The Design and Implementation of the Reactor
An Object-Oriented Framework for Event Demultiplexing (Part 2 of 2)

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1 Introduction

This is the second half of the third article in a series that describes techniques for encapsulating existing operating system (OS) interprocess communication (IPC) services using object-oriented (OO) C++ wrappers. In the first half of this article, a client/server application example was presented to motivate the utility of wrappers that encapsulate *event demultiplexing* mechanisms [1]. Event demultiplexing is useful for developing event-driven network servers that receive and process data arriving from multiple clients simultaneously. The previous article also examined the advantages and disadvantages of several alternative I/O demultiplexing schemes such as non-blocking I/O, multiple process or thread creation, and synchronous I/O demultiplexing (via the `select` and `poll` system calls).

This article focuses on the design and implementation of an object-oriented framework called the `Reactor`. The `Reactor` provides a portable interface to an integrated collection of extensible, reusable, and type-secure C++ classes that encapsulate and enhance the `select` and `poll` event demultiplexing mechanisms [2]. To help simplify network programming, the `Reactor` combines the demultiplexing of synchronous I/O-based events together with timer-based events. When these events occur, the `Reactor` automatically dispatches the method(s) of previously registered objects to perform application-specified services.

This article is organized as follows: Section 2 describes the primary features offered by the `Reactor` framework; Section 3 outlines the object-oriented design and implementation of the framework; Section 4 presents a distributed logging example that demonstrates how the `Reactor` simplifies the development of concurrent, event-driven network applications; and Section 5 discusses concluding remarks.

2 Primary Features of the Reactor

The `Reactor` provides an object-oriented interface that simplifies the development of distributed applications that utilize I/O-based and/or timer-based demultiplexing mechanisms. The following paragraphs describe the primary features offered by the `Reactor` framework:

• **Export Uniform Object-Oriented Interfaces:** Applications using the `Reactor` do not access the lower-level I/O demultiplexing system calls directly. Instead, they inherit from a common `Event_Handler` abstract base class to form composite concrete derived classes (as illustrated in Figure 1). The `Event_Handler` base class specifies a uniform interface consisting of virtual methods that handle (1) synchronous input, output, and exceptions and (2) timer-based events. Applications create objects of these derived classes and register them with instances of the `Reactor`.

• **Automate Event Handler Dispatching:** When events occur, the `Reactor` automatically invokes the appropriate virtual method event handler(s) belonging to the pre-registered derived class objects. Since C++ *objects* are registered with the `Reactor` (as opposed to stand-alone *subroutines*), any context information associated with an object is retained between invocations of its methods. This is particularly useful for developing "stateful" services that retain information in between client invocations.

• **Support Transparent Extensibility:** The functionality of both the `Reactor` and its registered objects may be extended transparently *without* modifying or recompiling existing code. To accomplish this, the `Reactor` framework employs inheritance, dynamic binding, and parameterized types to decouple the lower-level event demultiplexing and service dispatching *mechanisms* from the higher-level application processing *policies*. Example low-level mechanisms include (1) detecting events on multiple I/O handles, (2) handling timer expiration, and (3) invoking the appropriate method event handler(s) in response to events. Likewise, application-specified policies include (1) connection establishment, (2) data transmission and reception, and (3) processing service requests from other participating hosts.

• **Increase Reuse:** The `Reactor`'s demultiplexing and dispatching mechanisms may be reused by many network applications. By *reusing* rather than *redeveloping* these mechanisms, developers are free to concentrate on higher-level application-related issues, rather than repeatedly wrestling with lower-level event demultiplexing details. In addition, subsequent bug-fixes and enhancements are transparently shared by all applications that utilize the `Reactor`'s components. Conversely, developers that access `select` and `poll` directly must reimplement the same demultiplexing and dispatching code for every network application. Moreover, any modifications and improvements to this code must be replicated manually in all related applications.

• **Enhance Type-Security:** The `Reactor` shields application developers from error-prone, low-level details associated with programming existing I/O demultiplexing system calls. These details involve setting and clearing bitmasks, handling timeouts and interrupts, and dispatching "call-back" methods. In particular, the `Reactor` eliminates several subtle causes of errors with `poll` and `select` that involve the misuse of I/O handles and `fd_set` bitmasks.

• **Improve Portability:** The `Reactor` also shields applications from differences between `select` and `poll` that impede portability. As illustrated in Figure 5, the `Reactor` exports the same interface to applications, regardless of the underlying event demultiplexing system calls. Moreover, the `Reactor`'s object-oriented architecture improves its own internal portability. For example, porting the `Reactor` from a `select`-based OS platform to a `poll`-based platform required only a few well-defined changes to the framework.

In addition to simplifying application development, the `Reactor` also performs its demultiplexing and dispatching tasks efficiently. In particular, its event dispatching logic improves upon common techniques that use `select` directly. For instance, the `select`-based `Reactor` uses an `ACE_Handle_Set` class (described in Section 3.2) that avoids examining `fd_set` bitmasks one bit at a time in many circumstances. An article in a future issue of the C++ Report will empirically evaluate the performance of the `Reactor` and compare it against a non-object-oriented solution written in C that accesses I/O demultiplexing system calls directly.

3 The Object-Oriented Design and Implementation of the Reactor

This section summarizes the object-oriented design of the `Reactor` framework's primary class components, focusing on the interfaces and strategic design decisions. Where appropriate, tactical design decisions and certain implementation details are also discussed. Section 3.1 outlines the OS platform-independent components; Section 3.2 covers the platform-dependent components.

The `Reactor` was originally modeled after a C++ wrapper for `select` called the `Dispatcher` that is available with the InterViews distribution [3]. The `Reactor` framework described here includes several additional features. For example, the `Reactor` operates transparently on top of both the System V Release 4 `poll` interface and `select`, which is available on both UNIX and PC platforms (via the WINSOCK API). In addition, the `Reactor` framework contains support for multi-threading. In general, a single instance of the `Reactor` is active in a thread at any point in time. However, there may be multiple different instances of `Reactor` objects running in separate threads in a process. The framework provides the necessary synchronization operations to prevent race conditions [4].

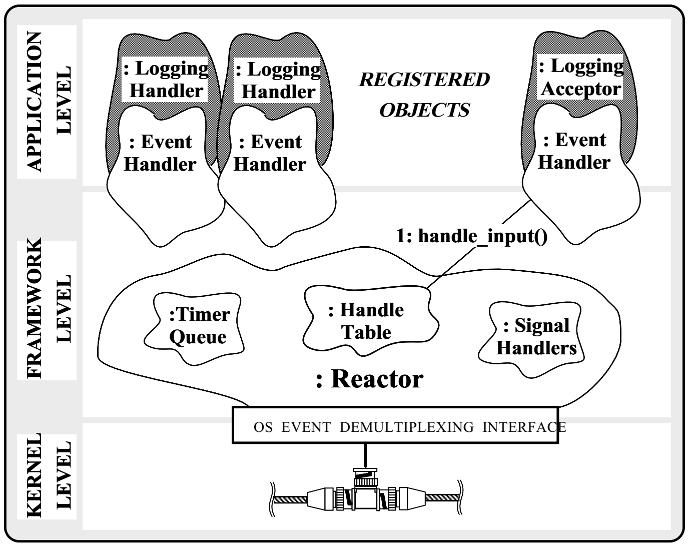


Figure 1: The Reactor Inheritance Hierarchy

3.1 Platform-Independent Class Components

The following paragraphs summarize the salient characteristics of the three platform-independent classes in the `Reactor`: the `ACE_Time_Value`, `ACE_Timer_Queue`, and `ACE_Event_Handler` classes:

• **ACE_Time_Value:** This class provides a C++ wrapper that encapsulates an underlying OS platform's date and time structure (such as the `struct timeval` data type on UNIX and POSIX platforms). The `timeval` structure contains two fields that represent time in terms of *seconds* and *microseconds*. However, other OS platforms use different representations, so the `ACE_Time_Value` class abstracts these details to provide a portable C++ interface.

The primary methods in the `ACE_Time_Value` class are illustrated in Figure 2. The `ACE_Time_Value` wrapper uses operator overloading to simplify time-based comparisons within the `Reactor`. Overloading permits the use of standard arithmetic syntax for relational expressions involving time comparisons. For example, the following code creates two `ACE_Time_Value` objects constructed by adding user-supplied command-line arguments to the current time, and then displaying the appropriate ordering relationship between the two objects:

```
int main (int argc, char *argv[])
{
  if (argc != 3) {
    cerr << "usage: " << argv[0]
         << " time1 time2" << endl;
    return 1;
  }

  ACE_Time_Value ct =
    ACE_OS::gettimeofday ();
  ACE_Time_Value tv1 = ct +
    ACE_Time_Value (ACE_OS::atoi (argv[1]));
  ACE_Time_Value tv2 = ct +
    ACE_Time_Value (ACE_OS::atoi (argv[2]));

  if (tv1 > tv2)
    cout << "timer 1 is greater" << endl;
  else if (tv2 > tv1)
    cout << "timer 2 is greater" << endl;
  else
    cout << "timers are equal" << endl;
  return 0;
}
```

Methods in the `ACE_Time_Value` class are implemented to compare "normalized" time quantities. Normalization adjusts the two fields in a `timeval` structure to use a canonical encoding scheme that ensures accurate comparisons. For example, after normalization, the quantity `ACE_Time_Value (1, 1000000)` will compare equal to `ACE_Time_Value (2)`. Note that a direct bitwise comparison of the non-normalized class fields would not detect this equality.

- **ACE_Timer_Queue:** The `Reactor`'s timer-based mechanisms are used useful for applications that require timer support. For example, WWW servers require watchdog timers to release resources if clients that connect do not send an HTTP request within a specific time interval. Likewise, certain daemon configuration frameworks (such as the `Service Control Manager` in Windows NT) require services under their control to periodically report their current status. These "heart-beat" messages are used to ensure that a service has not terminated abnormally.

The `ACE_Timer_Queue` class provides mechanisms that allow applications to register time-based objects that derive from the `ACE_Event_Handler` base class (described in the following bullet). The `ACE_Timer_Queue` ensures that the `handle_timeout` method in these objects is invoked at an application-specified time in the future. The methods of the `ACE_Timer_Queue` class illustrated in Figure 3 enable applications to schedule, cancel, and invoke the timer objects.

An application schedules an `ACE_Event_Handler` that will expire after `delay` amount of time. If it expires then `arg` is passed in as the value to the event handler's `handle_timeout` callback method. If `interval` does not equal `ACE_Time_Value::zero` it is used to reschedule the event handler automatically. The `schedule` method returns a handle to a timer that uniquely identifies this event handler in the timer queue's internal table. The timer handle can be used by `cancel` to remove an `ACE_Event_Handler` before it expires. If a non-NULL `arg` is passed to `cancel` it is set to the *Asynchronous Completion Token* (ACT) [5] passed in by the application when the timer was originally scheduled. This makes it possible to free up dynamically allocated ACTs to avoid memory leaks.

By default, the `ACE_Timer_Queue` is implemented as a linked list of tuples containing `ACE_Time_Value`,

```
// Time value structure from /usr/include/sys/time.h
// struct timeval { long secs; long usecs; };

class ACE_Time_Value
{
public:
  ACE_Time_Value (long sec = 0, long usec = 0);
  ACE_Time_Value (timeval t);

    // Returns sum of two ACE_Time_Values.
  friend ACE_Time_Value operator +
    (const ACE_Time_Value &lhs,
     const ACE_Time_Value &rhs);
    // Returns difference between two ACE_Time_Values.
  friend ACE_Time_Value operator -
    (const ACE_Time_Value &lhs,
     const ACE_Time_Value &rhs);

    // Relational and comparison operators for
    // normalized ACE_Time_Values.
  friend int operator <
    (const ACE_Time_Value &lhs,
     const ACE_Time_Value &rhs);
    // Other relation operators...
private:
  // ...
};
```

Figure 2: Interface for the ACE_Time_Value Class

```
class ACE_Timer_Queue
{
public:
  ACE_Timer_Queue (void);

    // True if queue is empty, else false.
  int is_empty (void) const;

    // Returns earliest time in queue.
  const ACE_Time_Value &earliest_time (void) const;

    // Schedule a HANDLER to be dispatched at
    // the FUTURE_TIME.
    // and at subsequent INTERVALs.
  int virtual schedule
    (ACE_Event_Handler *handler,
     const void *arg,
     const ACE_Time_Value &future_time,
     const ACE_Time_Value &interval);

    // Cancel all registered ACE_Event_Handlers
    // that match the address of HANDLER.
  int virtual cancel
    (ACE_Event_Handler *handler);

    // Cancel the single ACE_Event_Handler matching the
    // TIMER_ID value (returned from schedule()).
  int virtual cancel (int timer_id,
                      const void **arg = 0);

    // Expire all timers <= EXPIRE_TIME
    // (note, this routine must be called manually
    //  since  it is not invoked asychronously).
  void virtual expire
    (const ACE_Time_Value &expire_time);
private:
  // ...
};
```

Figure 3: Interface for the ACE_Timer_Queue Class

ACE_Event_Handler *, and void * members. These tuples are sorted by the ACE_Time_Value field in ascending order of their "time-to-execute." The ACE_Event_Handler * field is a pointer to the timer object scheduled to be run at the time specified by the ACE_Time_Value field. The void * field is an argument supplied when a timer object is originally scheduled. When a timer expires, this argument is automatically passed to the handle_timeout method (described in the following bullet).

Each ACE_Time_Value in the linked list is stored in "absolute" time units (such as those generated by the UNIX gettimeofday system call). However, since virtual methods are used in the class interface, applications can redefine the ACE_Timer_Queue implementation to use alternative data structures such as *delta-lists* [6] or *heaps* [7]. Delta-lists store time in "relative" units represented as offsets or "deltas" from the earliest ACE_Time_Value at the front of the list. Heaps, on the other hand, use a "partially-ordered, almost-complete binary tree" instead of a sorted list to reduce the average- and worst-case time complexity for inserting or deleting an entry from $O(n)$ to $O(\lg n)$. A heap representation may be more efficient for certain real-time application usage patterns [7].

• **ACE_Event_Handler:** This abstract base class specifies an extensible interface used by portions of the Reactor class that control and coordinate the automatic dispatching of I/O and timer mechanisms. The virtual methods in the ACE_Event_Handler interface are illustrated in Figure 4. The Reactor uses application-defined subclasses of the ACE_Event_Handler base class to implement its automated, event-driven call-back mechanisms. These subclasses may redefine certain virtual methods in the ACE_Event_Handler base class to perform application-defined processing in response to various types of events. These events include (1) different types (*e.g.,* "reading," "writing," and "exceptions") of synchronous I/O on one or more handles and (2) timer expiration.

An object of a subclass derived from ACE_Event_Handler typically supplies an I/O handle.[1] For example, the following Logging_Acceptor class fragment encapsulates a "passive-mode" ACE_SOCK_Acceptor factory provided by the SOCK_SAP socket wrappers [8].

```
class Logging_Acceptor :
  public ACE_Event_Handler
{
public:
  Logging_Acceptor (ACE_INET_Addr &addr)
    : acceptor_ (addr) { /* ... */ }

    // Double-dispatching hook.
  virtual ACE_HANDLE get_handle (void) const {
    return this->acceptor_.get_handle ();
  }

    // Factory that creates and activates
    // a Logging_Handler.
  virtual int handle_input (ACE_HANDLE) {
    ACE_SOCK_Stream peer_handler;

    this->acceptor_.accept (peer_handler);
    // Create and activate a Logging_Handler...
  }
  // ...

private:
    // Passive-mode socket acceptor.
  ACE_SOCK_Acceptor acceptor_;
};

int main (int argc, char *argv[])
{
  // Event demultiplexer.
  ACE_Reactor reactor;

  Logging_Acceptor acceptor
    ((ACE_INET_Addr) PORT_NUM);

  reactor.register_handler
    (&acceptor, ACE_Event_Handler::READ_MASK);

  // Loop ‘‘forever’’ accepting connections and
  // and handling logging records.
  for (;;)
    reactor.handle_events ();
  /* NOTREACHED */
}
```

Internally, the Reactor::register_handler method retrieves the underlying I/O handle by invoking the acceptor object's get_handle virtual method. When

```
typedef u_long Reactor_Mask;
typedef int ACE_HANDLE;

class ACE_Event_Handler
{
public:
    // It is possible to bitwise "or" these values
    // together to instruct the Reactor to check for
    // multiple I/O activities on a single handle.
  enum {
    READ_MASK = 01,
    WRITE_MASK  = 02,
    EXCEPT_MASK = 04,
    RWE_MASK = READ_MASK | WRITE_MASK | EXCEPT_MASK
  };

    // Returns the I/O handle associated with the
    // derived object (must be supplied by a subclass).
  virtual ACE_HANDLE get_handle (void) const = 0;

    // Called when object is removed from the Reactor.
  virtual int handle_close (ACE_HANDLE, Reactor_Mask);
    // Called when input becomes available.
  virtual int handle_input (ACE_HANDLE);
    // Called when output is possible.
  virtual int handle_output (ACE_HANDLE);
    // Called when urgent data is available.
  virtual int handle_except (ACE_HANDLE);

    // Called when timer expires (TV stores the
    // current time and ARG is the argument given
    // when the handler was originally scheduled).
  virtual int handle_timeout (const ACE_Time_Value &tv,
                              const void *arg = 0);

    // Called when signal is triggered by OS.
  virtual int handle_signal (int signum);
};
```

Figure 4: Interface for the ACE_Event_Handler Class

[1]I/O handles may be omitted in derived class objects that are purely timer-based.

the `Reactor::handle_events` method is invoked, handles of all registered objects are aggregated and passed to `select` (or `poll`). This OS-level event demultiplexing call detects the occurrence of I/O-based events on these handles. When input events occur or output events become possible, the I/O handles become "active." At this time, the `Reactor` notifies the appropriate derived objects by invoking the method(s) that handle the event(s).[2] For instance, in the example above, when a connection request arrives the `Reactor` calls the `handle_input` method of the `ACE_Acceptor` class. This method accepts the new connection and creates a `Logging_Handler` (not shown) that reads all data sent by the client and displays it on the standard output stream.

The `ACE_Timer_Queue` class described above handles time-based events. When a timer managed by this queue expires, the `handle_timeout` method of a previously scheduled `ACE_Event_Handler` derived object is invoked. This method is passed the current time, as well as the `void *` argument passed in when the derived object was originally scheduled.

When any method in an `ACE_Event_Handler` object returns -1, the `Reactor` automatically invokes that object's `handle_close` method. The `handle_close` method may be used to perform any user-defined termination activities (such as deleting dynamic memory allocated by the object, closing log files, etc.). Upon return of this call-back function, the `Reactor` removes the associated derived class object from its internal tables.

3.2 Platform-Dependent Class Components

The `ACE_Reactor` class provides the central interface for the `Reactor` framework. On UNIX platforms, this class is the only part of the framework that contains platform-dependent code (the private representation of the `ACE_Time_Value` class may differ on non-UNIX platforms, as well).

• **ACE_Reactor:** Figure 6 illustrates the primary methods in the `Reactor` class interface, which encapsulates and extends the functionality of `select` and `poll`. These methods may be grouped into the following general categories:

- *Manager methods* – The constructor and `open` methods create and initialize objects of the `ACE_Reactor` by dynamically allocating various data structures (described in Section 3.2.1 and 3.2.2 below). The destructor and `close` methods deallocate these data structures.
- *I/O-based event handler methods* – Objects that are derived from subclasses of the `ACE_Event_Handler` class may be instantiated and registered with an instance of the `Reactor` via the `register_handle` method. Event handlers may also be removed via the `remove_handler` method.
- *Timer-based event handler methods* –

  `ACE_Time_Value` arguments that are passed to the `ACE_Reactor`'s `schedule_timer` method are specified "relative" to the current time. For example, the following code schedules an object to print "hello world" every `interval` number of seconds, starting `delay` seconds into the future:

```
class Hello_World : public ACE_Event_Handler
{
public:
  virtual int handle_timeout (
      const ACE_Time_Value &tv,
      const void *arg) {
    ACE_DEBUG ((LM_DEBUG, "hello world\n"));
    return 0;
  }
  // ...
};

int main (int argc, char *argv[])
{
  if (argc != 3)
    ACE_ERROR_RETURN ((LM_ERROR,
                      "usage: %s delay interval\n",
                      argv[0]), -1);
  Reactor reactor;

  Hello_World handler; // timer object.

  ACE_Time_Value delay = ACE_OS::atoi (argv[1]);
  ACE_Time_Value interval = ACE_OS::atoi (argv[2]);

  reactor.schedule_timer (&handler, 0,
                          delay, interval);

  for (;;)
    reactor.handle_events ();
  /* NOTREACHED */
}
```

  However, the default implementation of the underlying `ACE_Timer_Queue` stores the values in "absolute" time units. That is, it adds the scheduled time to the current time of day.

  Since the interface of the `ACE_Reactor` class consists of `virtual` methods it is straight-forward to extend the `ACE_Reactor`'s default functionality via inheritance. For example, modifying the `ACE_Timer_Queue` implementation to use one of the alternative representations described in Section 3.1 requires no visible changes to the `ACE_Reactor`'s `public` or `private` interface.

- *Event-loop methods* –

  After registering I/O-based and/or timer-based objects, an application enters an event-loop that calls either of the two `Reactor::handle_events` methods continuously. These methods block for an application-specified time interval awaiting the occurrence of (1) synchronous I/O events on one or more handles and (2) timer-based events. As events occur, the `ACE_Reactor` dispatches the appropriate method(s) of objects that the application registered to handle these events.

[2] Note that the activated I/O handle is passed as an argument to the `handle_input` call-back function (though it is ignored in this case since the `acceptor` class instance variable keeps encapsulates the underlying handle).

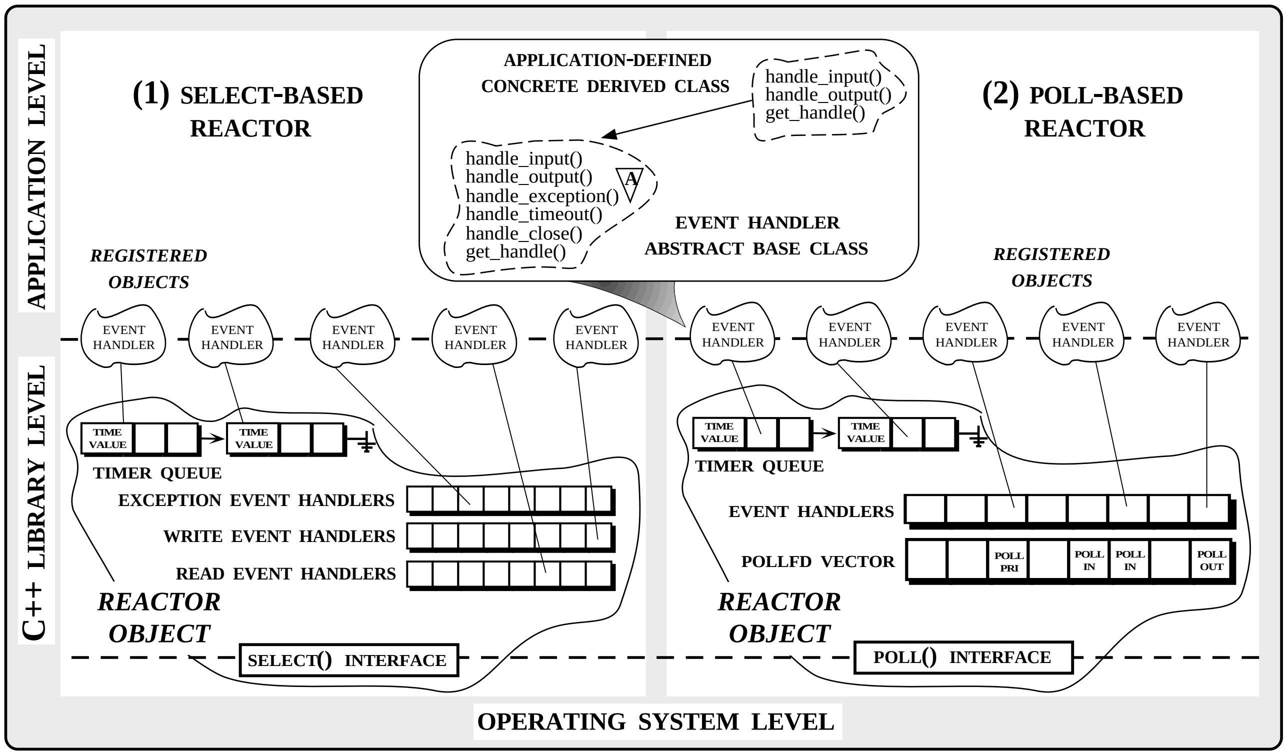


Figure 5: The Reactor's External Interfaces and Internal Data Structures

The following paragraphs describe the primary differences between the `poll`-based and `select`-based versions of the `ACE_Reactor`. Although the implementations of certain methods in the `ACE_Reactor` class differ across OS platforms, the method names and overall functionality remain the same. This uniformity stems from the modularity of the `ACE_Reactor`'s design and implementation, which enhances its reuse, portability, and maintainability.

3.2.1 Class Components for the select-based Reactor

As shown in Figure 5 (1), the `select`-based implementation of the `ACE_Reactor` contains three dynamically allocated `ACE_Event_Handler *` arrays. These arrays store pointers to the registered `ACE_Event_Handler` objects that process the reading, writing, exception, and/or timer-based events. The `ACE_Handle_Set` class provides an efficient C++ wrapper for the underlying `fd_set` bitmask data type. An `fd_set` maps the I/O handle name-space onto a compact bit-vector representation and provides several operations for enabling, disabling, and testing bits corresponding to I/O handles. One or more `fd_sets` is passed to the `select` call. The `ACE_Handle_Set` class optimizes several common `fd_set` operations by (1) using "full-word" comparisons to minimize unnecessary bit manipulations and (2) caching certain values to avoid recalculating bit-offsets on each call.

3.2.2 Class Components for the poll-based Reactor

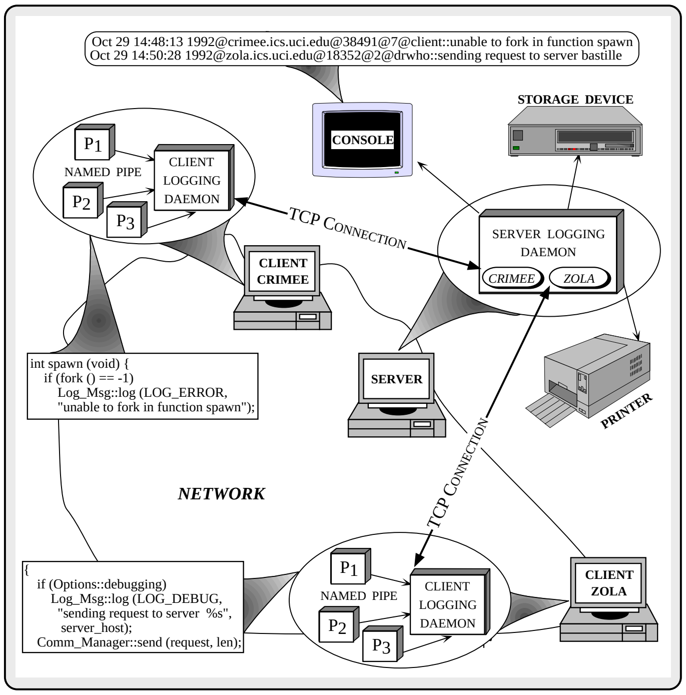
The `poll` interface is more general than `select`, allowing applications to wait for a wider-range of events (such as "priority-band" I/O events). Therefore, the `poll`-based `Reactor` implementation shown in Figure 5 (2) is somewhat smaller and less complicated than the `select`-based version. For example, the `poll`-based `ACE_Reactor` requires neither the three `ACE_Event_Handler *` arrays nor the `ACE_Handle_Set` class. Instead, a single array of `ACE_Event_Handler` pointers and an array of `pollfd` structures are dynamically allocated and used internally to store the registered `ACE_Event_Handler` derived class objects.

4 Using and Evaluating the Reactor

The `Reactor` framework is intended to simplify the development of distributed applications, particularly network servers. To illustrate a typical usage of the `Reactor`, the following section examines the design and implementation of the distributed logging application presented in [1]. This section describes the primary C++ class components in the logging application, compares the object-oriented `Reactor`-based solution with an earlier version written in C, and discusses the influence of C++ on both the `Reactor` framework and the distributed logging facility.

```
class Reactor
{
public:
  // = Initialization and termination methods.

  enum { DEFAULT_SIZE = FD_SETSIZE };

    // Initialize a Reactor instance that may
    // contain SIZE entries (RESTART indicates
    // to restart system calls after interrupts).
  Reactor (int size, int restart = 0);

  virtual int open (int size = DEFAULT_SIZE,
                    int restart = 0);

    // Default constructor.
  Reactor (void);

    // Perform cleanup activities to close down
    // an instance of a REACTOR.
  void close (void);

  // = I/O-based event handler methods

    // Register an ACE_Event_Handler object according
    // to the Reactor_Mask(s) (i.e., "reading,"
    // "writing," and/or "exceptions").
  virtual int register_handler (ACE_Event_Handler *,
                                Reactor_Mask);

    // Remove the handler associated with the
    // appropriate Reactor_Mask(s).
  virtual int remove_handler (ACE_Event_Handler *,
                              Reactor_Mask);

  // = Timer-based event handler methods

    // Register a handler to expire at time DELTA.
    // When DELTA expires the handle_timeout()
    // method will be called with the current time
    // and ARG as parameters.  If INTERVAL is > 0
    // then the handler is reinvoked periodically
    // at that INTERVAL.  DELTA is interpreted
    // "relative" to the current time of day.
  virtual void schedule_timer (
       ACE_Event_Handler *,
       const void *arg,
       const ACE_Time_Value &delta,
       const ACE_Time_Value &interval =
         ACE_Timer_Queue::zero);

    // Locate and cancel timer.
  virtual void cancel_timer (ACE_Event_Handler *);

  // = Event-loop methods

    // Block process until I/O events occur or timer
    // expires, then dispatch activated handler(s).
  virtual int handle_events (void);

    // Perform a timed event-loop that waits up to TV
    // time units for events to occur; if no events
    // occur then 0 is returned, otherwise return
    // TV - (actual_time_waited).
  virtual int handle_events (ACE_Time_Value &tv);

private:
  // ...
};
```

Figure 6: Interface for the Reactor Class



```
Oct 29 14:48:13 1992@crimee.ics.uci.edu@38491@7@client::unable to fork in function spawn
Oct 29 14:50:28 1992@zola.ics.uci.edu@18352@2@drwho::sending request to server bastille
```

```
int spawn (void) {
   if (fork () == -1)
      Log_Msg::log (LOG_ERROR,
      "unable to fork in function spawn");
```

```
{
   if (Options::debugging)
      Log_Msg::log (LOG_DEBUG,
        "sending request to server  %s",
         server_host);
   Comm_Manager::send (request, len);
```

Figure 7: Run-time Activities in the Distributed Logging Facility

4.1 Distributed Logging Facility Overview

The distributed logging facility presented below was originally designed for a commercial on-line transaction processing product. The logger facility uses a client/server architecture to provide logging services for workstations and symmetric multi-processors linked across local area and/or wide area networks. The logging facility combines the event demultiplexing and dispatching features of the `Reactor` together with the object-oriented interface to BSD sockets and the System V Transport Layer Interface (TLI) provided by the `IPC_SAP` wrapper library (described in [8]). Logging provides an "append-only" storage service that records diagnostic information sent from one or more applications. The primary unit of logging is the *record*. Incoming records are appended to the end of a log and all other types of write access are forbidden.

The distributed logging facility is comprised of the following three main components depicted in Figure 7:

• **Application Logging Interface:** Application processes (*e.g.*, P_1, P_2, P_3) running on client hosts use the `Log_Msg` C++ class to generate various types of logging records (such as LOG_ERROR and LOG_DEBUG). The `Log_Msg::log` method provides a `printf`-style interface. Figure 8 describes the priority levels and data format for records exchanged by the application interface and the logging daemons. When invoked by an application, the logging interface formats and timestamps these records and writes them to a well-known named pipe (also called a FIFO), where they are consumed by a *client logging daemon*.

• **Client Logging Daemon:** The client logging daemon is a single-threaded, iterative daemon that runs on every host machine participating in the distributed logging service. Each client logging daemon is connected to the read-side of the named pipe used to receive logging records from applications on this machine. Named pipes are used since they are an efficient form of localhost-only IPC. In addition, the semantics of named pipes in System V Release 4 UNIX have been expanded to allow "priority-band" messages that may be received in "order-of-importance," as well as in "order-of-arrival" (which is still the default behavior) [9].

The complete design of the client logging daemon and the application logging interface will appear in a subsequent C++ Report article that presents C++ wrappers for several "local-host" IPC mechanisms (such as System V Release 4 FIFOs, STREAM pipes, message queues, and UNIX-domain stream sockets). In general, a client logging daemon continuously receives the logging records in priority order from applications, converts the multi-byte record header fields into network-byte order, and forwards the records to the *server logging daemon* (which typically runs on a remote host).

• **Server Logging Daemon:** The server logging daemon is a concurrent daemon that continuously collects, reformats, and displays the incoming logging records to various external devices. These devices may include printers, persistent storage repositories, or logging management consoles. The remainder of this article focuses on the server logging daemon. In addition, several `Reactor` and `IPC_SAP` mechanisms are also illustrated and described throughout this example.

4.2 The Server Logging Daemon

The following section discusses the interface and implementation of the primary classes used to construct the server logging daemon. The logging server is a single-threaded, concurrent daemon that runs in a single process. Concurrency is provided by having the `Reactor` "time-slice" its attention to each active client in a round-robin fashion. In particular, during every invocation of the `Reactor::handle_events` method, a single logging record is read from each client whose I/O handle became active during this iteration. These logging records are written to the standard output of the server logging daemon. This output may be redirected to various devices such as printers, persistent storage repositories, or logging management consoles.

In addition to the main driver program shown below in Section 4.2.3, several other C++ class components appear in the logging facility architecture. The class inheritance and parameterization relationships between the various components are illustrated in Figure 9 using Booch notation [10]. To enhance reuse and extensibility, the component shown in this figure are designed to decouple the following aspects of the application architecture:

```
// The following data type indicates the relative
// priorities of the logging messages, from lowest
// to highest priority...

enum Log_Priority
{
    // Shutdown the logger.
  LM_SHUTDOWN = 1,
    // Messages indicating function-calling sequence
  LM_TRACE = 2,
    // Messages that contain information normally
    // use only when debugging a program
  LM_DEBUG = 3,
    // Informational messages
  LM_INFO = 4,
    // Conditions that are not error condition
    // but that may require special handling.
  LM_NOTICE = 5,
    // Warning messages
  LM_WARNING = 6,
    // Initialize the logger
  LM_STARTUP = 7,
    // Error messages
  LM_ERROR = 8,
    // Critical conditions, e.g., hard device errors
  LM_CRITICAL = 9,
    // A condition that should be corrected immediatey,
    // such as a corrupted system database.
  LM_ALERT = 10,
    // A panic condition (broadcast to all users)
  LM_EMERGENCY = 11,
    // Maximum logging priority + 1
  LM_MAX = 12
};

struct Log_Record
{
  enum {
    // Maximum number of bytes in logging record
    MAXLOGMSGLEN = 1024
  };

    // Type of logging record
  Log_Priority type_;
    // length of the logging record
  long length_;
    // Time logging record generated
  long time_stamp_;
    // Id of process that generated the record
  long pid_;
    // Logging record data
  char rec_data_[MAXLOGMSGLEN];
};
```

Figure 8: Logging Record Format

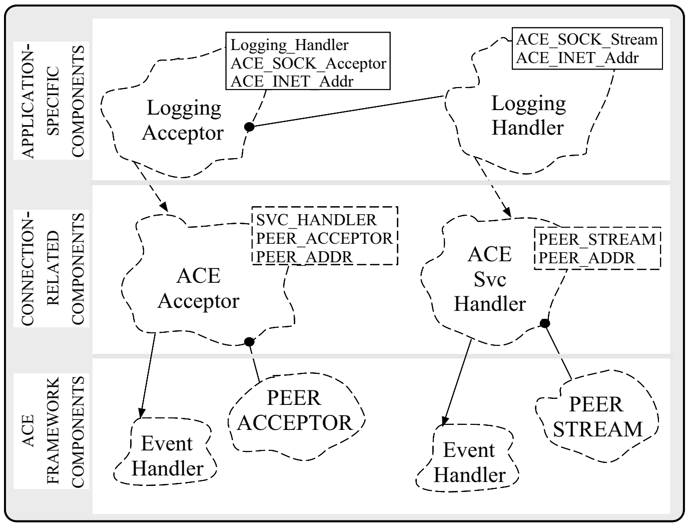


Figure 9: Class Components in the Server Logging Daemon

- `Reactor` *framework components* – The components in the `Reactor` framework discussed in Section 3 encapsulate the lowest-level mechanisms for performing the I/O demultiplexing and event handler dispatching.
- *Connection-related mechanisms* – The components discussed in Section 4.2.1 represent a set of generic templates that provide reusable connection-related mechanisms. In particular, the `ACE_Acceptor` template class is a general-purpose class designed to accept network connections with remote clients. Likewise, the `ACE_Svc_Handler` template class is another general-purpose class designed to send and/or receive data to/from connected clients.
- *Application-specific services* – The components discussed in Section 4.2.2 represent the application-specific portion of the distributed logging facility. In particular, the `Logging_Acceptor` class supplies specific parameterized types to the `ACE_Acceptor`, which creates a connection handling instantiation that is specific for the logging application. Likewise, the `Logging_Handler` class is instantiated to provide the application-specific functionality necessary to receive and process logging records from remote clients.

In general, by adopting this highly-decoupled object-oriented decomposition, the development and maintenance of the server logging daemon was simplified significantly, compared with the original approach.

4.2.1 Connection-related Mechanisms

• **The ACE_Acceptor Class:** This parameterized type provides a generic template for a family of classes that standardize and automate the steps necessary to accept network connection requests from clients. Figure 10 illustrates the interface for the `ACE_Acceptor` class.[3] This class inherits from `ACE_Event_Handler`, which enables it to interact with the `Reactor` framework. In addition, this template class is parameterized by a composite `PEER_HANDLER` subclass (which must understand how to perform I/O with clients), a `PEER_ACCEPTOR` class (which must understand how to accept client connections), and `PEER_ADDR` (which is a C++ wrapper for the appropriate address family).

```
// A template class for handling connection requests from
// a remote client.

template <class SVC_HANDLER,
          class PEER_ACCEPTOR,
          class PEER_ADDR>
class ACE_Acceptor : public ACE_Event_Handler
{
public:
  ACE_Acceptor (ACE_Reactor *r,
                const PEER_ADDR &a);
  ~ACE_Acceptor (void);

private:
  virtual ACE_HANDLE get_handle (void) const;
  virtual int handle_input (ACE_HANDLE);
  virtual int handle_close (ACE_HANDLE,
                            Reactor_Mask);

    // Accept connections.
  PEER_ACCEPTOR acceptor_;

    // Performs event demuxing.
  ACE_Reactor *reactor_;
};
```

Figure 10: Class Interface for Accepting Connections

Classes instantiated from the `ACE_Acceptor` template are capable of the following behavior:

1. Accepting connection requests sent from remote clients;
2. Dynamically allocating an object of the `PEER_HANDLER` subclass;
3. Registering this object with an instance of the `Reactor`. In turn, the `PEER_HANDLER` class must know how to process data exchanged with the client.

Figure 11 depicts the `ACE_Acceptor` class implementation. When one or more connection requests arrive, the `handle_input` method is automatically dispatched by the `Reactor`. This method behaves as follows. First, it dynamically creates a separate `PEER_HANDLER` object, which is responsible for processing the logging records received from each new client. Next, it accepts an incoming connection into that object. Finally, it calls the `open` hook. This hook can register the newly created `PEER_HANDLER` object with an instance of the `Reactor` or can spawn off a separate thread of control, etc.

• **The ACE_Svc_Handler Class:** This parameterized type provides a generic template for processing data sent from clients. In the distributed logging facility, for example, the

[3] This is a simplified version of the `ACE_Acceptor`. For a complete implementation see [11].

```
// Shorthand names
#define SH SVC_HANDLER
#define PL PEER_ACCEPTOR
#define PA PEER_ADDR

template <class SH, class PL, class PA>
ACE_Acceptor<SH, PL, PA>::ACE_Acceptor
  (ACE_Reactor *r, const PA &addr)
  : reactor_ (r),
    acceptor_ (addr)
{
}

template <class SH, class PL, class PA> ACE_HANDLE
ACE_Acceptor<SH, PL, PA>::get_handle (void) const
{
  return this->acceptor_.get_handle ();
}

template <class SH, class PL, class PA> int
ACE_Acceptor<SH, PL, PA>::handle_close
  (ACE_HANDLE, Reactor_Mask)
{
  return this->acceptor_.close ();
}

template <class SH, class PL, class PA>
ACE_Acceptor<SH, PL, PA>::~ACE_Acceptor (void)
{
  this->handle_close ();
}

// Generic factory for accepting connections from
// client hosts, creating and activating a
// service handler.

template <class SH, class PL, class PA> int
ACE_Acceptor<SH, PL, PA>::handle_input
  (ACE_HANDLE)
{
  // Create a new Svc_Handler.
  SH *svc_handler = new SH (this->reactor_);

  // Accept connection into the handler.
  this->acceptor_.accept (*svc_handler);

  // Activate the handler.
  svc_handler->open (0);
}
```

Figure 11: Class Implementation for Accepting Connections

```
// Receive client message from the remote clients.

template <class PEER_STREAM, class PA>
class ACE_Svc_Handler : public ACE_Event_Handler
{
public:
  ACE_Svc_Handler (ACE_Reactor *r)
    : reactor_ (r) {}

    // Must be filled in by subclass
  virtual int open (void *) = 0;

  operator PEER_STREAM &();

   // Demultiplexing hooks.
  virtual ACE_HANDLE get_handle (void) const;

protected:
    // Connection open to the client.
  PEER_STREAM peer_stream_;

    // Performs event demuxing.
  ACE_Reactor *reactor_;
};
```

Figure 12: Class Interface for Handling Services

```
#define PS PEER_STREAM

// Extract the underlying PS (e.g., for
// use by accept()).

template <class PS, class PA>
ACE_Svc_Handler<PS, PA>::operator PS &()
{
  return this->peer_stream_;
}

template <class PS, class PA>  ACE_HANDLE
ACE_Svc_Handler<PS, PA>::get_handle (void) const
{
  return this->peer_stream_.get_handle ();
}
```

Figure 13: Class Implementation for Service Handling

I/O format involves logging records. However, different formats are easily substituted for other applications. Typically, objects of classes instantiated from `ACE_Svc_Handler` are dynamically created and registered with the `Reactor` by the `handle_input` routine in the `ACE_Acceptor` class. The interface of the `ACE_Svc_Handler` class is depicted in Figure 12. As with the `ACE_Acceptor` class, this class inherits functionality from the `ACE_Event_Handler` base class.

Figure 13 illustrates the `ACE_Svc_Handler` class implementation. The class constructor caches the host address of the associated client when an object of this class is dynamically allocated. As illustrated by the "console" window in Figure 7, the name of this host is printed along with the logging records received from a client logging daemon.

The `ACE_Svc_Handler::handle_input` method simply invokes the pure virtual method `recv`. This `recv` function must be supplied by subclasses of `ACE_Svc_Handler`; it is responsible for performing application-specific I/O behavior. Note how the combination of inheritance, dynamic binding, and parameterized types further decouples the general-purpose portions of the framework (such as connection establishment) from the application-specific functionality (such as receiving logging records).

When the `ACE_Reactor` removes a `ACE_Svc_Handler` object from its internal tables, the object's `handle_close` method is called automatically. By default, this method deallocates the object's memory (which was originally allocated by the `handle_input` method in the `ACE_Acceptor` class). Objects are typically removed when a client logging daemon shuts down or when a serious transmission error occurs. To insure that `ACE_Svc_Handler` objects are only allocated and deallocated dynamically, the destructor is declared in the private section of the class (shown at the bottom of Figure 12).

4.2.2 Application-Specific Services

• **The Logging_Acceptor Class:** To implement the distributed logging application the `Logging_Acceptor` class is instantiated from the generic `ACE_Acceptor` template as follows:

```
typedef ACE_Acceptor
  <Logging_Handler,
   ACE_SOCK_Acceptor,
   ACE_INET_Addr> Logging_Acceptor;
```

The PEER_HANDLER parameter is instantiated with the Logging_Handler class (described in the following bullet below), PEER_ACCEPTOR is replaced by the ACE_SOCK_Acceptor class, and PEER_ADDR is the ACE_INET_Addr class.

The ACE_SOCK_* and ACE_INET_Addr instantiated types are part of a C++ wrapper called SOCK_SAP [8]. SOCK_SAP encapsulates the BSD socket interface for transferring data reliably between two processes that may run on different host machines. However, these classes could also be any other network interface that conformed to the interface used in the parameterized class (such as the TLI_SAP wrapper for the System V Transport Layer Interface (TLI)). For example, depending on certain properties of the underlying OS platform (such as whether it is a BSD or System V variant of UNIX), the logging application may instantiate the ACE_Svc_Handler class to use either SOCK_SAP or TLI_SAP as follows:

```
// Logging application.

#if defined (MT_SAFE_SOCKETS)
typedef ACE_SOCK_Stream PEER_STREAM;
#else
typedef ACE_TLI_Stream PEER_STREAM;
#endif // MT_SAFE_SOCKETS.

class Logging_Handler
  : public ACE_Svc_Handler<PEER_STREAM,
                           ACE_INET_Addr>
{
  // ...
};
```

The degree of flexibility offered by this template-based approach is extremely useful when developing applications that must run portability across multiple OS platforms. In fact, the ability to parameterize applications by transport interface is useful across variants of OS platforms (*e.g.,* SunOS 5.2 does not provide a thread-safe socket implementation).

• **The Logging_Handler Class:** This class is created by instantiating the ACE_Svc_Handler class as follows:

```
class Logging_Handler :
  public ACE_Svc_Handler<ACE_SOCK_Stream,
                         ACE_INET_Addr>
{
public:
    // Open hook.
  virtual int open (void) {
    // Register ourselves with the Reactor so
    // we can be dispatched automatically when
    // I/O arrives from clients.
    reactor_.register_handler
      (this, ACE_Event_Handler::READ_MASK);
  }

    // Demultiplexing hook.
  virtual int handle_input (ACE_HANDLE);
};
```

The PEER_STREAM parameter is replaced with the ACE_SOCK_Stream class and the PEER_ADDR parameter is replaced with the ACE_INET_Addr class. The handle_input method is called automatically by the ACE_Reactor when input arrives on the underlying ACE_SOCK_Stream. It is implemented as follows:[4]

```
// Callback routine for handling the reception of
// remote logging transmissions from clients.

int
Logging_Handler::handle_input (ACE_HANDLE)
{
  size_t len;

  ssize_t n = this->peer_stream_.recv
    (&len, sizeof len);
  if (n == sizeof len) {
    Log_Record lr;

    len = ntohl (len);
    n = this->peer_stream_.recv_n (&lr, len));

    if (n != len)
      ACE_ERROR_RETURN ((LM_ERROR, "%p at host %s\n",
        "client logger", this->host_name), -1);

    lr.decode ();

    if (lr.len == n)
      lr.print (this->host_name, 0, stderr);
    else
      ACE_ERROR_RETURN ((LM_DEBUG,
                        "error, lr.len = %d, n = %d\n",
                        lr.len, n), -1);
    return 0;
  }
  else
    return n;
}
```

Note how this example perform two recvs to simulate a message-oriented service via the underlying TCP connection (recall that TCP provides bytestream-oriented, rather than record-oriented, service). The first recv reads the length (stored as a fixed-size integer) of the following logging record. The second recv then reads "length" bytes to obtain the actual record. Naturally, the client sending this message must also follow this message framing protocol.

4.2.3 The Main Driver Program

The following event-loop drives the Reactor-based logging server:

```
int
main (int argc, char *argv[])
{
  // Event demultiplexer.
  ACE_Reactor reactor;

  const char *program_name = argv[0];
  ACE_LOG_MSG->open (program_name);

  if (argc != 2)
    ACE_ERROR_RETURN ((LM_ERROR,
                      "usage: %n port-number"), -1);

  u_short server_port = ACE_OS::atoi (argv[1]);
```

[4]Note that this implementation is not entirely robust in its handling of "short reads."

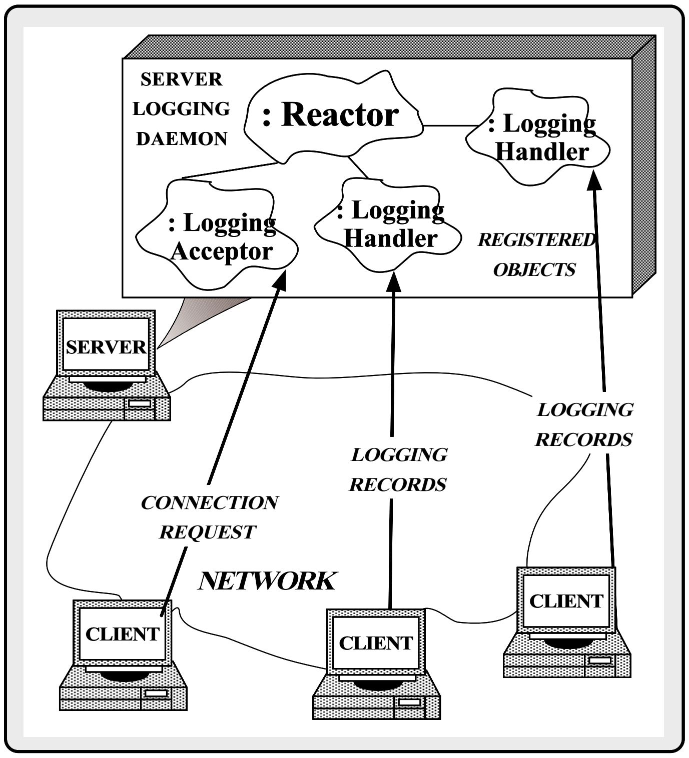


Figure 14: Run-time Configuration of the Server Logging Daemon

```
  Logging_Acceptor acceptor
    (&reactor, (ACE_INET_Addr) server_port);

  reactor.register_handler (&acceptor);

  // Loop forever, handling client requests.

  for (;;)
    reactor.handle_events ();

  /* NOTREACHED */
  return 0;
}
```

The main program starts by opening a logging channel that directs any logging records generated by the server to its own standard error stream. The example code in Figures 11 and 13 illustrates how the server uses the application logging interface to log its own diagnostic messages locally. Note that since this arrangement does *not* recursively use the server logging daemon there is no danger causing of an "infinite-logging-loop."

The server then opens an instance of the `Reactor`, instantiates a `Logging_Acceptor` object, and registers this object with the `Reactor`. Next, the server enters an endless loop that blocks in the `handle_events` method until events are received from client logging daemons. Figure 14 illustrates the state of the logging server daemon after two clients have contacted the `Reactor` and become participants in the distributed logging service. As shown in the figure, a `Logging_Handler` object has been dynamically instantiated and registered for each client. As incoming events arrive, the `Reactor` handles them by automatically dispatching (1) the `handle_input` method of the `Logging_Acceptor` and `Logging_Handler` class. When connection requests arrive from client logging daemons, the `Logging_Acceptor::handle_input` function is invoked. Likewise, when logging records or shutdown messages arrive from previously connected client logging daemons, the `Logging_Handler::handle_input` function is invoked.

Figure 7 portrays the entire system during execution. Logging records are generated from the application logging interface, forwarded to client logging daemons, transmitted across the network to the server logging daemon, and finally displayed on the server logging console. The logging information that is displayed indicates (1) the time the logging record was generated by the application interface, (2) the host machine the application was running on, (3) the process identifier of the application, (4) the priority level of the logging record, (5) the command-line name (*i.e.*, "`argv[0]`") of the application, and (6) an arbitrary text string that contains the text of the logging message.

4.3 Evaluating Alternative Logging Implementations

This section compares the object-oriented and non-object-oriented versions of the distributed logging facility in terms of several software quality factors such as modularity, extensibility, reusability, and portability.

4.3.1 Non-Object-Oriented Version

The `Reactor`-based distributed logging facility is an object-oriented reimplementation of an earlier functionally equivalent, non-object-oriented logging facility. The original version was developed for a BSD UNIX-based commercial on-line transaction processing product. It was initially written in C and used BSD sockets and `select` directly. Later, it was ported to a system that provided only the System V-based TLI and `poll` interfaces.

The original C implementation is difficult to modify, extend, and port due to (1) tightly-coupled functionality and (2) an excessive use of global variables. For example, the event demultiplexing, service dispatching, and event processing operations in the original version are tightly-coupled with both the acceptance of client connection requests and the reception of client logging records. In addition, several global data structures are used to maintain the relationship between (1) per-client context information (such as the client hostname and current processing status) and (2) I/O handles that identify the appropriate context record. Therefore, any enhancements or modifications to the program directly affects the existing source code.

4.3.2 Object-Oriented Version

The object-oriented `Reactor`-based version uses data abstraction, inheritance, dynamic binding, and templates to (1) minimize the reliance on global variables and (2) decouple the application *policies* that process incoming connections and data from the lower-level *mechanisms* that perform demultiplexing and dispatching. The `Reactor`-based logging facility contains no global variables. Instead, each `Logging_Handler` object registered with the `Reactor` encapsulates the client address and the underlying I/O handle used to communicate with clients.

By decoupling the policies and mechanisms, a number of software quality factors are enhanced. For example, the reusability and extensibility of system components was improved, which simplified both the initial development effort and subsequent modifications. Since the `Reactor` framework performs all the lower-level event demultiplexing and service dispatching, only a small amount of additional code is required to implement the server logging daemon described in Section 4.1. Moreover, the additional code is primarily concerned with application processing activities (such as accepting new connections and receiving client logging records). In addition, templates help to localize application-specific code to within a few, well-defined modules.

The separation of policies and mechanisms in the `Reactor`'s architecture facilitates extensibility and portability both "above" and "below" its public interface. For example, extending the server logging daemon's functionality (*e.g.,* adding an "authenticated logging" features) is straight-forward. Such extensions simply inherit from the `ACE_Event_Handler` base class and selectively implement the necessary virtual method(s). Likewise, by instantiating the `ACE_Acceptor` and `ACE_Svc_Handler` templates, subsequent applications may be produced without redeveloping existing infrastructure. On the other hand, modifying the original non-object-oriented C version in this manner, however, would require direct changes to the existing code.

It is also possible to modify the `Reactor`'s underlying I/O demultiplexing mechanism without affecting existing application code. For example, porting the `Reactor`-based distributed logging facility from a BSD platform to a System V platform requires no visible changes to application code. On the other hand, porting the original C version of the distributed logging facility from sockets/`select` to TLI/`poll` was tedious and time consuming. It also introduced several subtle errors into the source code that did not manifest themselves until run-time. Furthermore, in certain communication-intensive applications, data is always available immediately on one or more handles. Therefore, polling these handles via non-blocking I/O may be more efficient than using `select` or `poll`. As before, extending the `Reactor` to support this alternative demultiplexing implementation not modify its public interface.

4.4 C++ Language Impact

Several C++ language features are instrumental to both the design of the `Reactor` and the distributed logging facility that utilizes its functionality. For example, the data hiding capabilities provided by C++ classes improves portability by encapsulating and isolating the differences between `select` and `poll`. Likewise, the technique of registering C++ class *objects* (rather that stand-alone *subroutines*) with the `Reactor` helps integrate application-specific context information together with multiple method that access this information. Parameterized types are useful for increasing the reusability of the `ACE_Acceptor` class by allowing it to be instantiated with `PEER_HANDLER`s other than `Logging_Handler` and `PEER_ACCEPTOR`s other than `ACE_SOCK_Acceptor`. In addition, inheritance and dynamic binding facilitate transparent extensibility by allowing developers to enhance the functionality of the `Reactor` and its associated applications without modifying existing code.

Dynamic binding is used extensively in the `Reactor`. A previous C++ Report article on the `IPC_SAP` wrapper [8] discusses why avoiding dynamic binding is often advisable when designing "thin" C++ wrappers. In particular, the overhead resulting from indirect virtual table dispatching may discourage developers from using the more modular and type-secure OO interfaces. However, unlike `IPC_SAP`, the `Reactor` framework provides more than just a thin OO veneer around the underlying OS system calls. Therefore, the significant increase in clarify, extensibility, and modularity compensates for the slight decrease in efficiency. Moreover, the `Reactor` is typically used to develop distributed systems. A careful examination of the major sources of overhead in distributed systems reveals that most performance bottlenecks result from activities such as caching, latency, network/host interface hardware, presentation-level formatting, memory-to-memory copying, and process management [12]. Therefore, the additional memory reference overhead caused by dynamic binding is insignificant in comparison [13].

To justify these claims empirically, an upcoming article in the C++ Report will present the results of a benchmarking experiment that measures the performance of `IPC_SAP` and the `Reactor`. These performance results are based upon a distributed system benchmarking tool that measures client/server performance in a distributed environment. This tool also indicates the overhead of using C++ wrappers for IPC mechanisms. In particular, there are two functionally equivalent versions of the benchmarking tool: (1) an object-oriented version that uses the `IPC_SAP` and `Reactor` C++ wrappers and (2) a non-object-oriented version written in C that uses the sockets, `select`, and `poll` system calls directly. The experiment measures the performance of the object-oriented implementation and the non-object-oriented implementation in a controlled manner.

5 Concluding Remarks

The `Reactor` is a object-oriented framework that simplifies the development of concurrent, event-driven distributed systems by making it easier to write correct, compact, portable, and efficient applications. It accomplishes this by encapsulating existing operating system demultiplexing mechanisms within an object-oriented C++ interface. In general, by separating *policies* and *mechanisms*, the `Reactor` supports reuse of existing system components, improves portability, and provides transparent extensibility.

One disadvantage with the `Reactor`-based approach is that it is somewhat difficult at first to conceptualize where an application's main thread of control occurs. This is a typical problem with event-loop-driven dispatchers such as the `Reactor` or the higher-level X-windows toolkits. However, the confusion surrounding this "indirect event-callback" dispatching model typically disappears quickly after writing several applications that use this approach.

The source code and documentation for the `Reactor` and `IPC_SAP` C++ wrappers is available online at `http://www.cs.wustl.edu/~schmidt/ACE.html`. Also included with this release are a suite of test programs and examples, as well as many other C++ wrappers that encapsulate named pipes, STREAM pipes, `mmap`, and the System V IPC mechanisms (*i.e.,* message queues, shared memory, and semaphores). Upcoming articles in the C++ Report will describe the design and implementation of these wrappers.

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