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

AOSD 2005 Tutorial

University of Erlangen-Nuremberg
Computer Science 4

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Schedule

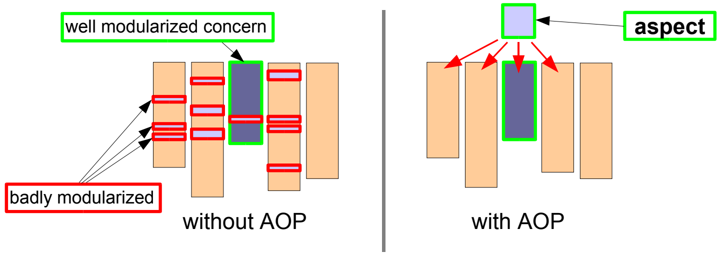
Part	Title	Time
I	Introduction	10m
II	AOP with pure C++	40m
III	AOP with AspectC++	70m
IV	Tool support for AspectC++	30m
V	Real-World Examples	20m
VI	Summary and Discussion	10m

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

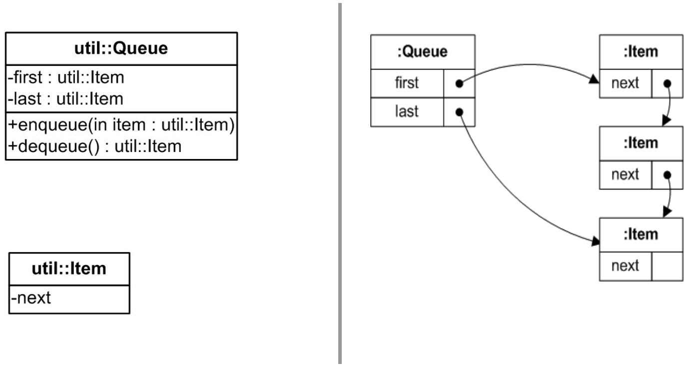


- Examples: tracing, synchronization, security, buffering, error handling, constraint checks, ...

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



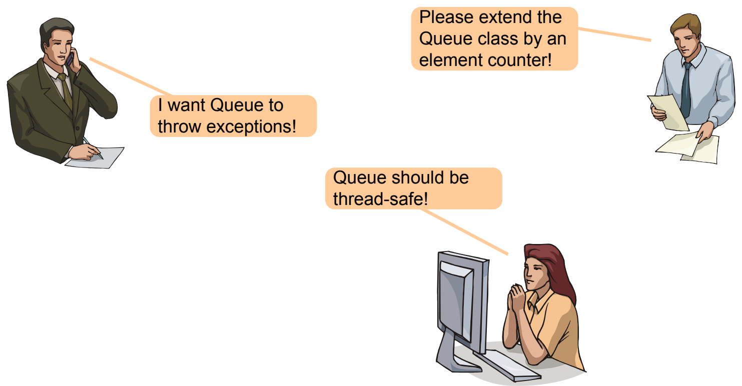
The Simple Queue Class

```
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++

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Part II – AOP with C++

Outline

- We go through the Queue example and...
  - decompose the "one-fits-all" code into modular units
  - apply simple AOP concepts
  - use only C/C++ language idioms and elements
- After we went through the example, we...
  - will try to understand the benefits and limitations of a pure C++ approach
  - motivate the need for an advanced language with built-in AOP concepts: AspectC++

Configuring with the Preprocessor?

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

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


Preprocessor

- While we are able to enable/disable features
  - the code is **not expressed in a modular fashion**
  - aspectual code is spread out over the entire code base
  - the code is almost unreadable
- Preprocessor is the "typical C way" to solve problems
- Which C++ mechanism could be used instead?

  Templates!

Templates

- Templates can be used to construct **generic** code
  - To actually use the code, it has to be **instantiated**
- Just as preprocessor directives
  - templates are evaluated at compile-time
  - do not cause any direct runtime overhead (if applied properly)

```
#define add1(T, a, b) \
  (((T)a)+((T)b))

template <class T>
T add2(T a, T b) { return a + b; }

printf("%d", add1(int, 1, 2));
printf("%d", add2<int>(1, 2));
```


Using Templates

Templates are typically used to implement generic abstract data types:

```
// Generic Array class
// Elements are stored in a resizable buffer
template< class T >
class Array {
  T* buf; // allocated memory
public:
  T operator[]( int i ) const {
    return buf[ i ];
  }
  ...
};
```


AOP with Templates

- Templates allow us to encapsulate aspect code independently from the component code
- Aspect code is "woven into" the component code by instantiating these templates

```
// component code
class Queue {
  ...
  void enqueue(Item* item) {
    if (last) { last->next = item; last = item; }
    else { last = first = item; }
  }
  Item* dequeue() {
    Item* res = first;
    if (first == last) first = last = 0;
    else first = first->next;
    return res;
  }
};
```


Aspects as Wrapper Templates

The counting aspect is expressed as a wrapper template class, that derives from the component class:

```
// generic wrapper (aspect), that adds counting to any queue class
// Q, as long it has the proper interface
template <class Q>               // Q is the component class this
class Counting_Aspect : public Q { // aspect should be applied on
  int counter;
public:
  void enqueue(Item* item) { // execute advice code after join point
    Q::enqueue(item); counter++;
  }
  Item* dequeue() { // again, after advice
    Item* res = Q::dequeue(item);
    if (counter > 0) counter--;
    return res;
  }
  // this method is added to the component code (introduction)
  int count() const { return counter; }
};
```

Weaving

We can define a type alias (typedef) that combines both, component and aspect code (**weaving**):

```
// component code
class Queue { ... }
// The aspect (wrapper class)
template <class Q>
class Counting_Aspect : public Q { ... }
// template instantiation
typedef Counting_Aspect<Queue> CountingQueue;

int main() {
  CountingQueue q;
  q.enqueue(new Item);
  q.enqueue(new Item);
  printf("number of items in q: %u\n", q.count());
  return 0;
}
```


Our First Aspect – Lessons Learned

- Aspects can be implemented by template wrappers
  - Aspect inherits from component class, overrides relevant methods
  - Introduction of new members (e.g. counter variable) is easy
  - Weaving takes place by defining (and using) type aliases
- The aspect code is generic
  - It can be applied to "any" component that exposes the same interface (enqueue, dequeue)
  - Each application of the aspect has to be specified explicitly
- The aspect code is clearly separated
  - All code related to counting is gathered in one template class
  - Counting aspect and queue class can be evolved independently (as long as the interface does not change)

Error Handling Aspect

Adding an error handling aspect (exceptions) is straight-forward. We just need a wrapper template:

```
// another aspect (as wrapper template)
template <class Q>
class Exceptions_Aspect : public Q {
  void enqueue(Item* item) { // this advice is executed before the
    if (item == 0)          // component code (before advice)
      throw QueueInvalidItemError();
    Q::enqueue(item);
  }

  Item* dequeue() { // after advice
    Item* res = Q::dequeue();
    if (res == 0) throw QueueEmptyError();
    return res;
  }
}
```


Combining Aspects

We already know how to weave with a single aspect. Weaving with multiple aspects is also straightforward:

```
// component code
class Queue { ... }
// wrappers (aspects)
template <class Q>
class Counting_Aspect : public Q { ... }
template <class Q>
class Exceptions_Aspect : public Q { ... }
// template instantiation (weaving)
typedef Exceptions_Aspect< Counting_Aspect< Queue > > ExceptionsCountingQueue;
```


Ordering

- In what order should we apply our aspects?

  Aspect code is executed outermost-first:

```
typedef Exceptions_Aspect< // first Exceptions, then Counting
        Counting_Aspect< Queue > > ExceptionsCountingQueue;

typedef Counting_Aspect< // first Counting, then Exceptions
        Exceptions_Aspect< Queue > > ExceptionsCountingQueue;
```

- Aspects should be independent of ordering
  - For dequeue(), both Exceptions_Aspect and Counting_Aspect give after advice. Shall we count first or check first?
  - Fortunately, our implementation can deal with both cases:

```
Item* res = Q::dequeue(item);
// its ok if we run before Exceptions_Wrapper
if (counter > 0) counter--;
return res;
```


Locking Aspect

With what we learned so far, putting together the locking aspect should be simple:

```
template <class Q>
class Locking_Aspect : public Q {
public:
  Mutex lock;
  void enqueue(Item* item) {
    lock.enter();
    try {
      Q::enqueue(item);
    } catch (...) {
      lock.leave();
      throw;
    }
    lock.leave();
  }
```

```
  Item* dequeue() {
    Item* res;
    lock.enter();
    try {
      res = Q::dequeue(item);
    } catch (...) {
      lock.leave();
      throw;
    }
    lock.leave();
    return res;
  }
};
```


Locking Advice (2)

Locking_Aspect uses an **around advice**, that **proceeds** with the component code in the middle of the aspect code:

```
template <class Q>
class Locking_Aspect : public Q {
public:
  Mutex lock;
  void enqueue(Item* item) {
    lock.enter();
    try {
      Q::enqueue(item);
    } catch (...) {
      lock.leave();
      throw;
    }
    lock.leave();
  }
```

```
  Item* dequeue() {
    Item* res;
    lock.enter();
    try {
      res = Q::dequeue(item);
    } catch (...) {
      lock.leave();
      throw;
    }
    lock.leave();
    return res;
  }
};
```


Advice Code Duplication

Specifying the same advice for several **joinpoints** leads to code duplication:

```
template <class Q>
class Locking_Aspect : public Q {
public:
  Mutex lock;
  void enqueue(Item* item) {
    lock.enter();
    try {
      Q::enqueue(item);
    } catch (...) {
      lock.leave();
      throw;
    }
    lock.leave();
  }
```

```
  Item* dequeue() {
    Item* res;
    lock.enter();
    try {
      res = Q::dequeue(item);
    } catch (...) {
      lock.leave();
      throw;
    }
    lock.leave();
    return res;
  }
};
```

Dealing with Joinpoint Sets

To specify advice for a set of joinpoints, the joinpoints must have a uniform interface:

```
template <class Q>
class Locking_Aspect2 : public Q {
public:
  Mutex lock;

  // wrap joinpoint invocations into action classes
  struct EnqueueAction {
    Item* item;
    void proceed(Q* q) { q->enqueue(item); }
  };

  struct DequeueAction {
    Item* res;
    void proceed(Q* q) { res = q->dequeue(); }
  };
  ...
```


Reusable Advice Code

The advice code is expressed as template function, which is later instantiated with an action class:

```
template <class Q>
class Locking_Aspect : public Q {
  ...
  template <class action> // template inside another template
  void advice(action* a) {
    lock.enter();
    try {
      a->proceed(this);
    } catch (...) {
      lock.leave();
      throw;
    }
    lock.leave();
  }
  ...
};
```


Binding Advice to Joinpoints

Using the action classes we have created, the advice code is now nicely encapsulated in a single function:

```
template <class Q>
class Locking_Aspect2 : public Q {
  ...
  void enqueue(Item* item) {
    EnqueueAction tjp = {item};
    advice(&tjp);
  }
  Item* dequeue() {
    DequeueAction tjp;
    advice(&tjp);
    return tjp.res;
  }
  ...
};
```


Reusing Advice – Lessons Learned

- We avoided advice code duplication, by...
  - delegating the invocation of the original code (proceed) to action classes
  - making the aspect code itself a template function
  - instantiating the aspect code with the action classes
- Compilers will probably generate less efficient code
  - Additional overhead for storing argument/result values

Putting Everyting Together

We can now instantiate the combined Queue class, which uses all aspects:

(For just 3 aspects, the typedef is already getting rather complex)

```
typedef Locking_Aspect2<Exceptions_Aspect<Counting_Aspect
   <Queue> > > CountingQueueWithExceptionsAndLocking;

// maybe a little bit more readable ...

typedef Counting_Aspect<Queue> CountingQueue;
typedef Exceptions_Aspect<CountingQueue> CountingQueueWithExceptions;
typedef Locking_Aspect<CountingQueueWithExceptions>
   CountingQueueWithExceptionsAndLocking;
```


"Obliviousness"

... is an essential property of AOP: the component code should not have to be aware of aspects, but ...

- the extended Queue cannot be named "Queue"
  - our aspects are selected through a naming scheme (e.g. `CountingQueueWithExceptionsAndLocking`).
- using wrapper class names violates the idea of obliviousness

Preferably, we want to hide the aspects from client code that uses affected components.

Hiding Aspects

- Aspects can be hidden using C++ **namespaces**
- Three separate namespaces are introduced
  - namespace **components**: component code for class Queue
  - namespace **aspects**: aspect code for class Queue
  - namespace **configuration**: selection of desired aspects for class Queue
- The complex naming schemes as seen on the previous slide is avoided

Hiding Aspects (2)

```
namespace components {
   class Queue { ... };
}
namespace aspects {
  template <class Q>
  class Counting_Aspect : public Q { ... };
}
namespace configuration {
   // select counting queue
   typedef aspects::Counting_Aspect<components::Queue> Queue;
}

// client code can import configuration namespace and use
// counting queue as "Queue"
using namespace configuration;

void client_code () {
  Queue queue; // Queue with all configured aspects
  queue.enqueue (new MyItem);
}
```

Obliviousness – Lessons Learned

- Aspect configuration, aspect code, and client code can be separated using C++ namespaces
  - name conflicts are avoided
- Except for using the configuration namespace the client code does not have to be changed
  - obliviousness is (mostly) achieved on the client-side

What about obliviousness in the extended classes?

Limitations

For simple aspects the presented techniques work quite well, but a closer look reveals limitations:

- Joinpoint types
  - no destinction between function call and execution
  - no generic interface to joinpoint context
  - no advice for private member functions
- Quantification
  - no flexible way to describe the target components (like AspectJ/AspectC++ pointcuts)
  - applying the same aspect to classes with different interfaces is impossible or ends with excessive template metaprogramming

Limitations (continued)

- Scalibility
  - the wrapper code can easily outweigh the aspect code
  - explicitly defining the aspect order for **every** affected class is error-prone and cumbersome
  - excessive use of templates and namespaces makes the code hard to understand and debug

"AOP with pure C++ is like OO with pure C"

Conclusions

- C++ templates can be used for separation of concerns in C++ code without special tool support
- However, the lack of expressiveness and scalibility restricts these techniques to projects with ...
  - only a small number of aspects
  - few or no aspect interactions
  - aspects with a non-generic nature
  - component code that is "aspect-aware"
- However, switching to tool support is **easy**!
  - aspects have already been extracted and modularized.
  - transforming template-based aspects to code expected by dedicated AOP tools is only mechanical labor

References/Other Approaches

K. Czarnecki, U.W. Eisenecker et. al.: *"Aspektorientierte Programmierung in C++"*, iX – Magazin für professionelle Informationstechnik, 08/09/10, 2001

- A comprehensive analysis of doing AOP with pure C++: what's possible and what not
- http://www.heise.de/ix/artikel/2001/08/143/

A. Alexandrescu: *"Modern C++ Design – Generic Programming and Design Patterns Applied"*, Addison-Wesley, C++ in depth series, 2001

- Introduces "policy-based design", a technique for advanced separation of concerns in C++
- Policy-based design tries to achieve somewhat similar goals as AOP does
- http://www.moderncppdesign.com/

Other suggestions towards AOP with pure C++:

- **C. Diggins:** *"Aspect Oriented Programming in C++"*
  http://www.heron-language.com/aspect-cpp.html
- **D. Vollmann**: *"Visibility of Join-Points in AOP and Implementation Languages"*
  http://i44w3.info.uni-karlsruhe.de/~pulvermu/workshops/aosd2002/submissions/vollmann.pdf

Aspect-Oriented Programming
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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 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 );
  }
};
```

Aspect member elements can be accessed from within the advice body

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

  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

```
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();
  }
};
```

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

ErrorException.ah

ErrorException - Elements

```
namespace util {
  struct QueueInvalidItemEr
  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 QueueInvalidItemEr
  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

Queue should be thread-safe!

II. Errorhandling
(signaling of errors by exceptions)

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();
  }
};
```

LockingIRQ2.ah

Solution
Using the **cflow** pointcut function

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();
  }
};
```

LockingIRQ2.ah

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 – 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.

```
#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

```
#include "LockingA.ah"

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

LockingQueue.ah

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**)

Generic Advice

Uses static JP-specific type information in advice code

- in combination with C++ overloading
- ...nplate 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 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 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?

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

AOSD 2005 Tutorial

Part IV – Tool Support

Overview

- ac++ compiler
  - open source and base of the other presented tools
- ag++ wrapper
  - easy to use wrapper around g++ for make-based projects
- AspectC++ Add-In for Microsoft® Visual Studio®
  - commercial product by pure-systems GmbH
- AspectC++ plugin for Eclipse®
  - sophisticated environment for AspectC++ development

➔ demonstration with the **tutorial CD**

About ac++

- Available from **www.aspectc.org**
  - Linux, Win32, Solaris, MacOS X binaries + source (GPL)
  - documentation: Compiler Manual, Language Reference, ...
- Transforms AspectC++ to C++ code
  - machine code is created by the back-end (cross-)compiler
  - supports g++ and Visual C++ specific language extensions
- Current version: 1.0
  - stable
  - (almost) feature-complete
  - no optimizations for compilation speed, yet

Aspect Transformation

```
aspect Transform {
  advice call("% foo()") : before() {
    printf("before foo call\n");
  }
  advice execution("% C::%()") : after()
{
    printf(tjp->signature ());
  }
};
```

Transform.ah

```
class Transform {
  static Transform __instance;
  // ...
  void __a0_before () {
    printf ("before foo call\n");
  }
  template<class JoinPoint>
    void __a1_after (JoinPoint *tjp) {
      printf (tjp->signature ());
    }
};
```

Transform.ah'

Aspect Transformation

```
aspect Transform {
  advice call("% foo()") : before() {
    printf("before foo call\n");
  }
  advice execution("% C::%()") : after()
{
    printf(tjp->signature ());
  }
};
```

Transform.ah

Aspects are transformed into **ordinary classes**

```
class Transform {
  static Transform __instance;
  // ...
  void __a0_before () {
    printf ("before foo call\n");
  }
  template<class JoinPoint>
    void __a1_after (JoinPoint *tjp) {
      printf (tjp->signature ());
    }
};
```

Transform.ah'

Aspect Transformation

```
aspect Transform {
  advice call("% foo()") : before() {
    printf("before foo call\n");
  }
  advice execution("% C::%()") : after()
{
    printf(tjp->signature ());
  }
};
```

Transform.ah

One global aspect **instance** is created by default

```
class Transform {
  static Transform __instance;
  // ...
  void __a0_before () {
    printf ("before foo call\n");
  }
  template<class JoinPoint>
    void __a1_after (JoinPoint *tjp) {
      printf (tjp->signature ());
    }
};
```

Transform.ah'

Aspect Transformation

```
aspect Transform {
  advice call("% foo()") : before() {
    printf("before foo call\n");
  }
  advice execution("% C::%()") : after()
{
    printf(tjp->signature ());
  }
};
```

Transform.ah

Advice becomes a **member function**

```
class Transform {
  static Transform __instance;
  // ...
  void __a0_before () {
    printf ("before foo call\n");
  }
  template<class JoinPoint>
    void __a1_after (JoinPoint *tjp) {
      printf (tjp->signature ());
    }
};
```

Transform.ah'

Aspect Transformation

```
aspect Transform {
  advice call("% foo()") : before() {
    printf("before foo call\n");
  }
  advice execution("% C::%()") : after()
{
    printf(tjp->signature ());
  }
};
```

Transform.ah

"Generic Advice" becomes a **template member function**

```
class Transform {
  static Transform __instance;
  // ...
  void __a0_before () {
    printf ("before foo call\n");
  }
  template<class JoinPoint>
    void __a1_after (JoinPoint *tjp) {
      printf (tjp->signature ());
    }
};
```

Transform.ah'

Joinpoint Transformation

```
int main() {
  foo();
  return 0;
}
```

main.cc

```
int main() {
  struct __call_main_0_0 {
    static inline void invoke (){
      AC::..._a0_before ();
      ::foo();
    }
  };
  __call_main_0_0::invoke ();
  return 0;
}
```

main.cc'

Joinpoint Transformation

```
int main() {
  foo();
  return 0;
}
```

main.cc

the function call is replaced by a call to a wrapper function

```
int main() {
  struct __call_main_0_0 {
    static inline void invoke (){
      AC::..._a0_before ();
      ::foo();
    }
  };
  __call_main_0_0::invoke ();
  return 0;
}
```

main.cc'

Joinpoint Transformation

```
int main() {
  foo();
  return 0;
}
```

main.cc

a local class invokes the advice code for this joinpoint

```
int main() {
  struct __call_main_0_0 {
    static inline void invoke (){
      AC::..._a0_before ();
      ::foo();
    }
  };
  __call_main_0_0::invoke ();
  return 0;
}
```

main.cc'

Translation Modes

- Whole Program Transformation-Mode
  - e.g. `ac++ -p src -d gen -e cpp -Iinc -DDEBUG`
  - transforms whole directory trees
  - generates manipulated headers, e.g. for libraries
  - can be chained with other whole program transformation tools
- Single Translation Unit-Mode
  - e.g. `ac++ -c a.cc -o a-gen.cc -p .`
  - easier integration into build processes

Tool Demos

- AspectC++ Add-In for Microsoft® Visual Studio®
  - by pure-systems GmbH (www.pure-systems.com)
- AspectC++ plugin for Eclipse®
  - sophisticated environement for AspectC++ development

Summary

- Tool support for AspectC++ programming is based on the ac++ command line compiler
  - full “obliviousness and quantification”
  - delegates the binary code generation to your favorite compiler
- Commercial and a non-commercial IDE integration is available
  - Microsoft® Visual Studio®
  - Eclipse®

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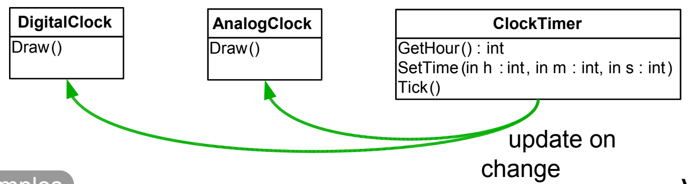
Part V – Examples

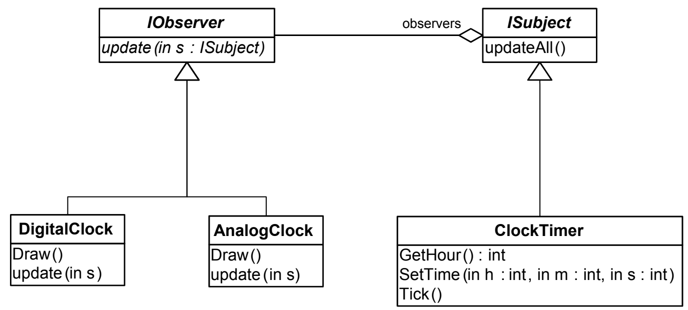
AspectC++ in Practice - Examples

- **Applying the observer protocol**
  - Example: a typical scenario for the widely used observer pattern
  - Problem: implementing observer requires several design and code transformations
- **Errorhandling in legacy code**
  - Example: a typical Win32 application
  - Problem: errorhandling often “forgotten” as too much of a bother
- **Product line development**
  - Example: an embedded weather station software family
  - Problem: optional crosscutting concerns in optional components (a typical case for the #ifdef hell)

Observer Pattern: Scenario

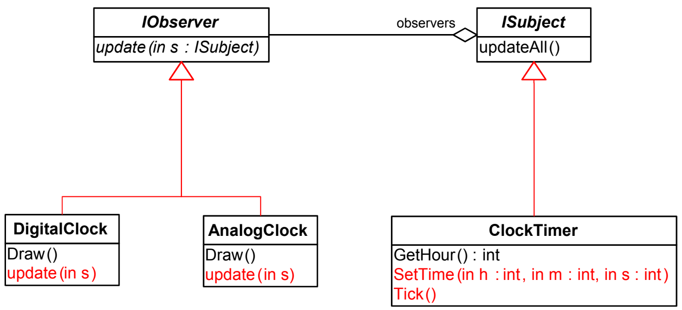


Observer Pattern: Implementation



Observer Pattern: Problem

The 'Observer Protocol' Concern...



...crosscuts the module structure

Solution: Generic Observer Aspect

```
aspect ObserverPattern {
  ...
public:
  struct ISubject {};
  struct IObserver {
    virtual void update (ISubject *) = 0;
  };

  pointcut virtual observers() = 0;
  pointcut virtual subjects() = 0;

  pointcut virtual subjectChange() =  execution( "% ...::%(...)"
                    && !"% ...::%(...) const" ) && within( subjects() );

  advice observers () : baseclass( IObserver );
  advice subjects() : baseclass( ISubject );

  advice subjectChange() : after () {
    ISubject* subject = tjp->that();
    updateObservers( subject );
  }

  void updateObservers( ISubject* subject ) { ... }
  void addObserver( ISubject* subject, IObserver* observer ) { ... }
  void remObserver( ISubject* subject, IObserver* observer ) { ... }
};
```


Solution: Generic Observer Aspect


```
aspect ObserverPattern {
  ...
public:
  struct ISubject {};
  struct IObserver {
    virtual void update (ISubject *) = 0;
  };

  pointcut virtual observers() = 0;
  pointcut virtual subjects() = 0;

  pointcut virtual subjectChange() =  execution( "% ...::%(...)"
                    && !"% ...::%(...) const" ) && within( subjects() );

  advice observers () : baseclass( IObserver );
  advice subjects() : baseclass( ISubject );

  advice subjectChange() : after () {
    ISubject* subject = tjp->that();
    updateObservers( subject );
  }

  void updateObservers( ISubject* subject ) { ... }
  void addObserver( ISubject* subject, IObserver* observer ) { ... }
  void remObserver( ISubject* subject, IObserver* observer ) { ... }
};
```


Interfaces for the subject/observer roles

Solution: Generic Observer Aspect


```
aspect ObserverPattern {
  ...
public:
  struct ISubject {};
  struct IObserver {
    virtual void update (ISubject *) = 0;
  };

  pointcut virtual observers() = 0;
  pointcut virtual subjects() = 0;

  pointcut virtual subjectChange() =  execution( "% ...::%(...)"
                    && !"% ...::%(...) const" ) && within( subjects() );

  advice observers () : baseclass( IObserver );
  advice subjects() : baseclass( ISubject );

  advice subjectChange() : after () {
    ISubject* subject = tjp->that();
    updateObservers( subject );
  }

  void updateObservers( ISubject* subject ) { ... }
  void addObserver( ISubject* subject, IObserver* observer ) { ... }
  void remObserver( ISubject* subject, IObserver* observer ) { ... }
};
```


abstract pointcuts that define subjects/observers

(need to be overridden by a derived aspect)

Solution: Generic Observer Aspect

```
aspect ObserverPattern {
  ...
public:
  struct ISubject {};
  struct IObserver {
    virtual void update (ISubject *) = 0;
  };

  pointcut virtual observers() = 0;
  pointcut virtual subjects() = 0;

  pointcut virtual subjectChange() =  execution( "% ...::%(...)"
                      && !"% ...::%(...) const" ) && within( subjects() );

  advice observers () : baseclass( IObserver );
  advice subjects() : baseclass( ISubject );

  advice subjectChange() : after () {
    ISubject* subject = tjp->that();
    updateObservers( subject );
  }

  void updateObservers( ISubject* subject ) { ... }
  void addObserver( ISubject* subject, IObserver* observer ) { ... }
  void remObserver( ISubject* subject, IObserver* observer ) { ... }
};
```

virtual pointcut defining all state-changing methods.

(Defaults to the execution of any non-const method in subjects)

Solution: Generic Observer Aspect

```
aspect ObserverPattern {
  ...
public:
  struct ISubject {};
  struct IObserver {
    virtual void update (ISubject *) = 0;
  };

  pointcut virtual observers() = 0;
  pointcut virtual subjects() = 0;

  pointcut virtual subjectChange() =  execution( "% ...::%(...)"
                      && !"% ...::%(...) const" ) && within( subjects() );

  advice observers () : baseclass( IObserver );
  advice subjects() : baseclass( ISubject );

  advice subjectChange() : after () {
    ISubject* subject = tjp->that();
    updateObservers( subject );
  }

  void updateObservers( ISubject* subject ) { ... }
  void addObserver( ISubject* subject, IObserver* observer ) { ... }
  void remObserver( ISubject* subject, IObserver* observer ) { ... }
};
```

Introduction of the role interface as additional **baseclass** into subjects / observers

Solution: Generic Observer Aspect

```
aspect ObserverPattern {
  ...
public:
  struct ISubject {};
  struct IObserver {
    virtual void update (ISubject *) = 0;
  };

  pointcut virtual observers() = 0;
  pointcut virtual subjects() = 0;

  pointcut virtual subjectChange() =  execution( "% ...::%(...)"
                      && !"% ...::%(...) const" ) && within( subjects() );

  advice observers () : baseclass( IObserver );
  advice subjects() : baseclass( ISubject );

  advice subjectChange() : after () {
    ISubject* subject = tjp->that();
    updateObservers( subject );
  }

  void updateObservers( ISubject* subject ) { ... }
  void addObserver( ISubject* subject, IObserver* observer ) { ... }
  void remObserver( ISubject* subject, IObserver* observer ) { ... }
};
```

After advice to update observers after execution of a state-changing method

Solution: Putting Everything Together

Applying the Generic Observer Aspect to the clock example

```
aspect ClockObserver : public ObserverPattern {
  // define the participants
  pointcut subjects()   = "ClockTimer";
  pointcut observers()  = "DigitalClock"||"AnalogClock";
public:
  // define what to do in case of a notification
  advice observers() : void update( ObserverPattern::ISubject* s ) {
    Draw();
  }
};
```

Observer Pattern: Conclusions

- Applying the observer protocol is now very easy!
  - all necessary transformations are performed by the generic aspect
  - programmer just needs to define participants and behaviour
  - multiple subject/observer relationships can be defined
- More reusable and less error-prone component code
  - observer no longer “hard coded” into the desing and code
  - no more forgotten calls to update() in subject classes
- Full source code on Tutorial CD

Examples

Errorhandling in Legacy Code: Scenario

A typical Win32 application

```
LRESULT WINAPI WndProc( HWND hWnd, UINT nMsg, WPARAM wParam, LPARAM lParam ) {
  HDC dc = NULL; PAINTSTRUCT ps = {0};

  switch( nMsg ) {
    case WM_PAINT:
      dc = BeginPaint( hWnd, &ps );
      ...
      EndPaint(hWnd, &ps);
      break;
    ...
}}

int WINAPI WinMain( ... ) {
  HANDLE hConfigFile = CreateFile( "example.config", GENERIC_READ, ... );

  WNDCLASS wc = {0, WndProc, 0, 0, ... , "Example_Class"};
  RegisterClass( &wc );
  HWND hwndMain = CreateWindowEx( 0, "Example_Class", "Example", ... );
  UpdateWindow( hwndMain );

  MSG msg;
  while( GetMessage( &msg, NULL, 0, 0 ) ) {
    TranslateMessage( &msg );
    DispatchMessage( &msg );
  }
  return 0;
}
```


Errorhandling in Legacy Code: Scenario

These Win32 API functions may fail!

```
LRESULT WINAPI WndProc( HWND hWnd, UINT nMsg, WPARAM wParam, LPARAM lParam ) {
  HDC dc = NULL; PAINTSTRUCT ps = {0};

  switch( nMsg ) {
    case WM_PAINT:
      dc = BeginPaint( hWnd, &ps );
      ...
      EndPaint(hWnd, &ps);
      break;
    ...
}}

int WINAPI WinMain( ... ) {
  HANDLE hConfigFile = CreateFile( "example.config", GENERIC_READ, ... );

  WNDCLASS wc = {0, WndProc, 0, 0, ... , "Example_Class"};
  RegisterClass( &wc );
  HWND hwndMain = CreateWindowEx( 0, "Example_Class", "Example", ... );
  UpdateWindow( hwndMain );

  MSG msg;
  while( GetMessage( &msg, NULL, 0, 0 ) ) {
    TranslateMessage( &msg );
    DispatchMessage( &msg );
  }
  return 0;
}
```


Win32 Errorhandling: Goals

- Detect failed calls of Win32 API functions
  - by giving after advice for any call to a Win32 function
- Throw a *helpful* exception in case of a failure
  - describing the exact circumstances and reason of the failure

Problem: Win32 failures are indicated by a “magic” return value

- magic value to compare against depends on the ***return type*** of the function
- error reason (`GetLastError()`) only valid in case of a failure

return type	magic value
BOOL	FALSE
ATOM	(ATOM) 0
HANDLE	INVALID_HANDLE_VALUE or NULL
HWND	NULL

Examples

Detecting the failure: Generic Advice

```
advice call(win32API ()) :
after () {
  if (isError (*tjp->result()))
    // throw an exception
}
```

```
bool isError(ATOM);
bool isError(BOOL);
bool isError(HANDLE);
bool isError(HWND);
...
```


Describing the failure: Generative Advice

```
template <int I> struct ArgPrinter {
  template <class JP> static void work (JP &tjp, ostream &s) {
    ArgPrinter<I–1>::work (tjp, s);
    s << “, “ << *tjp. template arg<I-1>();
  }
};
```

```
advice call(win32API ()) : after () {
  // throw an exception
  ostringstream s;
  DWORD code = GetLastError();
  s << “WIN32 ERROR ” << code << ...
    << win32::GetErrorText( code ) << ... <<
    << tjp->signature() << “WITH: ” << ...;
    ArgPrinter<JoinPoint::ARGS>::work (*tjp, s);

  throw win32::Exception( s.str() );
}
```

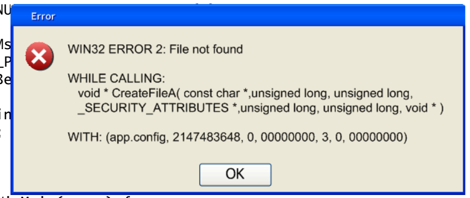

Reporting the Error

```
LRESULT WINAPI WndProc( HWND hWnd, UINT nMsg, WPARAM wParam, LPARAM lParam ) {
  HDC dc = NU
  
  switch( nMs
    case WM_P
      dc = Be
      ...
      EndPain
      break;
    ...
}}

int WINAPI WinMain( ... ) {
  HANDLE hConfigFile = CreateFile( "example.config", GENERIC_READ, ... );

  WNDCLASS wc = {0, WndProc, 0, 0, ... , "Example_Class"};
  RegisterClass( &wc );
  HWND hwndMain = CreateWindowEx( 0, "Example_Class", "Example", ... );
  UpdateWindow( hwndMain );

  MSG msg;
  while( GetMessage( &msg, NULL, 0, 0 ) ) {
    TranslateMessage( &msg );
    DispatchMessage( &msg );
  }
  return 0;
}
```



Errorhandling in Legacy Code: Conclusions

- Easy to apply errorhandling for Win32 applications
  - previously undetected failures are reported by exceptions
  - rich context information is provided
- Uses advanced AspectC++ techniques
  - error detection by generic advice
  - context propagation by generative advice
- Full source code on tutorial CD

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

AOSD 2005 Tutorial

Part VI – Summary

Pros and Cons

AOP with pure C++

+ no special tool required
- requires in-depth understanding of C++ templates
- lack of "obliviousness"
  the component code has to be aspect-aware
- lack of "quantification"
  no pointcut concept, no match expressions

AspectC++

+ the ac++ compiler transforms AspectC++ into C++
+ various supported joinpoint types, e.g. execution and calls
+ built-in support for advanced AOP concepts:
  cflow, joinpoint-API
- longer compilation times

Summary – This Tutorial ...

- showed basic techniques for AOP with pure C++
  - using templates to program generic wrapper code
  - using action classes to encapsulate the "proceed-code"
  - using namespaces to substitute types transparently
- introduced the AspectC++ language extension for C++
  - AspectJ-like language extension
  - ac++ transforms AspectC++ into C++
  - supports AOP even in resource constrained environments
- demonstrated the AspectC++ tools
- discussed the pros and cons of each approach

Future Work – Roadmap

- Parser improvements
  - full template support
  - speed optimization
  - full g++ 3.x and Visual C++ compatibility
- Language design/weaver
  - weaving in templates
  - advice for object access (set/get pointcut functions)
  - advice for object instantiations
- Tools
  - dependency handling

Thank you for your attention!