which informs us to quit.

  for (;;)
    {
      int result = getq (mb);

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

      if (length > 0)
        write (STDOUT, mb->rd_ptr (), length);

      delete mb;

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


Main Driver Function

- *e.g.*,

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

  // Create Producer and Consumer Modules and push
  // them onto the Stream.  All processing is then
 // performed in the Stream.

  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 ourselves.
  Thread_Manager::instance ()->wait ();
  return 0;
}
```


Evaluation of the Stream Class Category

- Structuring active objects via a `Stream` allows "interpositioning"
  - Similar to adding a filter in a UNIX pipeline
- New functionality may be added by "pushing" a new processing Module onto a `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));
```


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
  - *e.g.*, file I/O
- Make sure that `main` terminates via `thr_exit(3T)` rather than `exit(2)` or "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 "Tokens" 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*
- *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

Passive Object Strategy

- A more OO locking strategy is to use a "Passive Object"
  - Also known as a "monitor"
- Passive Object synchonization 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 implements this approach

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 `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 a Token or a Recursive Mutex

Recursive Mutex

- Not all thread libraries support recursive mutexes
  - Here is portable implementation available in ACE:

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

private:
  Thread_Mutex nesting_mutex_;
  Condition_Thread_Mutex mutex_available_;
  thread_t owner_id_;
  int nesting_level_;
};
```

```
// Acquire a recursive mutex (increments the nesting
// level and don't deadlock if owner of the mutex calls
// this method more than once).

Recursive_Thread_Mutex::acquire (void) const
{
  thread_t t_id = Thread::self ();

  Guard<Thread_Mutex> mon (nesting_mutex_);

  // If there's no contention, grab mutex.
  if (nesting_level_ == 0) {
    owner_id_ = t_id;
    nesting_level_ = 1;
  } else if (t_id == owner_id_)
    // 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_id_ = t_id;
    nesting_level_ = 1;
  }
  return 0;
```



```
// Releases a recursive mutex.

Recursive_Thread_Mutex::release (void) const
{
  thread_t t_id = Thread::self ();

  // Automatically acquire mutex.
  Guard<Thread_Mutex> mon (nesting_mutex_);

  nesting_level_--;

  if (nesting_level_ == 0) {
    // This may not be strictly necessary, but
    // it does put the mutex into a known state...
    owner_id_ = OS::NULL_thread;

    // Inform waiters that the mutex is free.
    mutex_available_.signal ();
  }
  return 0;
}

Recursive_Thread_Mutex::Recursive_Thread_Mutex (void)
  : nesting_level_ (0),
    owner_id_ (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 a "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 from other threads
  - 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 "inversion of control" for reactive dispatching may be 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++*
  - Many language features are not widely implemented
  - Development environments are primitive
  - Language has many dark corners and sharp edges

Software Principles for Distributed Applications

1. *Use patterns and frameworks to separate policies from mechanisms*
   - Enhance reuse of common concurrent programming components
2. *Decouple service functionality from configuration-related mechanisms*
   - Improve flexibility and performance
3. *Utilize OO class abstractions, inheritance, dynamic binding, and parameterized types*
   - Improve extensibility and modularity

Software Principles for Distributed Applications (cont'd)

1. *Use advanced OS mechanisms to enhance performance and functionality*
   - *e.g.*, implicit and explicit dynamic linking and multi-threading

2. *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
  - September, 1999, Monticello, Illinois, USA
  - st-www.cs.uiuc.edu/users/patterns/patterns.html

- The European Pattern Languages of Programming conference
  - July, 1999, Kloster Irsee, Germany
  - www.cs.wustl.edu/~schmidt/patterns.html

- USENIX COOTS
  - May 3–7, 1999, San Diego, CA
  - www.usenix.org/events/coots99/

Patterns and Frameworks Literature

- *Books*
  - Gamma et al., "Design Patterns: Elements of Reusable Object-Oriented Software" AW, 1994
  - *Pattern Languages of Program Design* series by AW, 1995–97.
  - Siemens, *Pattern-Oriented Software Architecture*, Wiley and Sons, 1996

- *Special Issues in Journals*
  - October '96 CACM (guest editors: Douglas C. Schmidt, Ralph Johnson, and Mohamed Fayad)
  - October '97 CACM (guest editors: Douglas C. Schmidt and Mohamed Fayad)

- *Magazines*
  - C++ Report and JOOP, columns by Coplien, Vlissides, Vinoski, Schmidt, and Martin

Obtaining ACE

- The ADAPTIVE Communication Environment (ACE) is an OO toolkit designed according to key network programming patterns

- 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

Concluding Remarks

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