Aspect-Oriented Programming with C++ and AspectC++

AOSD 2005 Tutorial

University of Erlangen-Nuremberg
Computer Science 4

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Schedule

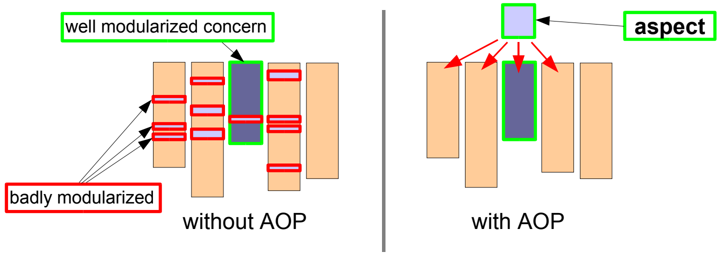
Part	Title	Time
I	Introduction	10m
II	AOP with pure C++	40m
III	AOP with AspectC++	70m
IV	Tool support for AspectC++	30m
V	Real-World Examples	20m
VI	Summary and Discussion	10m

This Tutorial is about ...

- Writing aspect-oriented code with **pure C++**
  - basic implementation techniques using C++ idioms
  - limitations of the pure C++ approach
- Programming with **AspectC++**
  - language concepts, implementation, tool support
  - **this is an AspectC++ tutorial**
- Programming languages and concepts
  - no coverage of other AOSD topics like analysis or design

Aspect-Oriented Programming

- AOP is about modularizing crosscutting concerns

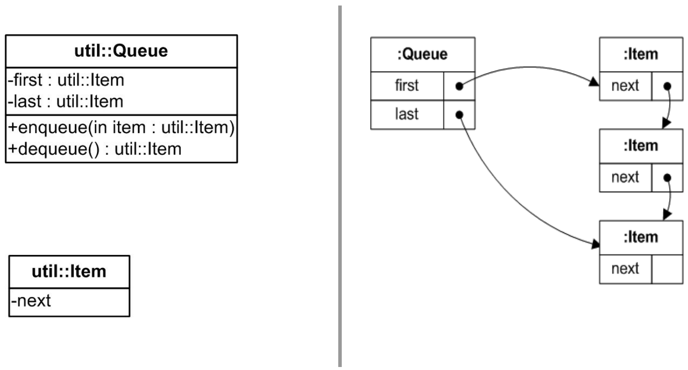


- Examples: tracing, synchronization, security, buffering, error handling, constraint checks, ...

Why AOP with C++?

- Widely accepted benefits from using AOP
  - avoidance of code redundancy, better reusability, maintainability, configurability, the code better reflects the design, ...
- Enormous existing C++ code base
  - maintainance: extensions are often crosscutting
- Millions of programmers use C++
  - for many domains C++ is *the* adequate language
  - they want to benefit from AOP (as Java programmers do)
- How can the AOP community help?
  - Part II: describe how to apply AOP with built-in mechanisms
  - Part III-V: provide special language mechanisms for AOP

Scenario: A Queue utility class



The Simple Queue Class

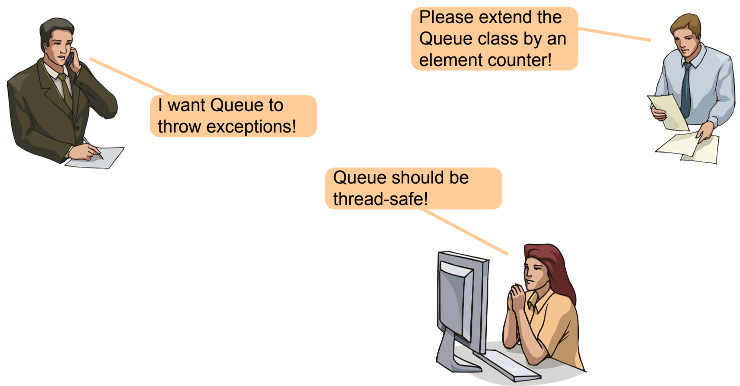
```
namespace util {
  class Item {
    friend class Queue;
    Item* next;
  public:
    Item() : next(0){}
  };

  class Queue {
    Item* first;
    Item* last;
  public:
    Queue() : first(0), last(0) {}

    void enqueue( Item* item ) {
      printf( "  > Queue::enqueue()\n" );
      if( last ) {
        last->next = item;
        last = item;
      } else
        last = first = item;
      printf( "  < Queue::enqueue()\n" );
    }
    Item* dequeue() {
      printf("  > Queue::dequeue()\n");
      Item* res = first;
      if( first == last )
        first = last = 0;
      else
        first = first->next;
      printf("  < Queue::dequeue()\n");
      return res;
    }
  }; // class Queue
} // namespace util
```

Scenario: The Problem

Various users of Queue demand extensions:



The Not So Simple Queue Class

```
class Queue {
  Item *first, *last;
  int counter;
  os::Mutex lock;
public:
  Queue () : first(0), last(0) {
    counter = 0;
  }
  void enqueue(Item* item) {
    lock.enter();
    try {
      if (item == 0)
        throw QueueInvalidItemError();
      if (last) {
        last->next = item;
        last = item;
      } else { last = first = item; }
      ++counter;
    } catch (...) {
      lock.leave(); throw;
    }
    lock.leave();
  }
```

```
  Item* dequeue() {
    Item* res;
    lock.enter();
    try {
      res = first;
      if (first == last)
        first = last = 0;
      else first = first->next;
      if (counter > 0) –counter;
      if (res == 0)
        throw QueueEmptyError();
    } catch (...) {
      lock.leave();
      throw;
    }
    lock.leave();
    return res;
  }
  int count() { return counter; }
}; // class Queue
```


What Code Does What?

```
class Queue {
  Item *first, *last;
  int counter;
  os::Mutex lock;
public:
  Queue () : first(0), last(0) {
    counter = 0;
  }
  void enqueue(Item* item) {
    lock.enter();
    try {
      if (item == 0)
        throw QueueInvalidItemError();
      if (last) {
        last->next = item;
        last = item;
      } else { last = first = item; }
      ++counter;
    } catch (...) {
      lock.leave(); throw;
    }
    lock.leave();
  }
```

```
  Item* dequeue() {
    Item* res;
    lock.enter();
    try {
      res = first;
      if (first == last)
        first = last = 0;
      else first = first->next;
      if (counter > 0) –counter;
      if (res == 0)
        throw QueueEmptyError();
    } catch (...) {
      lock.leave();
      throw;
    }
    lock.leave();
    return res;
  }
  int count() { return counter; }
}; // class Queue
```


Problem Summary

The component code is “polluted” with code for several logically independent concerns, thus it is ...

- hard to **write** the code
  - many different things have to be considered simultaneously
- hard to **read** the code
  - many things are going on at the same time
- hard to **maintain** and **evolve** the code
  - the implementation of concerns such as locking is **scattered** over the entire source base (a “*crosscutting concern*”)
- hard to **configure** at compile time
  - the users get a “one fits all” queue class

Aspect-Oriented Programming
with
C++ and AspectC++

AOSD 2005 Tutorial

Part III – Aspect C++

The Simple Queue Class Revisited

```
namespace util {
  class Item {
    friend class Queue;
    Item* next;
  public:
    Item() : next(0){}
  };

  class Queue {
    Item* first;
    Item* last;
  public:
    Queue() : first(0), last(0) {}

    void enqueue( Item* item ) {
      printf( "  > Queue::enqueue()\n" );
      if( last ) {
        last->next = item;
        last = item;
      } else
        last = first = item;
      printf( "  < Queue::enqueue()\n" );
    }
```

```
    Item* dequeue() {
      printf("  > Queue::dequeue()\n");
      Item* res = first;
      if( first == last )
        first = last = 0;
      else
        first = first->next;
      printf("  < Queue::dequeue()\n");
      return res;
    }
  }; // class Queue

} // namespace util
```


Queue: Demanded Extensions

I. Element counting

Please extend the Queue class by an element counter!

II. Errorhandling
(signaling of errors by exceptions)

III. Thread safety
(synchronization by mutex variables)

Element counting: The Idea

- Increment a counter variable after each execution of `util::Queue::enqueue()`
- Decrement it after each execution of `util::Queue::dequeue()`

ElementCounter1

```
aspect ElementCounter {

  int counter;
  ElementCounter() {
    counter = 0;
  }

  advice execution("% util::Queue::enqueue(...)") : after() {
    ++counter;
    printf( "  Aspect ElementCounter: # of elements = %d\n", counter );
  }
  advice execution("% util::Queue::dequeue(...)") : after() {
    if( counter > 0 ) --counter;
    printf( "  Aspect ElementCounter: # of elements = %d\n", counter );
  }
};
```

ElementCounter1.ah

ElementCounter1 - Elements

```
aspect ElementCounter {

  int counter;
  ElementCounter() {
    counter = 0;
  }

  advice execution("% util::Queue::enqueue(...)") : after() {
    ++counter;
    printf( "  Aspect ElementCounter: # of elements = %d\n", counter );
  }
  advice execution("% util::Queue::dequeue(...)") : after() {
    if( counter > 0 ) --counter;
    printf( "  Aspect ElementCounter: # of elements = %d\n", counter );
  }
};
```

We introduced a new **aspect** named *ElementCounter*.
An aspect starts with the keyword aspect and is syntactically much like a class.

ElementCounter1.ah

ElementCounter1 - Elements

```
aspect ElementCounter {

  int counter;
  ElementCounter() {
    counter = 0;
  }

  advice execution("% util::Queue::enqueue(...)") : after() {
    ++counter;
    printf( "  Aspect ElementCounter: # of elements = %d\n", counter );
  }
  advice execution("% util::Queue::dequeue(...)") : after() {
    if( counter > 0 ) --counter;
    printf( "  Aspect ElementCounter: # of elements = %d\n", counter );
  }
};
```

Like a class, an aspect can define data members, constructors and so on

ElementCounter1.ah

ElementCounter1 - Elements

```
aspect ElementCounter {

  int counter;
  ElementCounter() {
    counter = 0;
  }

  advice execution("% util::Queue::enqueue(...)") : after() {
    ++counter;
    printf( "  Aspect ElementCounter: # of elements = %d\n", counter );
  }
  advice execution("% util::Queue::dequeue(...)") : after() {
    if( counter > 0 ) --counter;
    printf( "  Aspect ElementCounter: # of elements = %d\n", counter );
  }
};
```

We give **after advice** (= some crosscuting code to be executed after certain control flow positions)

ElementCounter1.ah

ElementCounter1 - Elements

This **pointcut expression** denotes where the advice should be given. (After **execution** of methods that match the pattern)

```
aspect ElementCounter {

  int counter;
  ElementCounter() {
    counter = 0;
  }

  advice execution("% util::Queue::enqueue(...)") : after() {
    ++counter;
    printf( "  Aspect ElementCounter: # of elements = %d\n", counter );
  }
  advice execution("% util::Queue::dequeue(...)") : after() {
    if( counter > 0 ) --counter;
    printf( "  Aspect ElementCounter: # of elements = %d\n", counter );
  }
};
```

ElementCounter1.ah

ElementCounter1 - Elements

Aspect member elements can be accessed from within the advice body

```
aspect ElementCounter {

  int counter;
  ElementCounter() {
    counter = 0;
  }

  advice execution("% util::Queue::enqueue(...)") : after() {
    ++counter;
    printf( "  Aspect ElementCounter: # of elements = %d\n", counter );
  }
  advice execution("% util::Queue::dequeue(...)") : after() {
    if( counter > 0 ) --counter;
    printf( "  Aspect ElementCounter: # of elements = %d\n", counter );
  }
};
```

ElementCounter1.ah

ElementCounter1 - Result

```
int main() {
  util::Queue queue;

  printf("main(): enqueueing an item\n");
  queue.enqueue( new util::Item );

  printf("main(): dequeueing two items\n");
  Util::Item* item;
  item = queue.dequeue();
  item = queue.dequeue();
}
```

main.cc

```
main(): enqueueing am item
  > Queue::enqueue(00320FD0)
  < Queue::enqueue(00320FD0)
  Aspect ElementCounter: # of elements = 1
main(): dequeueing two items
  > Queue::dequeue()
  < Queue::dequeue() returning 00320FD0
  Aspect ElementCounter: # of elements = 0
  > Queue::dequeue()
  < Queue::dequeue() returning 00000000
  Aspect ElementCounter: # of elements = 0
```

<Output>

ElementCounter1 – What's next?

- The aspect is not the ideal place to store the counter, because it is shared between all Queue instances
- Ideally, counter becomes a member of Queue
- In the next step, we
  - move counter into Queue by **introduction**
  - **expose context** about the aspect invocation to access the current Queue instance

ElementCounter2

```
aspect ElementCounter {
private:
  advice "util::Queue" : int counter;
public:

  advice "util::Queue" : int count { return counter; } const

  advice execution("% util::Queue::enqueue(...)")
                 && that(queue) : after( util::Queue& queue )  {
    ++queue.counter;
    printf( "  Aspect ElementCounter: # of elements = %d\n", queue.count() );
  }
  advice execution("% util::Queue::dequeue(...)")
                 && that(queue) : after( util::Queue& queue )  {
    if( queue.count() > 0 ) --queue.counter;
    printf( "  Aspect ElementCounter: # of elements = %d\n", queue.count() );
  }
  advice construction("util::Queue")
                 && that(queue) : before( util::Queue& queue ) {
    queue.counter = 0;
  }
};
```

ElementCounter2.ah

ElementCounter2 - Elements

```
aspect ElementCounter {
private:
  advice "util::Queue" : int counter;
public:

  advice "util::Queue" : int count { return counter; } const

  advice execution("% util::Queue::enqueue(...)")
                 && that(queue) : after( util::Queue& queue )  {
    ++queue.counter;
    printf( "  Aspect ElementCounter: # of elements = %d\n", queue.count() );
  }
  advice execution("% util::Queue::dequeue(...)")
                 && that(queue) : after( util::Queue& queue )  {
    if( queue.count() > 0 ) --queue.counter;
    printf( "  Aspect ElementCounter: # of elements = %d\n", queue.count() );
  }
  advice construction("util::Queue")
                 && that(queue) : before( util::Queue& queue ) {
    queue.counter = 0;
  }
};
```

Introduces a new data member *counter* into all classes denoted by the pointcut "util::Queue"

ElementCounter2.ah

ElementCounter2 - Elements

```
aspect ElementCounter {
private:
  advice "util::Queue" : int counter;
public:

  advice "util::Queue" : int count { return counter; } const

  advice execution("% util::Queue::enqueue(...)")
                 && that(queue) : after( util::Queue& queue )  {
    ++queue.counter;
    printf( "  Aspect ElementCounter: # of elements = %d\n", queue.count() );
  }
  advice execution("% util::Queue::dequeue(...)")
                 && that(queue) : after( util::Queue& queue )  {
    if( queue.count() > 0 ) --queue.counter;
    printf( "  Aspect ElementCounter: # of elements = %d\n", queue.count() );
  }
  advice construction("util::Queue")
                 && that(queue) : before( util::Queue& queue ) {
    queue.counter = 0;
  }
};
```

We also introduce a public method to read the counter

ElementCounter2.ah

ElementCounter2 - Elements

```
aspect ElementCounter {
private:
  advice "util::Queue" : int counter;
public:

  advice "util::Queue" : int count { return counter; } const

  advice execution("% util::Queue::enqueue(...)")
                 && that(queue) : after( util::Queue& queue )  {
    ++queue.counter;
    printf( "  Aspect ElementCounter: # of elements = %d\n", queue.count() );
  }
  advice execution("% util::Queue::dequeue(...)")
                 && that(queue) : after( util::Queue& queue )  {
    if( queue.count() > 0 ) --queue.counter;
    printf( "  Aspect ElementCounter: # of elements = %d\n", queue.count() );
  }
  advice construction("util::Queue")
                 && that(queue) : before( util::Queue& queue ) {
    queue.counter = 0;
  }
};
```

A **context variable** *queue* is bound to *that* (the calling instance). The calling instance has to be an util::Queue

ElementCounter2.ah

ElementCounter2 - Elements

```
aspect ElementCounter {
private:
  advice "util::Queue" : int counter;
public:

  advice "util::Queue" : int count { return counter; } const

  advice execution("% util::Queue::enqueue(...)")
                 && that(queue) : after( util::Queue& queue )  {
    ++queue.counter;
    printf( "  Aspect ElementCounter: # of elements = %d\n", queue.count() );
  }
  advice execution("% util::Queue::dequeue(...)")
                 && that(queue) : after( util::Queue& queue )  {
    if( queue.count() > 0 ) --queue.counter;
    printf( "  Aspect ElementCounter: # of elements = %d\n", queue.count() );
  }
  advice construction("util::Queue")
                 && that(queue) : before( util::Queue& queue ) {
    queue.counter = 0;
  }
};
```

The context variable *queue* is used to access the calling instance.

ElementCounter2.ah

ElementCounter2 - Elements

```
aspect ElementCounter {
private:
  advice "util::Queue" : int counter;
public:

  advice "util::Queue" : int count { return counter; } const

  advice execution("% util::Queue::enqueue(...)")
                 && that(queue) : after( util::Queue& queue )  {
    ++queue.counter;
    printf( "  Aspect ElementCounter: # of elements = %d\n", queue.count() );
  }
  advice execution("% util::Queue::dequeue(...)")
                 && that(queue) : after( util::Queue& queue )  {
    if( queue.count() > 0 ) --queue.counter;
    printf( "  Aspect ElementCounter: # of elements = %d\n", queue.count() );
  }
  advice construction("util::Queue")
                 && that(queue) : before( util::Queue& queue ) {
    queue.counter = 0;
  }
};
```

By giving **construction advice** we ensure that counter gets initialized

ElementCounter2.ah

ElementCounter2 - Result

```
int main() {
  util::Queue queue;
  printf("main(): Queue contains %d items\n", queue.count());
  printf("main(): enqueueing some items\n");
  queue.enqueue(new util::Item);
  queue.enqueue(new util::Item);
  printf("main(): Queue contains %d items\n", queue.count());
  printf("main(): dequeueing one items\n");
  util::Item* item;
  item = queue.dequeue();
  printf("main(): Queue contains %d items\n", queue.count());
}
```

main.cc

ElementCounter2 - Result

```
int main() {
  util::Queue queue;
  printf("main(): Queue contains %d items\n", queue.count());
  printf("main(): enqueueing some items\n");
  queue.enqueue(new util::Item);
  queue.enqueue(new util::Item);
  printf("main(): Queue contains
  printf("main(): dequeueing one
  util::Item* item;
  item = queue.dequeue();
  printf("main(): Queue contains
}
```

main.cc

```
main(): Queue contains 0 items
main(): enqueueing some items
  > Queue::enqueue(00320FD0)
  < Queue::enqueue(00320FD0)
  Aspect ElementCounter: # of elements = 1
  > Queue::enqueue(00321000)
  < Queue]::enqueue(00321000)
  Aspect ElementCounter: # of elements = 2
main(): Queue contains 2 items
main(): dequeueing one items
  > Queue::dequeue()
  < Queue::dequeue() returning 00320FD0
  Aspect ElementCounter: # of elements = 1
main(): Queue contains 1 items
```

<Output>

ElementCounter – Lessons Learned

You have seen...

- the most important concepts of AspectC++
  - Aspects are introduced with the keyword *aspect*
  - They are much like a class, may contain methods, data members, types, inner classes, etc.
  - Additionaly, aspects can give *advice* to be woven in at certain positions (*joinpoints*). Advice can be given to
    - Functions/Methods/Constructors: code to execute (*code advice*)
    - Classes or structs: new elements (*introductions*)
  - Joinpoints are described by *pointcut expressions*
- We will now take a closer look at some of them

Syntactic Elements

aspect name | pointcut expression | advice type

```
aspect ElementCounter {

  advice execution("% util::Queue::enqueue(...)") : after()
  {
    printf( "  Aspect ElementCounter: after Queue::enqueue!\n" );
  }

  ...
};
```

ElementCounter1.ah

advice body

Joinpoints

- A **joinpoint** denotes a position to give advice
  - **Code** joinpoint
    a point in the **control flow** of a running program, e.g.
    - **execution** of a function
    - **call** of a function
  - **Name** joinpoint
    - a **named C++ program entity** (identifier)
    - class, function, method, type, namespace
- Joinpoints are given by **pointcut expressions**
  - a pointcut expression describes a **set of joinpoints**

Pointcut Expressions

- Pointcut expressions are made from ...
  - **match expressions**, e.g. "% util::queue::enqueue(...)"
    - are matched against C++ programm entities → name joinpoints
    - support wildcards
  - **pointcut functions**, e.g execution(...), call(...), that(...)
    - **execution:** all points in the control flow, where a function is about to be executed → code joinpoints
    - **call:** all points in the control flow, where a function is about to be called → code joinpoints
- Pointcut functions can be combined into expressions
  - using logical connectors: &&, ||, !
  - Example: call("% util::Queue::enqueue(...)") && within("% main(...)")

Advice

Advice to functions

- **before advice**
  - Advice code is executed **before** the original code
  - Advice may read/modify parameter values
- **after advice**
  - Advice code is executed **after** the original code
  - Advice may read/modify return value
- **around advice**
  - Advice code is executed **instead of** the original code
  - Original code may be called explicitly: `tjp->proceed()`

Introductions

- Additional methods, data members, etc. are added to the class
- Can be used to extend the interface of a class

Before / After Advice

with execution joinpoints:

advice execution(“void ClassA::foo()”) : **before**()

advice execution(“void ClassA::foo()”) : **after**()

```
class ClassA {
public:
  void foo(){
    printf(“ClassA::foo()”\n);
  }
}
```

with call joinpoints:

advice call (“void ClassA::foo()”) : **before**()

advice call (“void ClassA::foo()”) : **after**()

```
int main(){
  printf(“main()\n”);
  ClassA a;
  a.foo();
}
```


Around Advice

with execution joinpoints:

advice execution(“void ClassA::foo()”) : **around**()
before code

tjp->proceed()

after code

```
class ClassA {
public:
  void foo(){
    printf(“ClassA::foo()”\n);
  }
}
```

with call joinpoints:

advice call(“void ClassA::foo()”) : **around**()
before code

tjp->proceed()

after code

```
int main(){
  printf(“main()\n”);
  ClassA a;
  a.foo();
}
```


Introductions

private:
advice “ClassA” : *element to introduce*

public:
advice “ClassA” : *element to introduce*

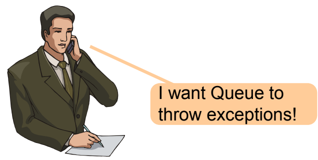
```
class ClassA {

public:

  void foo(){
    printf(“ClassA::foo()”\n);
  }
}
```

Queue: Demanded Extensions

I. Element counting



II. Errorhandling
(signaling of errors by exceptions)

III. Thread safety
(synchronization by mutex variables)

Errorhandling: The Idea

- We want to check the following constraints:
  - enqueue() is never called with a NULL item
  - dequeue() is never called on an empty queue
- In case of an error an exception should be thrown

- To implement this, we need access to ...
  - the parameter passed to enqueue()
  - the return value returned by dequeue()

  ... from within the advice

ErrorException

```
namespace util {
  struct QueueInvalidItemError {};
  struct QueueEmptyError {};
}

aspect ErrorException {

  advice execution("% util::Queue::enqueue(...)") && args(item)
      : before(util::Item* item) {
    if( item == 0 )
      throw util::QueueInvalidItemError();
  }
  advice execution("% util::Queue::dequeue(...)") && result(item)
      : after(util::Item* item) {
    if( item == 0 )
      throw util::QueueEmptyError();
  }
};
```

ErrorException.ah

ErrorException - Elements

We give advice to be executed *before* enqueue() and *after* dequeue()

```
namespace util {
  struct QueueInvalidItemError {};
  struct QueueEmptyError {};
}

aspect ErrorException {

  advice execution("% util::Queue::enqueue(...)") && args(item)
      : before(util::Item* item) {
    if( item == 0 )
      throw util::QueueInvalidItemError();
  }
  advice execution("% util::Queue::dequeue(...)") && result(item)
      : after(util::Item* item) {
    if( item == 0 )
      throw util::QueueEmptyError();
  }
};
```

ErrorException.ah

ErrorException - Elements

```
namespace util {
  struct QueueInvalidItemError {};
  struct QueueEmptyError {};
}

aspect ErrorException {

  advice execution("% util::Queue::enqueue(...)") && args(item)
      : before(util::Item* item) {
    if( item == 0 )
      throw util::QueueInvalidItemError();
  }
  advice execution("% util::Queue::dequeue(...)") && result(item)
      : after(util::Item* item) {
    if( item == 0 )
      throw util::QueueEmptyError();
  }
};
```

A **context variable** *item* is bound to the first **argument** of type *util::Item** passed to the matching methods

ErrorException.ah

ErrorException - Elements

```
namespace util {
  struct QueueInvalidItemError {};
  struct QueueEmptyError {};
}

aspect ErrorException {

  advice execution("% util::Queue::enqueue(...)") && args(item)
      : before(util::Item* item) {
    if( item == 0 )
      throw util::QueueInvalidItemError();
  }
  advice execution("% util::Queue::dequeue(...)") && result(item)
      : after(util::Item* item) {
    if( item == 0 )
      throw util::QueueEmptyError();
  }
};
```

Here the **context variable** *item* is bound to the **result** of type *util::Item** returned by the matching methods

ErrorException.ah

ErrorException – Lessons Learned

You have seen how to ...

- use different types of advice
  - **before** advice
  - **after** advice
- expose context in the advice body
  - by using **args** to read/modify parameter values
  - by using **result** to read/modify the return value

Queue: Demanded Extensions

I. Element counting

II. Errorhandling
(signaling of errors by exceptions)

Queue should be thread-safe!

III. Thread safety
(synchronization by mutex variables)

Thread Safety: The Idea

- Protect enqueue() and dequeue() by a mutex object
- To implement this, we need to
  - introduce a mutex variable into class Queue
  - lock the mutex before the execution of enqueue() / dequeue()
  - unlock the mutex after execution of enqueue() / dequeue()
- The aspect implementation should be exception safe!
  - in case of an exception, pending after advice is not called
  - solution: use around advice

LockingMutex

```
aspect LockingMutex {
  advice "util::Queue" : os::Mutex lock;

  pointcut sync_methods() = "% util::Queue::%queue(...)";

  advice execution(sync_methods()) && that(queue)
  : around( util::Queue& queue ) {
    queue.lock.enter();
    try {
      tjp->proceed();
    }
    catch(...) {
      queue.lock.leave();
      throw;
    }
    queue.lock.leave();
  }
};
```

LockingMutex.ah

LockingMutex - Elements

```
aspect LockingMutex {
  advice "util::Queue" : os::Mutex lock;

  pointcut sync_methods() = "% util::Queue::%queue(...)";

  advice execution(sync_methods()) && that(queue)
  : around( util::Queue& queue ) {
    queue.lock.enter();
    try {
      tjp->proceed();
    }
    catch(...) {
      queue.lock.leave();
      throw;
    }
    queue.lock.leave();
  }
};
```

We introduce a mutex member into class Queue

LockingMutex.ah

LockingMutex - Elements

```
aspect LockingMutex {
  advice "util::Queue" : os::Mutex lock;

  pointcut sync_methods() = "% util::Queue::%queue(...)";

  advice execution(sync_methods()) && that(queue)
  : around( util::Queue& queue ) {
    queue.lock.enter();
    try {
      tjp->proceed();
    }
    catch(...) {
      queue.lock.leave();
      throw;
    }
    queue.lock.leave();
  }
};
```

Pointcuts can be named. *sync_methods* describes all methods that have to be synchronized by the mutex

LockingMutex.ah

LockingMutex - Elements

```
aspect LockingMutex {
  advice "util::Queue" : os::Mutex lock;

  pointcut sync_methods() = "% util::Queue::%queue(...)";

  advice execution(sync_methods()) && that(queue)
  : around( util::Queue& queue ) {
    queue.lock.enter();
    try {
      tjp->proceed();
    }
    catch(...) {
      queue.lock.leave();
      throw;
    }
    queue.lock.leave();
  }
};
```

LockingMutex.ah

sync_methods is used to give around advice to the execution of the methods

LockingMutex - Elements

```
aspect LockingMutex {
  advice "util::Queue" : os::Mutex lock;

  pointcut sync_methods() = "% util::Queue::%queue(...)";

  advice execution(sync_methods()) && that(queue)
  : around( util::Queue& queue ) {
    queue.lock.enter();
    try {
      tjp->proceed();
    }
    catch(...) {
      queue.lock.leave();
      throw;
    }
    queue.lock.leave();
  }
};
```

LockingMutex.ah

By calling tjp->proceed() the original method is executed

LockingMutex – Lessons Learned

You have seen how to ...

- use named pointcuts
  - to increase readability of pointcut expressions
  - to reuse pointcut expressions
- use around advice
  - to deal with exception safety
  - to explicit invoke (or don't invoke) the original code by calling `tjp->proceed()`
- use wildcards in match expressions
  - "% util::Queue::%queue(...)" matches both enqueue() and dequeue()

Queue: A new Requirement

I. Element counting

II. Errorhandling
(signaling of errors by exceptions)

III. Thread safety
(synchronization by mutex variables)

IV. Interrupt safety
(synchronization on interrupt level)

We need Queue to be synchronized on interrupt level!

Interrupt Safety: The Idea

- Scenario
  - Queue is used to transport objects between kernel code (interrupt handlers) and application code
  - If application code accesses the queue, interrupts must be disabled first
  - If kernel code accesses the queue, interrupts must not be disabled
- To implement this, we need to distinguish
  - if the call is made from kernel code, or
  - if the call is made from application code

LockingIRQ1

```
aspect LockingIRQ {

  pointcut sync_methods() = "% util::Queue::%queue(...)";
  pointcut kernel_code()  = "% kernel::%(...)";

  advice call(sync_methods()) && !within(kernel_code()) : around() {
    os::disable_int();
    try {
      tjp->proceed();
    }
    catch(...) {
      os::enable_int();
      throw;
    }
    os::enable_int();
  }
};
```

LockingIRQ1.ah

LockingIRQ1 – Elements

```
aspect LockingIRQ {

  pointcut sync_methods() = "% util::Queue::%queue(...)";
  pointcut kernel_code()  = "% kernel::%(...)";

  advice call(sync_methods()) && !within(kernel_code()) : around() {
    os::disable_int();
    try {
      tjp->proceed();
    }
    catch(...) {
      os::enable_int();
      throw;
    }
    os::enable_int();
  }
};
```

We define two pointcuts. One for the methods to be synchronized and one for all kernel functions

LockingIRQ1.ah

LockingIRQ1 – Elements

```
aspect LockingIRQ {

  pointcut sync_methods() = "% util::Queue::%queue(...)";
  pointcut kernel_code()  = "% kernel::%(...)";

  advice call(sync_methods()) && !within(kernel_code()) : around() {
    os::disable_int();
    try {
      tjp->proceed();
    }
    catch(...) {
      os::enable_int();
      throw;
    }
    os::enable_int();
  }
};
```

This pointcut expression matches any call to a *sync_method* that is **not** done from *kernel_code*

LockingIRQ1.ah

LockingIRQ1 – Result

```
util::Queue queue;
void do_something() {
  printf("do_something()\n");
  queue.enqueue( new util::Item );
}
namespace kernel {
  void irq_handler() {
    printf("kernel::irq_handler()\n");
    queue.enqueue(new util::Item);
    do_something();
  }
}
int main() {
  printf("main()\n");
  queue.enqueue(new util::Item);
  kernel::irq_handler();  // irq
  printf("back in main()\n");
  queue.dequeue();
}
```

main.cc

```
main()
os::disable_int()
  > Queue::enqueue(00320FD0)
  < Queue::enqueue()
os::enable_int()
kernel::irq_handler()
  > Queue::enqueue(00321030)
  < Queue::enqueue()
do_something()
os::disable_int()
  > Queue::enqueue(00321060)
  < Queue::enqueue()
os::enable_int()
back in main()
os::disable_int()
  > Queue::dequeue()
  < Queue::dequeue() returning 00320FD0
os::enable_int()
```

<Output>

LockingIRQ1 – Problem

```
util::Queue queue;
void do_something() {
  printf("do_something()\n");
  queue.enqueue( new util::Item );
}
namespace kernel {
  void irq_handler() {
    printf("kernel::irq_handler()\n");
    queue.enqueue(new util::Item);
    do_something();
  }
}
int main() {
  printf("main()\n");
  queue.enqueue(new util::Item);
  kernel::irq_handler();  // irq
  printf("back in main()\n");
  queue.dequeue();
}
```

main.cc

The pointcut within(*kernel_code*) does not match any **indirect** calls to *sync_methods*

```
ma
os
  < Queue::enqueue()
os::enable_int()
kernel::irq_handler()
  > Queue::enqueue(00321030)
  < Queue::enqueue()
do_something()
os::disable_int()
  > Queue::enqueue(00321060)
  < Queue::enqueue()
os::enable_int()
back in main()
os::disable_int()
  > Queue::dequeue()
  < Queue::dequeue() returning 00320FD0
os::enable_int()
```

<Output>

LockingIRQ2

```
aspect LockingIRQ {

  pointcut sync_methods() = "% util::Queue::%queue(...)";
  pointcut kernel_code()  = "% kernel::%(...)";

  advice execution(sync_methods())
  && !cflow(execution(kernel_code())) : around() {
    os::disable_int();
    try {
      tjp->proceed();
    }
    catch(...) {
      os::enable_int();
      throw;
    }
    os::enable_int();
  }
};
```

Solution
Using the **cflow** pointcut function

LockingIRQ2.ah

LockingIRQ2 – Elements

```
aspect LockingIRQ {

  pointcut sync_methods() = "% util::Queue::%queue(...)";
  pointcut kernel_code()  = "% kernel::%(...)";

  advice execution(sync_methods())
  && !cflow(execution(kernel_code())) : around() {
    os::disable_int();
    try {
      tjp->proceed();
    }
    catch(...) {
      os::enable_int();
      throw;
    }
    os::enable_int();
  }
};
```

This pointcut expression matches the execution of *sync_methods* if no *kernel_code* is on the call stack. cflow checks the call stack (control flow) at runtime.

LockingIRQ2.ah

LockingIRQ2 – Result

```
util::Queue queue;
void do_something() {
  printf("do_something()\n");
  queue.enqueue( new util::Item );
}
namespace kernel {
  void irq_handler() {
    printf("kernel::irq_handler()\n");
    queue.enqueue(new util::Item);
    do_something();
  }
}
int main() {
  printf("main()\n");
  queue.enqueue(new util::Item);
  kernel::irq_handler();  // irq
  printf("back in main()\n");
  queue.dequeue();
}
```

main.cc

```
main()
os::disable_int()
  > Queue::enqueue(00320FD0)
  < Queue::enqueue()
os::enable_int()
kernel::irq_handler()
  > Queue::enqueue(00321030)
  < Queue::enqueue()
do_something()
  > Queue::enqueue(00321060)
  < Queue::enqueue()
back in main()
os::disable_int()
  > Queue::dequeue()
  < Queue::dequeue() returning 00320FD0
os::enable_int()
```

<Output>

LockingIRQ – Lessons Learned

You have seen how to ...

- restrict advice invocation to a specific calling context
- use the within(...) and cflow(...) pointcut functions
  - **within** is evaluated at **compile time** and returns all code joinpoints of a class' or namespaces lexical scope
  - **cflow** is evaluated at **runtime** and returns all joinpoints where the control flow is below a specific code joinpoint

AspectC++: A First Summary

- The Queue example has presented the most important features of the AspectC++ language
  - aspect, advice, joinpoint, pointcut expression, pointcut function, ...
- Additionaly, AspectC++ provides some more advanced concepts and features
  - to increase the expressive power of aspectual code
  - to write broadly reusable aspects
  - to deal with aspect interdependence and ordering
- In the following, we give a short overview on these advanced language elements

AspectC++: Advanced Concepts

- Join Point API
  - provides a uniform interface to the aspect invocation context, both at runtime and compile-time
- Abstract Aspects and Aspect Inheritance
  - comparable to class inheritance, aspect inheritance allows to reuse parts of an aspect and overwrite other parts
- Generic Advice
  - exploits static type information in advice code
- Aspect Ordering
  - allows to specify the invocation order of multiple aspects
- Aspect Instantiation
  - allows to implement user-defined aspect instantiation models

The Joinpoint API

- Inside an advice body, the current joinpoint context is available via the **implicitly passed tjp** variable:

```
advice ... {
  struct JoinPoint {
    ...
  } *tjp;       // implicitly available in advice code
  ...
}
```

- You have already seen how to use tjp, to ...
  - execute the original code in around advice with **tjp->proceed()**
- The joinpoint API provides a rich interface
  - to expose context **independently** of the aspect target
  - this is especially useful in writing **reusable aspect code**

The Join Point API (Excerpt)

Types (compile-time)

```
// object type (initiator)
That
// object type (receiver)
Target
// result type of the affected function
Result
// type of the i'th argument of the affected
// function (with 0 <= i < ARGS)
Arg<i>::Type
Arg<i>::ReferredType
```

Consts (compile-time)

```
// number of arguments
ARGS
// unique numeric identifier for this join point
JPID
// numeric identifier for the type of this join
// point (AC::CALL, AC::EXECUTION, ...)
JPTYPE
```

Values (runtime)

```
// pointer to the object initiating a call
That* that()
// pointer to the object that is target of a call
Target* target()
// pointer to the result value
Result* result()
// typed pointer the i'th argument value of a
// function call (compile-time index)
Arg<i>::ReferredType* arg()
// pointer the i'th argument value of a
// function call (runtime index)
void* arg( int i )
// textual representation of the joinpoint
// (function/class name, parameter types...)
static const char* signature()
// executes the original joinpoint code
// in an around advice
void proceed()
// returns the runtime action object
AC::Action& action()
```


Abstract Aspects and Inheritance

- Aspects can inherit from other aspects...
  - Reuse aspect definitions
  - Override methods and pointcuts
- Pointcuts can be pure virtual
  - Postpone the concrete definition to derived aspects
  - An aspect with a pure virtual pointcut is called **abstract aspect**
- Common usage: Reusable aspect implementations
  - Abstract aspect defines advice code, but pure virtual pointcuts
  - Aspect code uses the joinpoint API to expose context
  - Concrete aspect inherits the advice code and overrides pointcuts

Abstract Aspects and Inheritance

The abstract locking aspect declares two **pure virtual pointcuts** and uses the **joinpoint API** for an context-independent advice implementation.

LockingA.ah

```
#include "mutex.h"
aspect LockingA {
  pointcut virtual sync_classes() = 0;
  pointcut virtual sync_methods() = 0;

  advice sync_classes() : os::Mutex lock;

  advice execution(sync_methods()) : around() {
    tjp->that()->lock.enter();
    try {
      tjp->proceed();
    }
    catch(...) {
      tjp->that()->lock.leave();
      throw;
    }
    tjp->that()->lock.leave();
  }
};
```

LockingQueue.ah

```
#include "LockingA.ah"

aspect LockingQueue : public LockingA {
  pointcut sync_classes() =
    "util::Queue";
  pointcut sync_methods() =
    "% util::Queue::%queue(...)";
};
```

Abstract Aspects and Inheritance

```
#include "mutex.h"
aspect LockingA {
  pointcut virtual sync_classes() = 0;
  pointcut virtual sync_methods() = 0;

  advice sync_classes() : os::Mutex lock;

  advice execution(sync_methods()) : around() {
    tjp->that()->lock.enter();
    try {
      tjp->proceed();
    }
    catch(...) {
      tjp->that()->lock.leave();
      throw;
    }
    tjp->that()->lock.leave();
  }
};
```

LockingA.ah

The concrete locking aspect **derives** from the abstract aspect and **overrides** the pointcuts.

```
#include "LockingA.ah"

aspect LockingQueue : public LockingA {
  pointcut sync_classes() =
    "util::Queue";
  pointcut sync_methods() =
    "% util::Queue::%queue(...)";
};
```

LockingQueue.ah

Generic Advice

Uses static JP-specific type information in advice code

- in combination with C++ overloading
- to instantiate C++ templates and template meta-programs

```
aspect TraceService {
  advice call(...) : after() {
    ...
    cout << *tjp->result();
  }
};
```

... operator <<(..., **int**)

... operator <<(..., **long**)

... operator <<(..., **bool**)

... operator <<(..., **Foo**)

Aspect C++

Generic Advice

Uses static JP-specific type information in advice code

- in combination with C++ overloading
- ...plate meta-programs

Resolves to the **statically typed** return value

- no runtime type checks are needed
- unhandled types are detected at compile-time
- functions can be inlined

```
aspect TraceService {
  advice call(...) : after() {
    ...
    cout << *tjp->result();
  }
};
```

... operator <<(..., **int**)

... operator <<(..., **long**)

... operator <<(..., **bool**)

... operator <<(..., **Foo**)

Aspect C++

Aspect Ordering

- Aspects should be independent of other aspects
  - However, sometimes inter-aspect dependencies are unavoidable
  - Example: Locking should be activated before any other aspects
- Order advice
  - The aspect order can be defined by ***order advice***
    advice *pointcut-expr* : order(*high, ..., low*)
  - Different aspect orders can be defined for different pointcuts
- Example

```
advice "% util::Queue::%queue(...)"
    : order( "LockingIRQ", "%" && !"LockingIRQ" );
```

Aspect C++

Aspect Instantiation

- Aspects are singletons by default
  - **aspectof()** returns pointer to the one-and-only aspect instance
- By overriding aspectof() this can be changed
  - e.g. one instance per client or one instance per thread

```
aspect MyAspect {
  // ....
  static MyAspect* aspectof() {
    static __declspec(thread) MyAspect* theAspect;
      if( theAspect == 0 )
        theAspect = new MyAspect;
    return theAspect;
  }
};
```

MyAspect.ah

Example of an user-defined aspectof() implementation for per-thread aspect instantiation by using thread-local storage.

(Visual C++)

Summary

- AspectC++ facilitates AOP with C++
  - AspectJ-like syntax and semantics
- Full obliviousness and quantification
  - aspect code is given by **advice**
  - joinpoints are given declaratively by **pointcuts**
  - implementation of crosscutting concerns is fully encapsulated in **aspects**
- Good support for reusable and generic aspect code
  - **aspect inheritance** and **virtual pointcuts**
  - rich **joinpoint API**

And what about tool support?