Implementing Multi-threaded CORBA Applications with ACE and TAO

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Outline

- Building multi-threaded distributed applications is hard
- To succeed, programmers must understand available tools, techniques, and patterns
- This tutorial examines how to build multi-threaded CORBA applications
  - Using ACE and TAO
- It also presents several concurrency models
  1. Thread-per-Connection
  2. Thread Pool

Overview of CORBA

- Simplifies application interworking
  - CORBA provides higher level integration than traditional "untyped TCP bytestreams"
- Provides a foundation for higher-level distributed object collaboration
  - e.g., Windows OLE and the OMG Common Object Service Specification (COSS)
- Benefits for distributed programming similar to OO languages for non-distributed programming
  - e.g., encapsulation, interface inheritance, and object-based exception handling

CORBA Quoter Example

```c
int main (void)
{
    // Use a factory to bind
    // to a Quoter.
    Quoter_var quoter =
        bind_quoter_service ();

    const char *name =
        "ACME ORB Inc.";

    CORBA::Long value =
        quoter->get_quote (name);
    cout << name << " = "
        << value << endl;
}
```

- Ideally, a distributed service should look just like a non-distributed service
- Unfortunately, life is harder when errors occur...
CORBA Quoter Interface

```idl
// IDL interface is like a C++
// class or Java interface.
interface Quoter{
    exception Invalid_Stock {};
    long get_quote
        (in string stock_name)
        raises (Invalid_Stock);
};
```

Using OMG IDL promotes language/platform independence, location transparency, modularity, and robustness.

Motivation for Concurrency in CORBA

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

Overview of The ACE ORB (TAO)

- An open-source, standards-based, real-time, high-performance CORBA ORB
- Runs on POSIX/UNIX, Win32, & RTOS platforms
  - e.g., VxWorks, Chorus, LynxOS
- Leverages ACE

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

Threading in TAO

- An application can choose to ignore threads and if it creates none, it need not be thread-safe
- TAO can be configured with various concurrency strategies:
  - Thread-per-Connection
  - Thread Pool
  - Thread-per-Endpoint
- TAO also provides many locking strategies
  - TAO doesn’t automatically synchronize access to application objects
  - Therefore, applications must synchronize access to their own objects
Overcoming Limitations with CORBA

- **Problem**
  - CORBA primarily addresses "communication" topics

- **Forces**
  - Real world distributed applications need many other components
    - e.g., concurrency control, layering, shared memory, event-loop integration, dynamic configuration, etc.

- **Solution**
  - Integrate CORBA with ACE OO communication framework

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ACE Statistics

- **ACE** contains > 200,000 lines of C++
  - Over 25 person-years of effort
- Ported to UNIX, Win32, MVS, and RT/embedded platforms
  - e.g., VxWorks, LynxOS, Chorus
- Large user community
  - ~schmidt/ACE-users.html
- Currently used by dozens of companies
  - Bellcore, BBN, Boeing, Ericsson, Hughes, Kodak, Lockheed, Lucent, Motorola, Nokia, Nortel, Raytheon, SAIC, Siemens, etc.
- Supported commercially by Riverace
  - www.riverace.com


**Class Categories in ACE**

- ACE is structured as a “forest” of class categories
- This design permits fine-grained subsetting of ACE components
  - Subsetting helps minimize ACE’s memory footprint

**ACE Class Category Responsibilities**

- **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 demuxing and event handler dispatching
- **Service Configurator** automates (re)configuration 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

**Overview of ACE Concurrency**

- ACE provides portable C++ threading and synchronization wrappers
- ACE classes we’ll examine include:
  - **Thread Management**
    * `ACE_Thread_Manager` → encapsulates threads
  - **Synchronization**
    * `ACE_Thread_Mutex` and `ACE_RW_Mutex` → encapsulates mutexes
    * `ACE_Atomic_Op` → atomically perform arithmetic operations
    * `ACE_Guard` → automatically acquire/release locks
  - **Queueing**
    * `ACE_Message_Queue` → thread-safe message queue
    * `ACE_Message_Block` → enqueued/dequeued on message queues

**Overview of ACE Concurrency (cont’d)**

- Several `ACE_Thread_Manager` class methods are particularly interesting:
  - `spawn` → Create 1 new thread of control running `func`
    ```c
    int spawn (void *(*)(void *) func,
                  void *arg,
                  long flags,
                  ....);
    ```
  - `spawn_n` → Create n new threads of control running `func`
    ```c
    int spawn_n (size_t n,
                 void *(*)(void *) func,
                 void *arg,
                 long flags,
                 ....);
    ```
  - `wait` → Wait for all threads in a manager to terminate
    ```c
    int wait (void);
    ```
**TAO Multi-threading Examples**

- Each example implements a concurrent CORBA stock quote service
  - Show how threads can be used on both the client and server side
- The server is implemented in two different ways:
  1. *Thread-per-Connection* → Every client connection causes a new thread to be spawned to process it
  2. *Thread Pool* → A fixed number of threads are generated in the server at start-up to service all incoming requests
- Note that clients are unaware which concurrency model is being used...

**Simple OMG IDL Quoter Definition**

```idl
module Stock {
  // Exceptions are similar to structs.
  exception Invalid_Stock {}
  exception Invalid_Factory {}

  // Interface is similar to a C++ class.
  interface Quoter {
    long get_quote (in string stock_name) raises (Invalid_Stock);
  }

  // A factory that creates Quoter objects.
  interface Quoter_Factory {
    // Factory Method that returns a new Quoter
    // selected by name e.g., "Dow Jones,"
    // "Reuters," etc.
    Quoter create_quoter (in string quoter_service) raises (Invalid_Factory);
  }
}
```

**TAO’s Thread-per-Connection Concurrency Architecture**

- The quote server(s) maintains the current stock prices
- Brokers access the quote server(s) via CORBA
- Note all the heterogeneity!
Thread-per-Connection Main Program

The server creates a single Quoter factory and waits in ORB's event loop

```c
int main (void)
{
    ORB_Manager orb_manager (argc, argv);
    const char *factory_name = "my quoter factory";
    // Create the servant, which registers with rootPOA
    // and Naming Service implicitly.
    My_Quoter_Factory factory (factory_name);
    // Block indefinitely waiting for incoming invocations
    // and dispatch upcalls.
    // After run() returns, the ORB has shutdown.
    orb_manager.run ();
}
```

The ORB's `svc.conf` file

```bash
static Resource_Factory "-ORBResources global -ORBReactorType select_mt"
static Server_Strategy_Factory "-ORBConcurrency thread-per-connection"
```

Pros

- Simple to implement and efficient for long-duration requests

Cons

- Excessive overhead for short-duration requests
- Permits unbounded number of concurrent requests

Thread-per-Connection: Quoter Interface

typedef u_long COUNTER; // Maintain request count.

// Implementation of the Quoter IDL interface
class My_Quoter :
    virtual public POA_Stock::Quoter,
    virtual public PortableServer::RefCountServantBase
{
    public:
        // Constructor.
        My_Quoter (const char *name);

        // Returns the current stock value.
        long get_quote (const char *stock_name)
            throw (CORBA::SystemException, Quoter::InvalidStock);

    private:
        // Maintain request count.
        static COUNTER req_count_;}
```

Thread-per-Connection Quoter Implementation

```c
// Implementation of multi-threaded Quoter callback invoked by
// the CORBA skeleton
long My_Quoter::get_quote (const char *stock_name)
    throw(CORBA::SystemException, Quoter::InvalidStock)
{
    // Increment the request count (beware...).
    ++My_Quoter::req_count_;

    // Obtain stock price (beware...).
    long value = Quote_Database::instance ()
        ->lookup_stock_price (stock_name);

    // Skeleton handles exceptions.
    if (value == -1)
        throw Stock::Invalid_Stock ();
    return value;
}
```
Eliminating Race Conditions

- **Problem**
  - The concurrent Quote server contains “race conditions” e.g.,
    * Auto-increment of static variable req_count_ is not serialized properly
    * Quote_Database also may not be serialized...

- **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

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

long
My_Quoter::get_quote (const char *stock_name)
throw(CORBA::SystemException,Quote::InvalidStock)
{
    mutex_lock (&lock);
    // Increment the request count.
    ++My_Quoter::req_count;
    // Obtain stock price.
    long value = Quote_Database::instance ()->
      lookup_stock_price (stock_name);
    if (value == -1)
        // Skeleton handles exceptions.
        throw Stock::Invalid_Stock ();
    mutex_unlock (&lock);
    return value;
}
```

Problems Galore!

- Problems with explicit mutex_* calls:
  - **Inelegant**
    * “Impedance mismatch” with C/C++
  - **Obtrusive**
    * Must find and lock all uses of lookup_stock_price and req_count_
  - **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:

```c
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

```cpp
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:

```cpp
long My_Quoter::get_quote (const char *stock_name)
    throw(CORBA::SystemException, Quoter::InvalidStock)
{
  Thread_Mutex lock;
  lock.acquire ();
  ++My_Quoter::req_count_; // Increment the request count.
  // Obtain stock price.
  long value = Quote_Database::instance ()->
                lookup_stock_price (stock_name);
  if (value == -1)
    // Skeleton handles exceptions.
    throw Stock::Invalid_Stock ();
  lock.release ();
  return value;
}
```

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

```cpp
template <class LOCK>
class Guard
{
public:
  Guard (LOCK &m): lock_ (m) { lock_.acquire (); }
  ~Guard (void) { lock_.release (); }
  // ...
private:
  LOCK &lock_;
}
```

Using the Guard Class

- Using the Guard class helps reduce errors:

```cpp
long My_Quoter::get_quote (const char *stock_name)
    throw(CORBA::SystemException, Quoter::InvalidStock)
{
  Guard<Thread_Mutex> mon (lock);
  ++My_Quoter::req_count_; // Increment the request count.
  // Obtain stock price.
  long value = Quote_Database::instance ()->
                lookup_stock_price (stock_name);
  if (value == -1)
    // Skeleton handles exceptions.
    throw Stock::Invalid_Stock ();
  return value;
}
```

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

```cpp
Guard uses the C++ idiom whereby a 'constructor acquires a resourceand the destructor releases the resource'
```
**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 Facade and Adapter patterns to provide identical interfaces that facilitate parameterization

**The Wrapper Facade 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 Facade Pattern**

1: method_k()

Wrapper Facade

method_1()
...method_m()

Functions

function_1()
...function_n()

2: function_k()

**Using the Wrapper Facade Pattern for Locking**

1: acquire()

Mutex

acquire()
release()
tryacquire()

Solaris

mutex_lock()
mutex_unlock()
mutex_trylock()

2: mutex_lock()
Using the Adapter Pattern for Locking

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

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

Thread-safe Version of Quote Server

- `req_count_` is now serialized automatically so only minimal scope is locked.
```
long My_Quoter::get_quote (const char *stock_name) {
  // Increment the request count by calling
  // ACE_Atomic.Op::operator++(void) decorator.
  ++My_Quoter::req_count_;
  // Obtain stock price via decorator.
  long value = Quote_Database::instance ()->lookup_stock_price (stock_name);
  if (value == -1) {
    // Skeleton handles exceptions.
    throw Stock::Invalid_Stock ();
  }
  return value;
}
Thread Pool

- This approach creates a thread pool to amortize the cost of dynamically creating threads.
- In this scheme, before waiting for input the server code creates the following:
  1. A Quoter Factory (as before)
  2. A pool of threads based upon the command line input
- Note the use of the ACE `spawn_n` method for spawning multiple pool threads.

### TAO's Thread Pool Concurrency Architecture

**Pros**

- Bounds the number of concurrent requests
- Scales nicely for multi-processor platforms, e.g., permits load balancing

**Cons**

- Potential for Deadlock

---

**Thread Pool Main Program**

```c
const int DEFAULT_POOL_SIZE = 8;

int main (int argc, char *argv[]) {
  try {
    ORB_Manager orb_manager (argc, argv);
    ORB_STUBS in args +
    return
  IDL
  SKEL
  Object Adapter
  ORB CORE
  IDL STUBS
  operation()
  orb->run() orb->run() orb->run() // Create a thread pool.
ACE_Thread_Manager::instance ()->spawn_n
(pool_size, &run_orb, (void *) orb_manager.orb (),
THR_DETACHED | THR_NEW_LWP);

// After run() returns, the ORB has shutdown.
) catch (...) { /* handle exception ... */ }
```

---

**Thread Pool Main Program (cont’d)**

```c
int pool_size = argc < 2 ? DEFAULT_POOL_SIZE : atoi (argv[1]);
```

---
Thread Pool Configuration

The run_orb adapter function

```c
void run_orb (void *arg)
{
    try {
        CORBA::ORB_ptr orb =
            ACE_reinterpret_cast (CORBA::ORB_ptr, arg);
        // Block indefinitely waiting for incoming
        // invocations and dispatch upcalls.
        orb->run ();
        // After run() returns, the ORB has shutdown.
    } catch (...) { /* handle exception ... */ }
}
```

The ORB's svc.conf file

```c
static Resource_Factory "-ORBReactorType tp"
```

Client/Server Structure

- The client works with any server concurrency model
- The client obtains a Quoter object reference, spawns n threads, and obtains a Quoter object reference per-thread
- Each thread queries the Quoter 100 times to obtain the value of ACME ORB's stock
- main() then waits for threads to terminate

Client Code

The entry point function that does a remote invocation to get a stock quote from the server

```c
// This method executes in one or more threads.
static void *get_quotes (void *arg)
{
    Quoter_Factory_ptr factory = static_cast<Quoter_Factory_ptr> (arg);
    CosLifeCycle::Key key = Options::instance ()->key ();
    Quoter_var quoter = Stock::Quoter::_narrow(factory->create_object (key));
    if (!CORBA::is_nil (quoter)) {
        for (int i = 0; i < 100; i++) {
            long value = quoter->get_quote ("ACME ORB");
            cout << "value = " << value << endl;
        }
        quoter->remove ();
    }
}
```

Main Client Program

Client spawns threads to run the get_quotes function and waits for threads to exit

```c
int main (int argc, char *argv[])
{
    Options::instance ()->parse_args (argc, argv);
    try {
        // Narrow to Quoter_Factory interface.
        Quoter_Factory_var factory =
            bind_service<Quoter_Factory> ("My_Quoter_Factory", argc, argv);
        // Create client threads.
        ACE_Thread_Manager::instance ()->spawn_n
            (Options::instance ()->threads (), get_quotes,
                (void *) factory, THR_DETACHED | THR_NEW_LWP);
        // Wait for the client threads to exit
        ACE_Thread_Manager::instance ()->wait ();
    } catch (...) { /* ... */ }
}
Obtaining an Object Reference via the Naming Service

```cpp
template <class T> T::ptr_type bind_service (const char *n, int argc, char *argv[])
{
    CORBA::Object_var obj; // "First time" check.
    if (CORBA::is_nil (name_context)) {
        // Get reference to name service.
        orb = CORBA::ORB_init (argc, argv, 0);
        name_context = CosNaming::NamingContext::_narrow (obj);
        if (CORBA::is_nil (name_context)) return 0;
    }
    CosNaming::Name svc_name; svc_name.length (1); svc_name[0].id = n;
    svc_name[0].kind = "object_impl";
    // Find object reference in the name service.
    obj = name_context->resolve (svc_name);
    // Narrow to the T interface and away we go!
    return T::narrow (obj);
}
```

Concluding Remarks

- TAO supports several threading models
  - Performance may determine model choice
- ACE provides key building blocks for simplifying concurrent application code
  - www.cs.wustl.edu/~schmidt/ACE.html
- More information on CORBA can be obtained at
  - www.cs.wustl.edu/~schmidt/corba.html
- C++ Report columns written with Steve Vinoski