Design Patterns and Frameworks for Concurrent CORBA Event Channels

Douglas C. Schmidt

Washington University, St. Louis

http://www.cs.wustl.edu/~schmidt/

schmidt@cs.wustl.edu

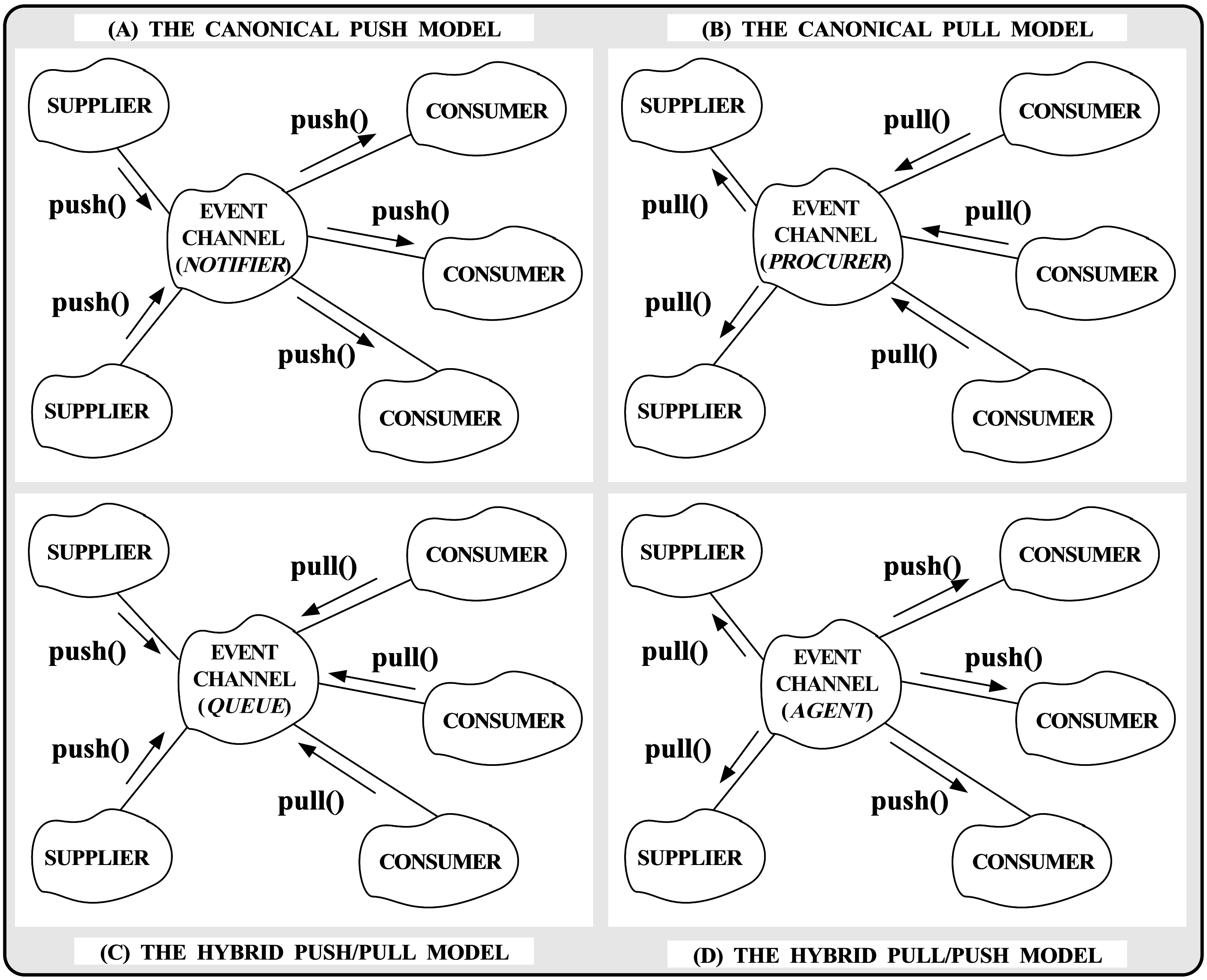
Motivation

- Asynchronous messaging and group communication are important for real-time applications

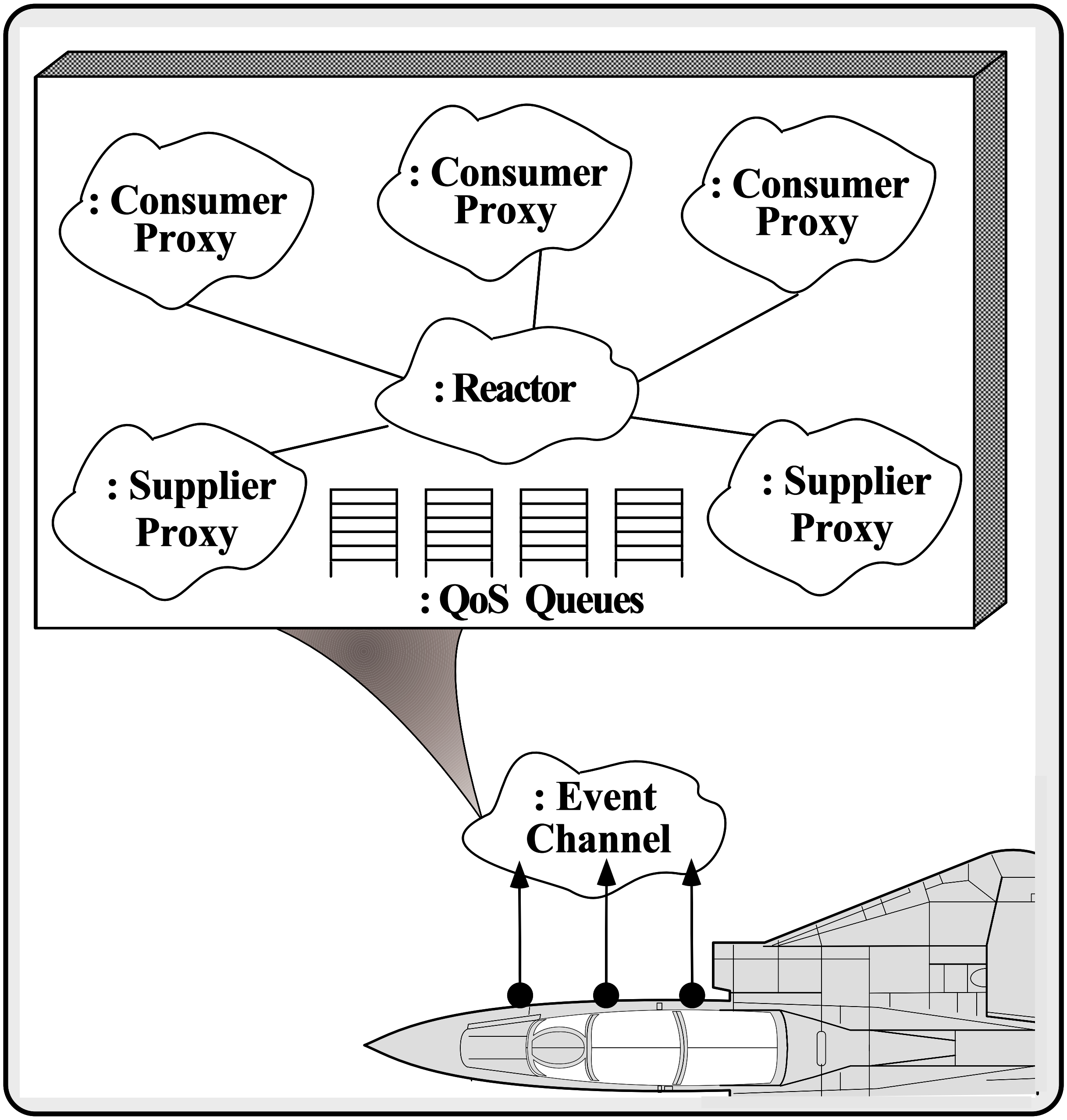
- This example explores the *design patterns* and *reusable framework* components used in an OO architecture for CORBA *Real-time Event Channels*

- CORBA Event Channels route events from Supplier(s) to Consumer(s)

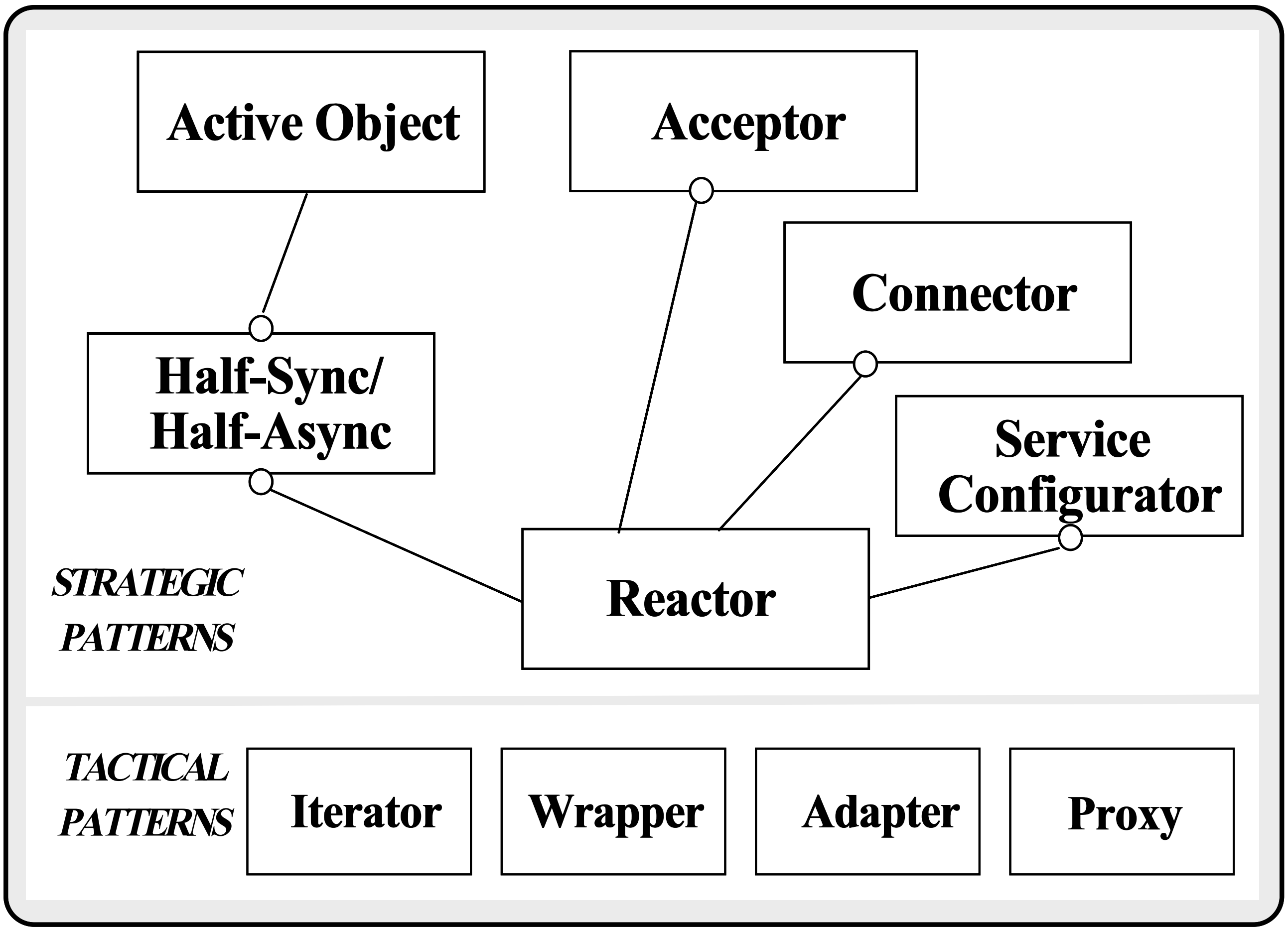
Communication Models for Event Channels



OO Software Architecture of the Event Channel



Design Patterns in the Event Channel



- The Event Channel components are based upon a system of design patterns

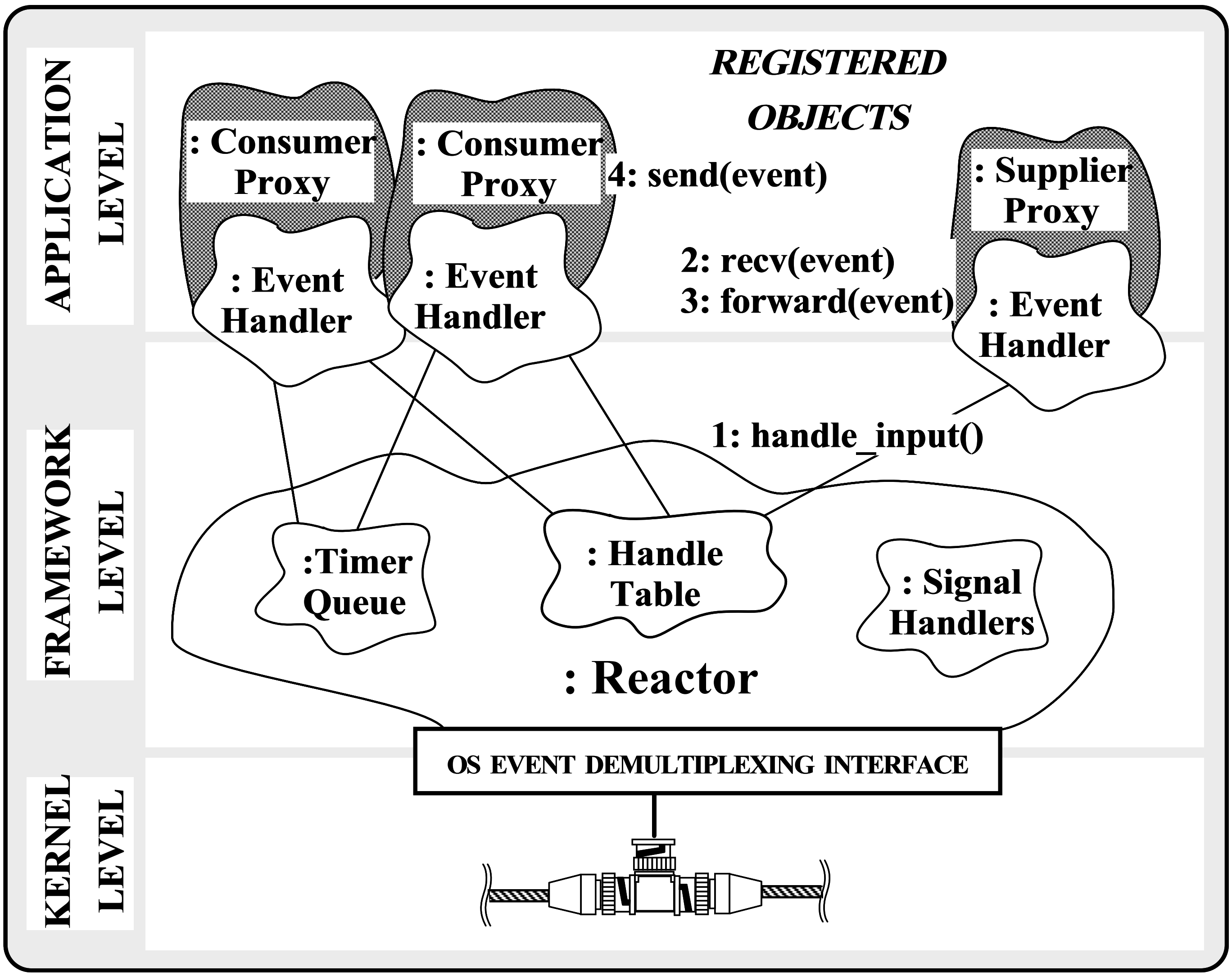
Design Patterns in the Event Channel (cont'd)

- *Reactor*
  - "Decouples event demultiplexing and event handler dispatching from application services performed in response to events"

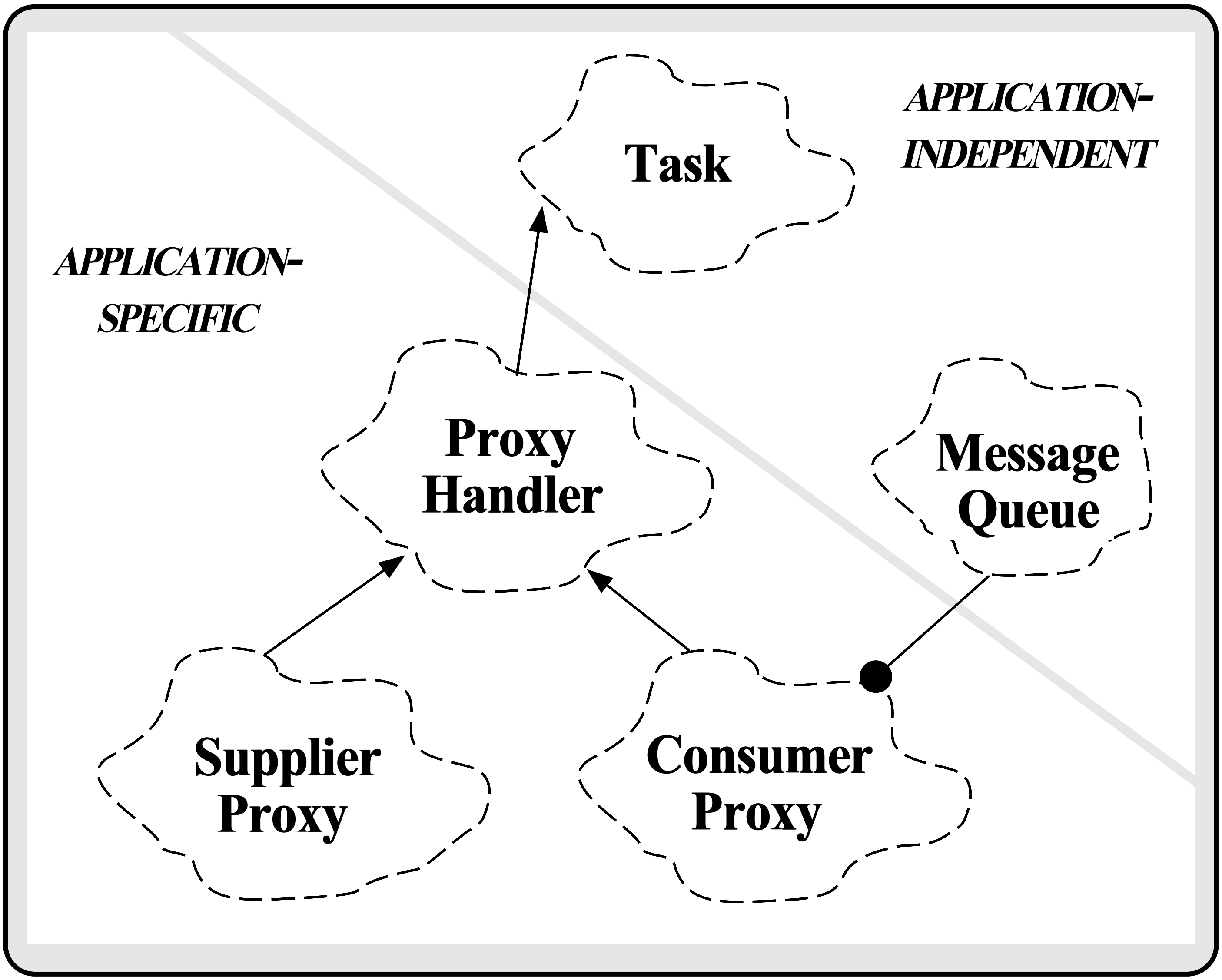
- *Half-Sync/Half-Async*
  - "Decouples synchronous I/O from asynchronous I/O in a system to simplify concurrent programming effort without degrading execution efficiency"

- *Active Object*
  - "Decouples method execution from method invocation and simplifies synchronized access to shared resources by concurrent threads"

Using the Reactor Pattern for the Single-Threaded Event Channel



Event Channel Inheritance Hierarchy



IO_Proxy Class Public Interface

- Common methods and data for I/O Proxys

```
  // Keeps track of events sent and received.
typedef u_long COUNTER;

// This is the type of the Consumer_Map.
typedef Null_Mutex MAP_LOCK;
typedef Map_Manager <Event_Header,
                     Consumer_Set,
                     MAP_LOCK> CONSUMER_MAP;

class Proxy_Handler : public Task<Null_Synch>
{
public:
    // Initialize the Proxy.
  virtual int open (void * = 0);

private:
  static COUNTER events_sent_;
  static COUNTER events_received_;
```

Supplier_Proxy Interface

- Handle input processing and routing of events from Suppliers

```
class Supplier_Proxy : public Proxy_Handler
{
protected:
    // Notified by Reactor when Supplier
    // event arrives.
  virtual int handle_input (void);

    // Low-level method that receives
    // an event from a Supplier.
  virtual int recv (Message_Block *&);

    // Forward an event from
    // a Supplier to Consumer(s).
  int forward (Message_Block *);
};
```

Consumer_Proxy Interface

- Handle output processing of events sent to Consumers

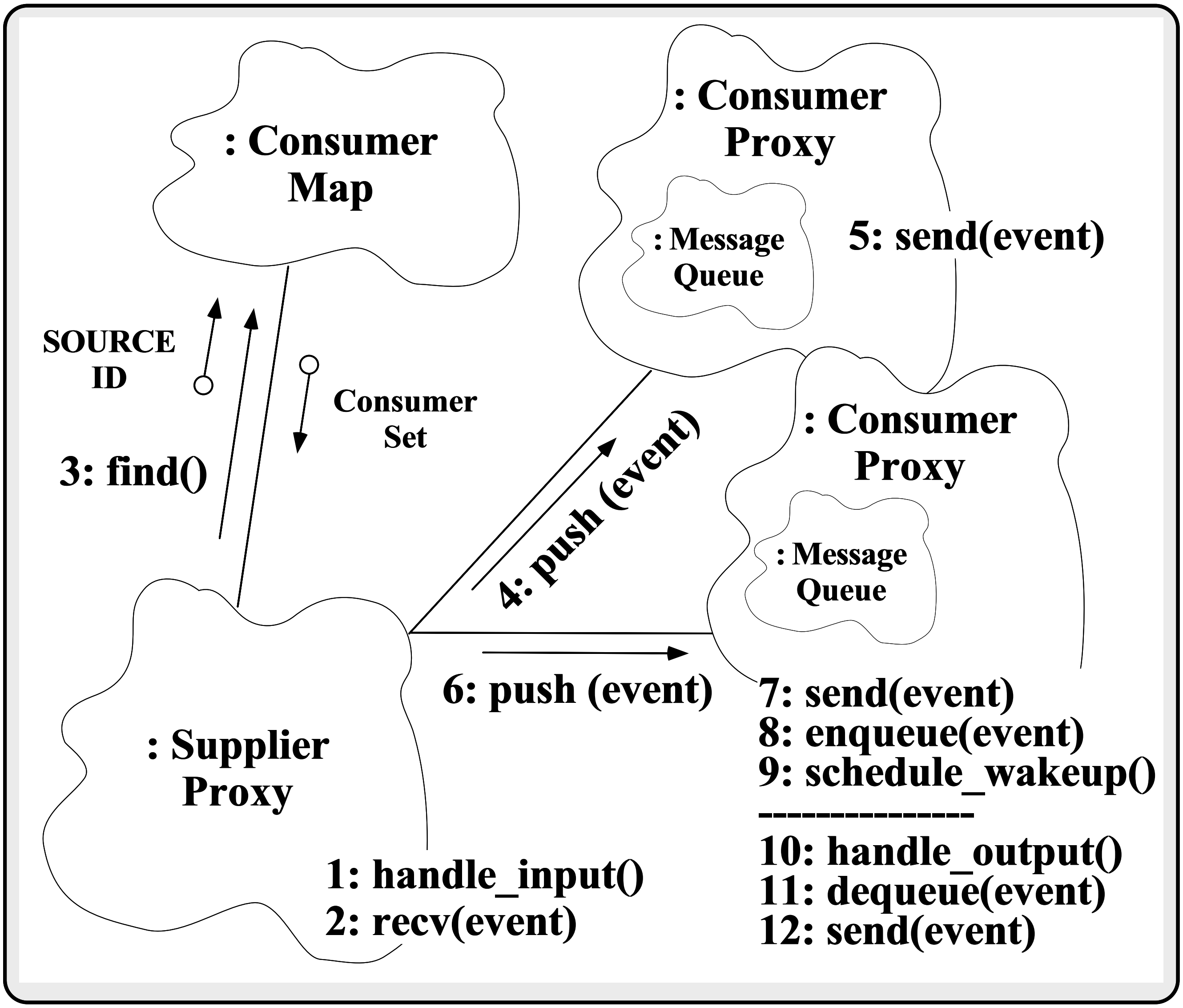
```
class Consumer_Proxy : public Proxy_Handler
{
public:
    // Send an event to a Consumer.
  virtual int push (Message_Block *);

protected:
    // Perform a non-blocking push() (will
    // may queue if flow control occurs).
  int nonblk_push (Message_Block *event);

    // Finish sending an event when flow control
    // abates.
  virtual int handle_output (void);

    // Low-level method that sends an event to
    // a Consumer.
  virtual int send (Message_Block *);
};
```

Collaboration in Single-threaded Event Channel Forwarding



```
// Receive input event from Supplier and forward
// the event to Consumer(s).

int
Supplier_Proxy::handle_input (void)
{
  Message_Block *event = 0;

  // Try to get the next event from the
  // Supplier.
  if (recv (event) == COMPLETE_EVENT)
  {
    Proxy_Handler::events_received_++;
    forward (event);
  }
}

// Send an event to a Consumer (queue if necessary).

int
Consumer_Proxy::push (Message_Block *event)
{
  if (msg_queue ()->is_empty ())
    // Try to send the Message_Block *without* blocking!
    nonblk_put (event);
  else
    // Events are queued due to flow control.
    msg_queue ()->enqueue_tail (event);
}
```

```
// Forward event from Supplier to Consumer(s).

int
Supplier_Proxy::forward (Message_Block *event)
{
  Consumer_Set *c_set = 0;

  // Determine route.
  Consumer_Map::instance ()->find (event, c_set);

  // Initialize iterator over Consumers(s).
  Set_Iterator<Consumer_Proxy *> iter (c_set);

  // Multicast event.
  for (Consumer_Proxy *ch;
       si.next (ch) != -1;
       si.advance ()) {
    // Make a "logical copy" (via reference counting).
    Message_Block *new_event = event->duplicate ();

    if (ch->push (new_event) == -1) // Drop event.
      new_event->release (); // Decrement reference count.
  }

  event->release (); // Delete event.
}
```

Event Structure

- An Event contains two portions
  - The **Event_Header** identifies the Event
    - ▷ Used for various types of filtering

      and correlation

```
class Event_Header {
public:
  Supplier_Id s_id_;
  int priority_;
  Event_Type type_;
  time_t time_stamp_;
  size_t length_;
};
```

  - The **Event** contains a header plus a variable-sized message

```
class Event {
public:
    // The maximum size of an event.
  enum { MAX_PAYLOAD_SIZE = /* ... */ };
  Event_Header header_; // Fixed-sized header portion.
  char payload_[MAX_PAYLOAD_SIZE]; // Event payload.
};
```

OO Design Interlude

- Q: *What should happen if push() fails?*
  - *e.g.*, if a Consumer queue becomes full?

- A: The answer depends on whether the error handling policy is different for each router object or the same. . .
  - Bridge/Strategy pattern: *give reasonable default, but allow substitution*

- A related design issue deals with avoiding output blocking if a Consumer connection flow controls

OO Design Interlude

- Q: *How can a flow controlled Consumer_Proxy 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 `Consumer_Proxy` is able to transmit again

Performing Non-blocking Push Operations

- The following method will push the event without blocking
  - We need to queue if flow control conditions occur

```
int Consumer_Proxy::nonblk_push (Message_Block *event)
{
  // Try to send the event using non-blocking I/O
  if (send (event) == EWOULDBLOCK)
  {
    // Queue in *front* of the list to preserve order.
    msg_queue ()->enqueue_head (event);

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

    Service_Config::reactor ()->schedule_wakeup
      (this, Event_Handler::WRITE_MASK);
  }
  else
    Proxy_Handler::events_sent_++;
}
```

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

int
Consumer_Proxy::handle_output (void)
{
  Message_Block *event = 0;

  // Take the first event off the queue.
  msg_queue ()->dequeue_head (event);

  if (nonblk_push (event) != 0)
  {
    // 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 ()
      Service_Config::reactor ()->cancel_wakeup
        (this, Event_Handler::WRITE_MASK);
  }
}
```

Event_Channel Class Public Interface

- Maintains maps of the `Consumer_Proxy` object references and the `Supplier_Proxy` object references

```
// Parameterized by the type of I/O Proxys.
template <class Supplier_Proxy, // Supplier policies
          class Consumer_Proxy> // Consumer policies
class Event_Channel
{
public:
    // Perform initialization.
  virtual int init (int argc, char *argv[]);

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

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

Dynamically Configuring Services into an Application

- Main program is generic

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

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

  // Run forever, performing configured services.

  daemon.run_reactor_event_loop ();

  /* NOTREACHED */
}
```

Dynamic Linking an Event_Channel Service

- Service configuration file

```
% cat ./svc.conf
static Svc_Manager "-p 5150"
dynamic Event_Channel_Service Service_Object *
        Event_Channel.dll:make_Event_Channel () "-d"
```

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

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

extern "C" Service_Object *make_Event_Channel (void);

Service_Object *
make_Event_Channel (void)
{
  return new Event_Channel<Supplier_Proxy,
                           Consumer_Proxy>;
  // ACE automatically deletes memory.
}
```

Concurrency Strategies for Event Channel

- The single-threaded Event Channel has several limitations

  1. Fragile program structure due to cooperative multi-tasking

  2. Doesn't take advantage of multi-processing platforms

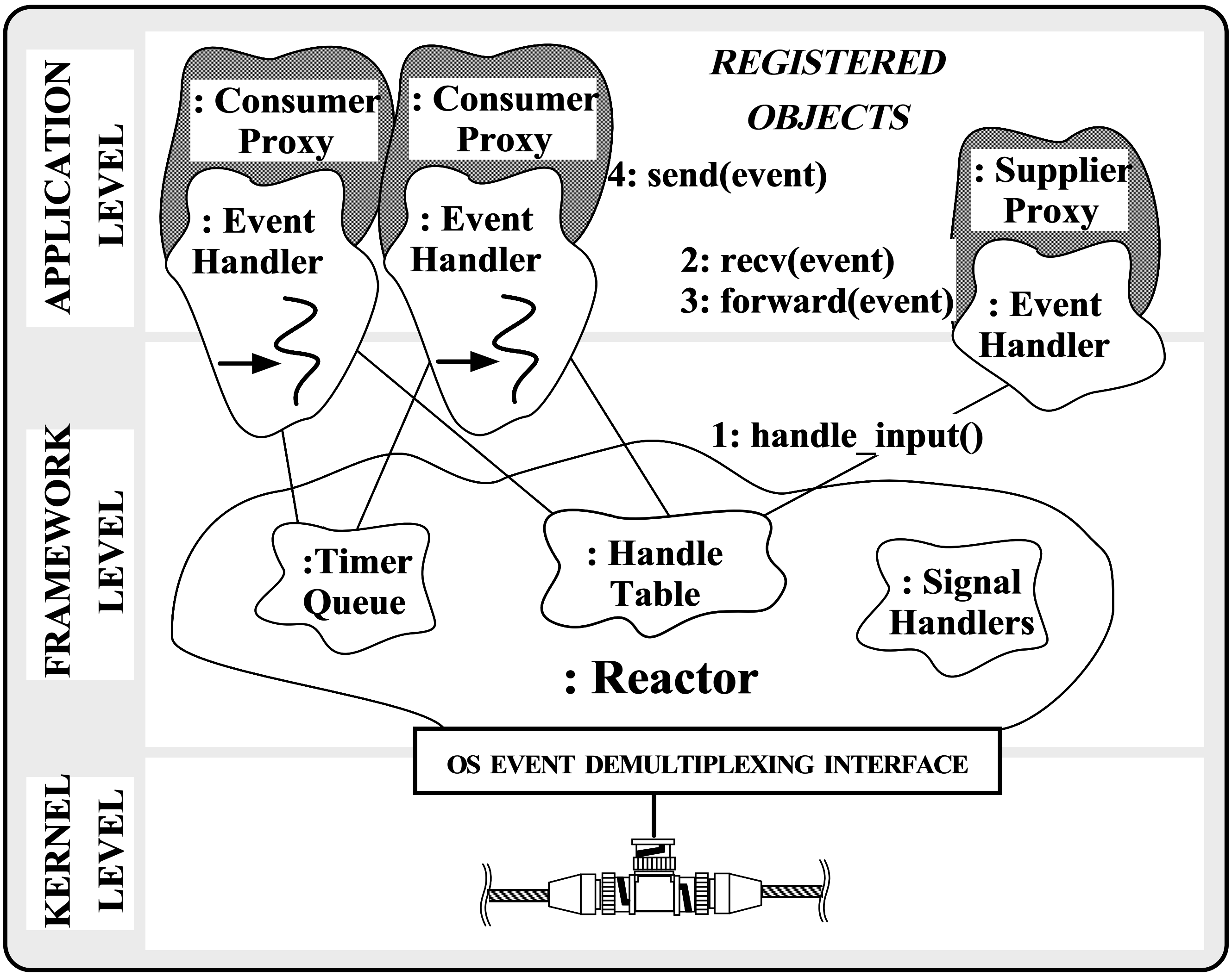
- Therefore, a concurrent solution may be beneficial

  – Though it can also increase concurrency control overhead

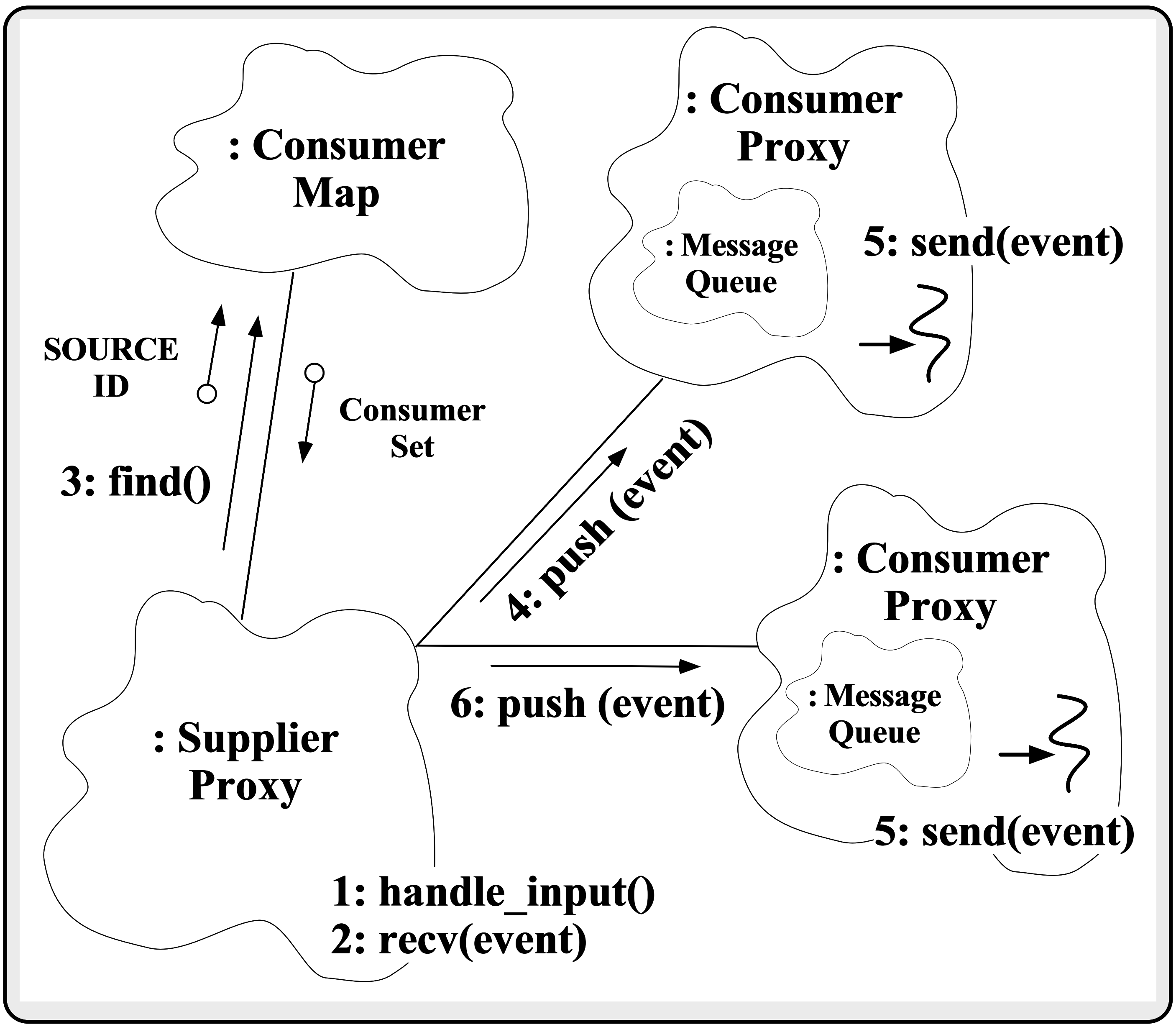
- The following slides illustrate how OO techniques push this decision to the "edges" of the design

  – This greatly increases reuse, flexibility, and performance tuning

Using the Active Object Pattern for the Multi-threaded Event_Channel



Collaboration in the Active Object-based Event_Channel Forwarding

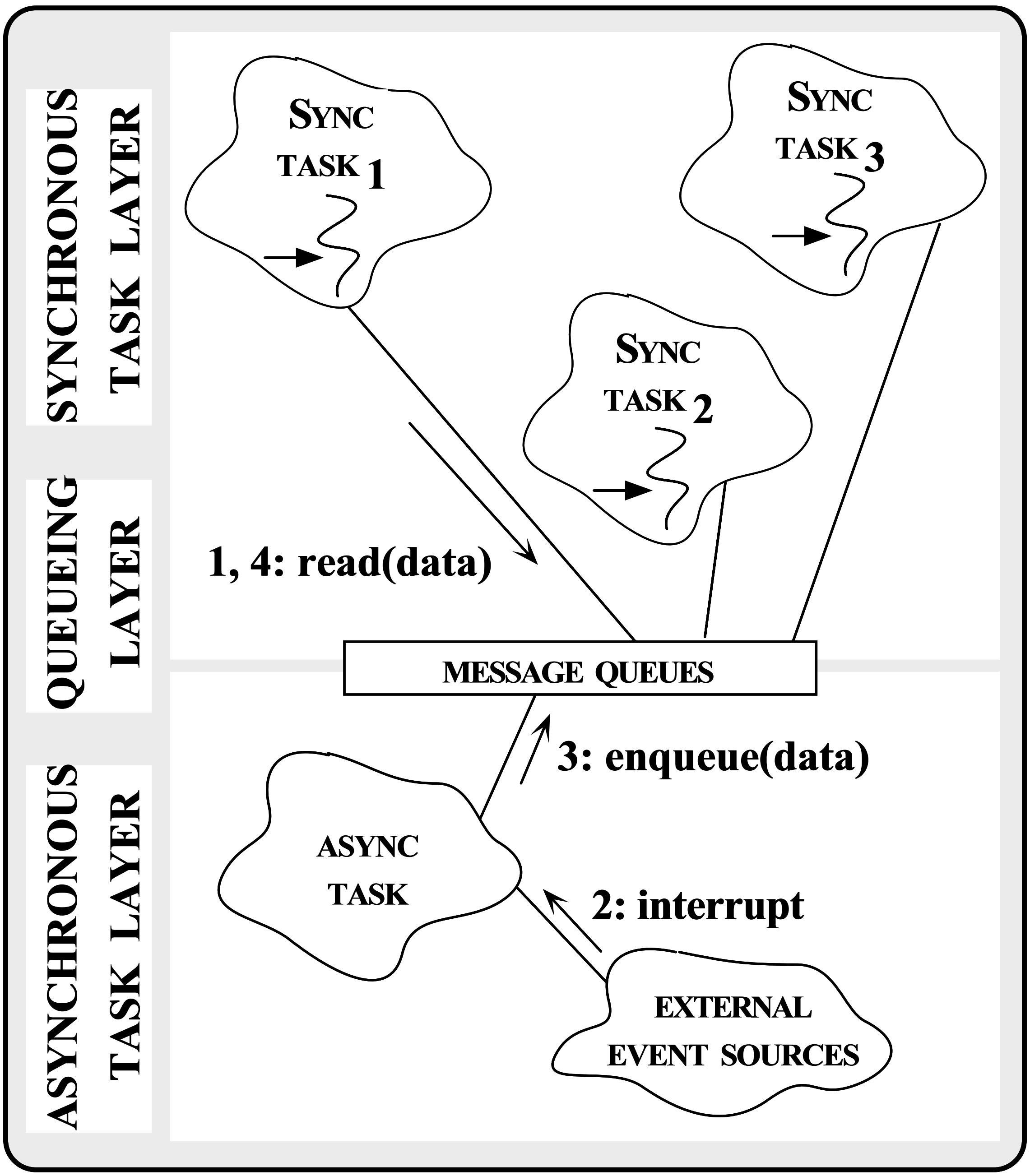


Half-Sync/Half-Async Pattern

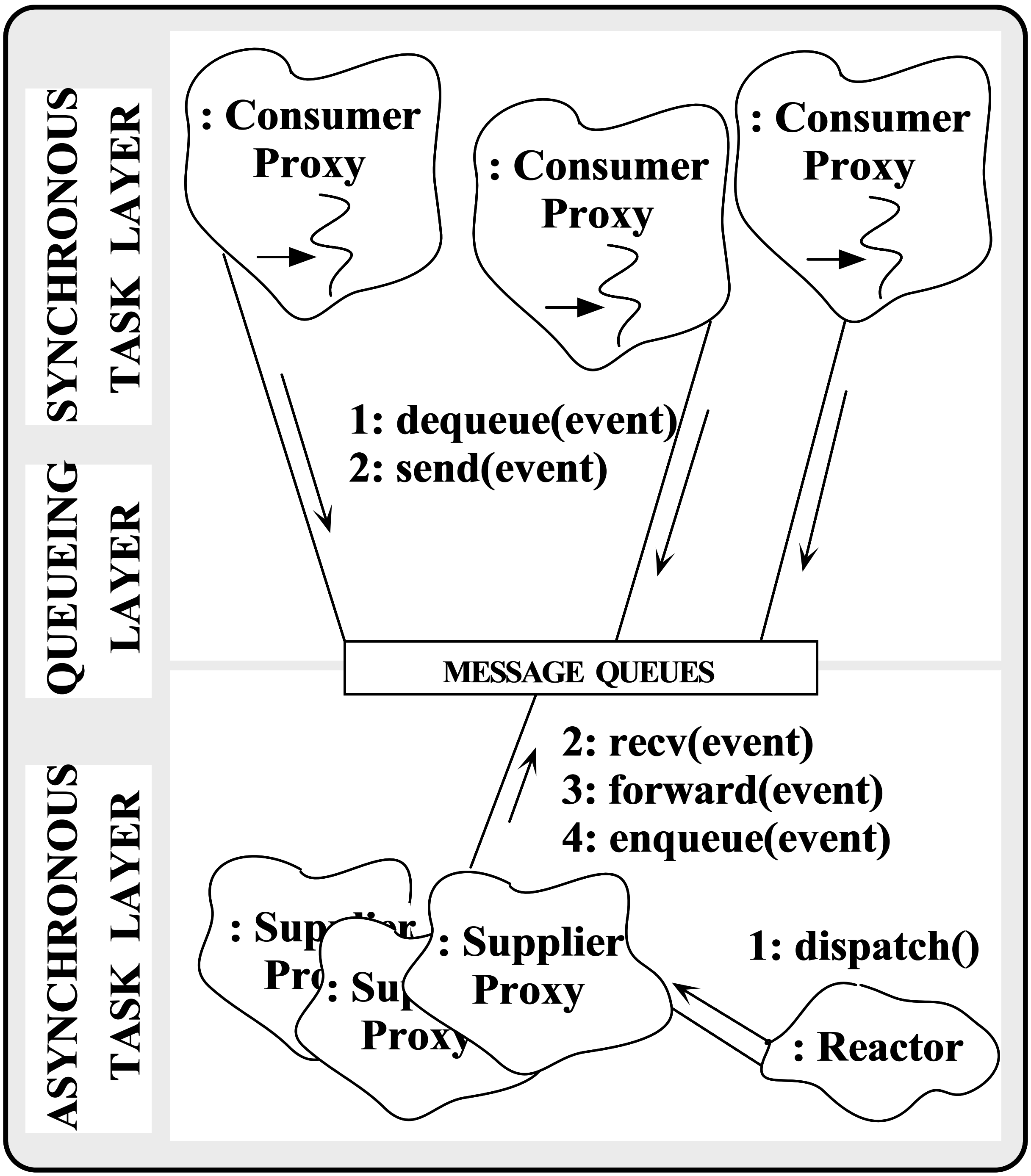
- *Intent*
  - "Decouple synchronous I/O from asynchronous I/O in a system to simplify concurrent programming effort without degrading execution efficiency"

- 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 Reactor)

Structure of the Half-Sync/Half-Async Pattern



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



Configuring Synchronization Mechanisms

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

typedef Null_Mutex MAP_LOCK;

// This is the type of the Consumer_Map.
typedef Map_Manager <Event_Header,
                     Consumer_Set,
                     MAP_LOCK> CONSUMER_MAP;

class Proxy_Handler : public Task<SYNCH>
{ /* ... */ };
```

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 Mutex MUTEX;
  typedef Condition<Mutex> CONDITION;
};
```

  – Contrast with `NULL_SYNCH`

```
class NULL_SYNCH { public:
  typedef Null_Mutex MUTEX;
  typedef Null_Condition<Null_Mutex> CONDITION;
};
```

Thr_Consumer_Proxy Class Interface

- New subclass of `Proxy_Handler` uses the Active Object pattern for the `Consumer_Proxy`
  - Uses multi-threading and synchronous I/O to transmit events to Consumers
  - Transparently improve performance on a multi-processor platform and simplify design

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

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

    // Send an event to a Consumer.
  virtual int push (Message_Block *);

private:
    // Transmit Supplier events to Consumer within
    // separate thread.
  virtual int svc (void);
```

Thr_Consumer_Proxy 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 Consumer_Proxy class.

int
Thr_Consumer_Proxy::open (void *)
{
  // Become an active object by spawning a
  // new thread to transmit events to Consumers.

  activate (THR_NEW_LWP | THR_DETACHED);
}
```

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

```
// Queue up an event for transmission (must not block
// since all Supplier_Proxys are single-threaded).

int
Thr_Consumer_Proxy::push (Message_Block *event)
{
  // Perform non-blocking enqueue.
  msg_queue ()->enqueue_tail (event);
}

// Transmit events to the Consumer (note simplification
// resulting from threads...)

int
Thr_Consumer_Proxy::svc (void)
{
  Message_Block *event = 0;
  // Since this method runs in its own thread it
  // is OK to block on output.

  while (msg_queue ()->dequeue_head (event) != -1) {
    send (event);
    Proxy_Handler::events_sent_++;
  }
}
```

Dynamic Linking an Event_Channel Service

- Service configuration file

```
% cat ./svc.conf
remove Event_Channel_Service
dynamic Event_Channel_Service Service_Object *
        thr_Event_Channel.dll:make_Event_Channel () "-d"
```

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

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

extern "C" Service_Object *make_Event_Channel (void);

Service_Object *
make_Event_Channel (void)
{
  return new Event_Channel<Supplier_Proxy,
                           Thr_Consumer_Proxy>;
  // ACE automatically deletes memory.
}
```

Eliminating Race Conditions

- *Problem*
  - The concurrent Event Channel contains "race conditions" *e.g.*,
    - ▷ Auto-increment of static variable `events_sent_` is not serialized properly

- *Forces*
  - Modern shared memory multi-processors use *deep caches* and *weakly ordered* memory models
  - Access to shared data must be protected from corruption

- *Solution*
  - Use synchronization mechanisms

Basic Synchronization Mechanisms

- One approach to solve the serialization problem is to use OS mutual exclusion mechanisms explicitly, *e.g.*,

```
// SunOS 5.x, implicitly "unlocked".
mutex_t lock;

int
Thr_Consumer_Proxy::svc (void)
{
  Message_Block *event = 0;
  // Since this method runs in its own thread it
  // is OK to block on output.

  while (msg_queue ()->dequeue_head (event) != -1) {
    send (event);
    mutex_lock (&lock);
    Proxy_Handler::events_sent_++;
    mutex_unlock (&lock);
  }
}
```

Problems Galore!

- Adding these `mutex_*` calls explicitly is *inelegant*, *obtrusive*, *error-prone*, and *non-portable*
  - *Inelegant*
    - ▷ "Impedance mismatch" with C/C++
  - *Obtrusive*
    - ▷ Must find and lock all uses of **`events_sent_`**
  - *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

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 Thread_Mutex to Windows NT

- Win32 version of Thread_Mutex

```
class Thread_Mutex
{
public:
  Thread_Mutex (void) {
    InitializeCriticalSection (&lock_);
  }
  ~Thread_Mutex (void) {
    DeleteCriticalSection (&lock_);
  }
  int acquire (void) {
    EnterCriticalSection (&lock_); return 0;
  }
  int tryacquire (void) {
    TryEnterCriticalSection (&lock_); return 0;
  }
  int release (void) {
    LeaveCriticalSection (&lock_); return 0;
  }
private:
  CRITICAL_SECTION lock_; // Win32 locking mechanism.
  // ...
```

Using the C++ Thread_Mutex Wrapper

- Using the C++ wrapper helps improve portability and elegance:

```
Thread_Mutex lock;

int
Thr_Consumer_Proxy::svc (void)
{
  Message_Block *event = 0;

  while (msg_queue ()->dequeue_head (event) != -1) {
    send (event);
    lock.acquire ();
    Proxy_Handler::events_sent_++;
    lock.release ();
  }
}
```

- However, it does not solve the *obtrusiveness* 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*

Using the Guard Class

- Using the Guard class helps reduce errors:

```
Thread_Mutex lock;

int
Thr_Consumer_Proxy::svc (void)
{
  Message_Block *event = 0;
  // Since this method runs in its own thread it
  // is OK to block on output.

  while (msg_queue ()->dequeue_head (event) != -1) {
    send (event);
    {
      // Constructor releases lock.
      Guard<Thread_Mutex> mon (lock);
      Proxy_Handler::events_sent_++;
      // Destructor releases lock.
    }
  }
}
```

- However, using the Thread_Mutex and Guard classes is still overly obtrusive and subtle (may lock too much scope...)

OO Design Interlude

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

- A: there are many locking mechanisms that benefit from `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 classes use the Wrapper and Adapter patterns to provide identical interfaces that facilitate parameterization

The Wrapper Pattern

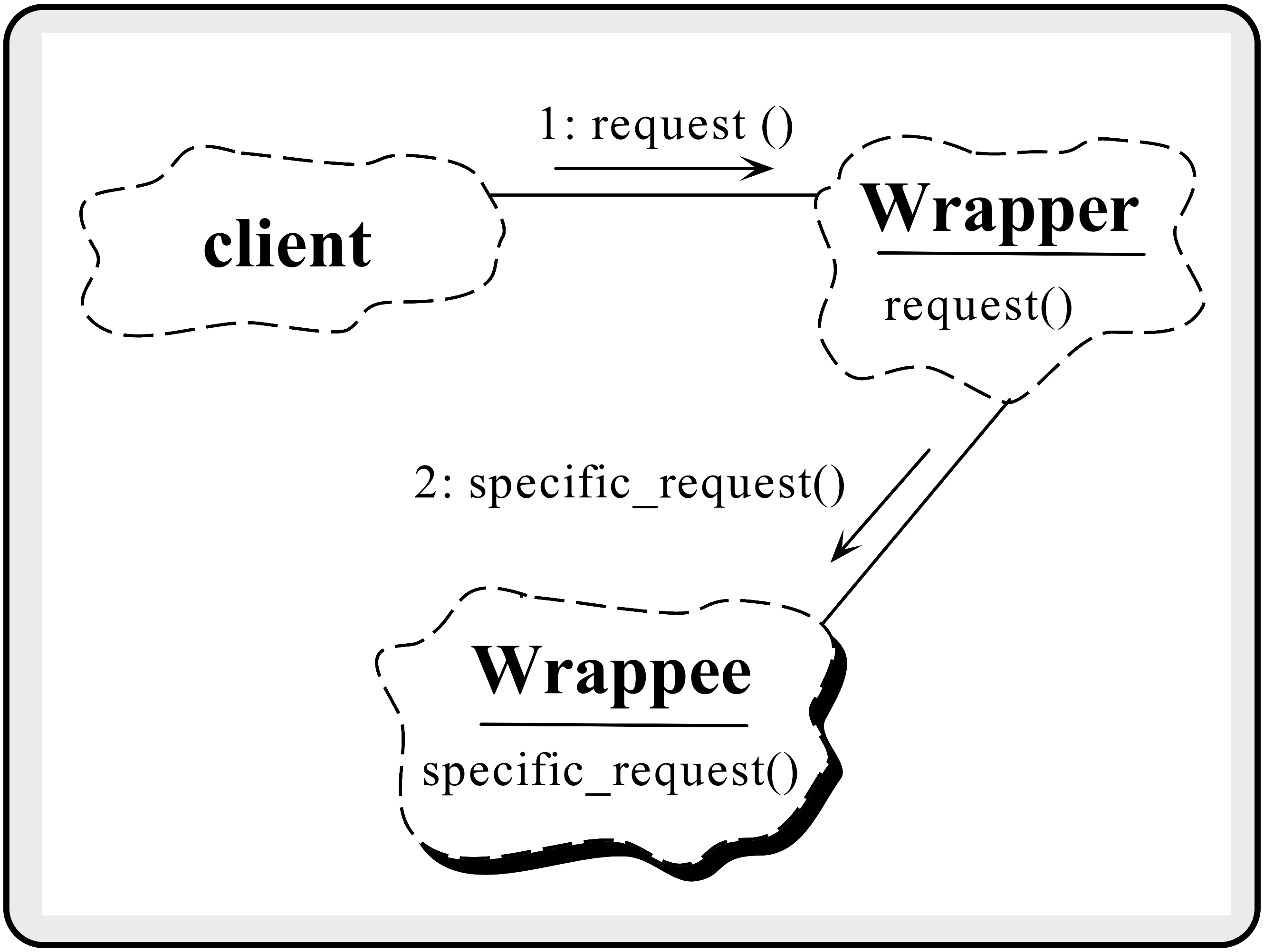
- *Intent*
  - "Encapsulate low-level, stand-alone functions within type-safe, modular, and portable class interfaces"

- This pattern resolves the following forces that arises when using native C-level OS APIs

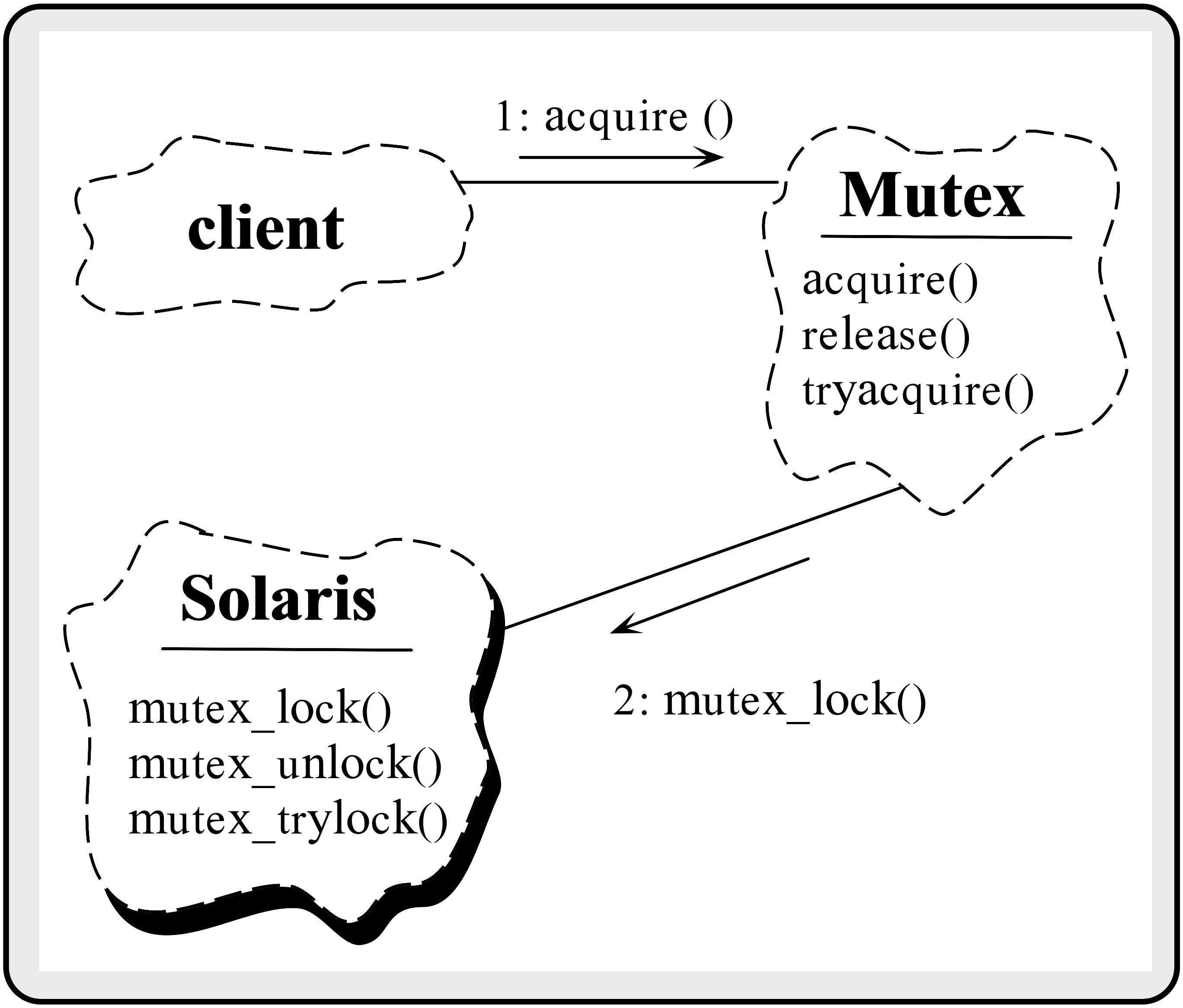
  1. *How to avoid tedious, error-prone, and non-portable programming of low-level IPC and locking mechanisms*

  2. *How to combine multiple related, but independent, functions into a single cohesive abstraction*

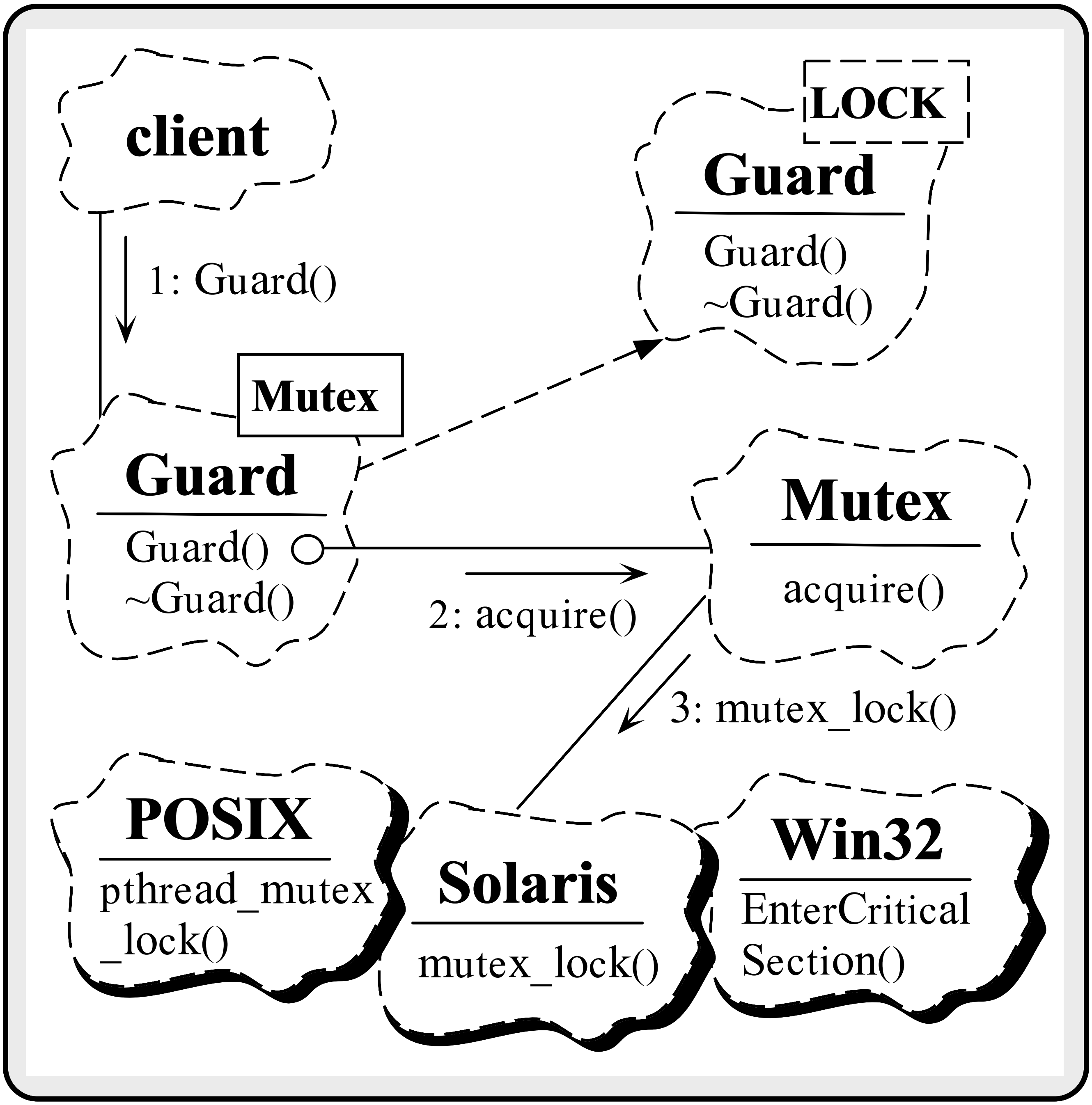
Structure of the Wrapper Pattern



Using the Wrapper Pattern for Locking



Using the Adapter Pattern for Locking



Transparently Parameterizing Synchonization 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_;
  }

  operator TYPE () {
    Guard<LOCK> m (lock_);
    return count_;
  }
  // Other arithmetic operations omitted...

private:
  LOCK lock_;
  TYPE  count_;
};
```

Using Atomic_Op

- A few minor changes are made to the class header:

```
#if defined (MT_SAFE)
typedef Atomic_Op<> COUNTER; // Note default parameters...
#else
typedef Atomic_Op<ACE_Null_Mutex> COUNTER;
#endif /* MT_SAFE */
```

- In addition, we add a lock, producing:

```
class Proxy_Handler
{
// ...

  // Maintain count of events sent.
  static COUNTER events_sent_;
};
```

Thread-safe Version of Consumer_Proxy

- `events_sent_` is now serialized automatically and we only lock the minimal scope necessary

```
int
Thr_Consumer_Proxy::svc (void)
{
  Message_Block *event = 0;

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

  while (msg_queue ()->dequeue_head (event) != -1) {
    send (event);
    // Calls Atomic_Op<>::operator++.
    Proxy_Handler::events_sent_++;
  }
}
```

Benefits of Design Patterns

- *Design patterns enable large-scale reuse of software architectures*

- *Patterns explicitly capture expert knowledge and design tradeoffs*

- *Patterns help improve developer communication*

- *Patterns help ease the transition to object-oriented technology*

Drawbacks to Design Patterns

- *Patterns do not lead to direct code reuse*
- *Patterns are deceptively simple*
- *Teams may suffer from pattern overload*
- *Patterns are validated by experience rather than by testing*
- *Integrating patterns into a software development process is a human-intensive activity*

Suggestions for Using Patterns Effectively

- *Do not recast everything as a pattern*
  - Instead, develop strategic domain patterns and reuse existing tactical patterns

- *Institutionalize rewards for developing patterns*

- *Directly involve pattern authors with application developers and domain experts*

- *Clearly document when patterns apply and do not apply*

- *Manage expectations carefully*

Patterns Literature

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

- *Special Issues in Journals*
  - Dec. '96 "Theory and Practice of Object Systems" (guest editor: Stephen P. Berczuk)
  - October '96 "Communications of the ACM" (guest editors: Douglas C. Schmidt, Ralph Johnson, and Mohamed Fayad)

- *Magazines*
  - C++ Report and Journal of Object-Oriented Programming, columns by Coplien, Vlissides, 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
  - Anonymously ftp to `wuarchive.wustl.edu`
  - Transfer the files `/languages/c++/ACE/*.gz`

- Mailing lists

  * ace-users@cs.wustl.edu
  * ace-users-request@cs.wustl.edu
  * ace-announce@cs.wustl.edu
  * ace-announce-request@cs.wustl.edu

- WWW URL
  - http://www.cs.wustl.edu/~schmidt/ACE.html