Konfigurierbare Systemsoftware (KSS)

VL 3 – Aspect-Oriented Programming (AOP)

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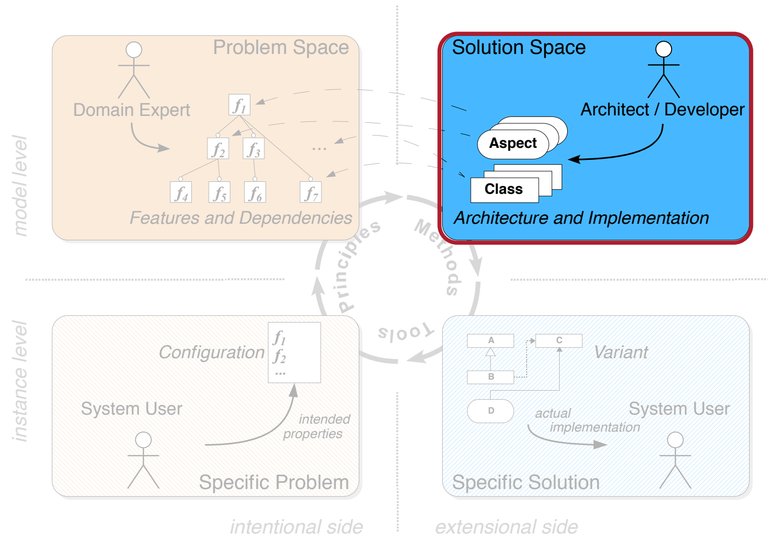
http://www4.informatik.uni-erlangen.de/Lehre/SS16/V_KSS

About this Lecture

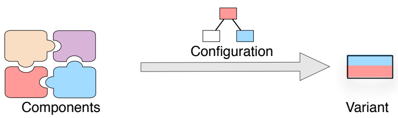


Implementation Techniques: Classification

- Decompositional Approaches

  - Text-based filtering (untyped)
  - Preprocessors

- Compositional Approaches



  - Language-based composition mechanisms (typed)
  - OOP, **AOP**, Templates

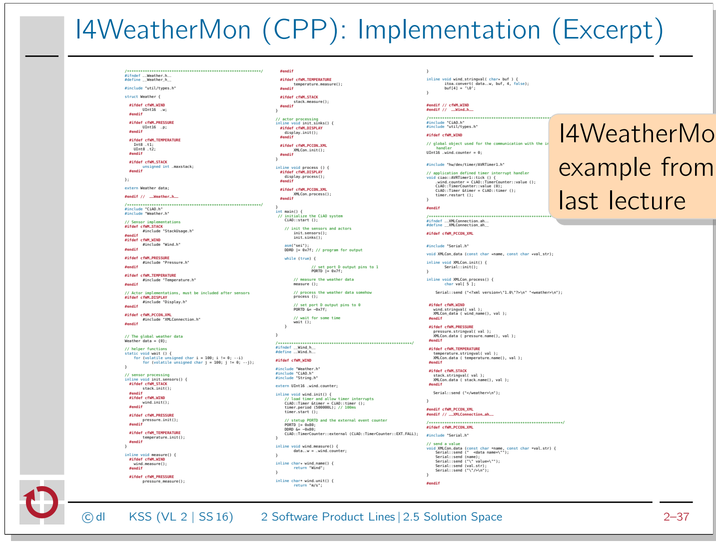
- Generative Approaches

  - Metamodel-based generation of components (typed)
  - MDD, C++ TMP, generators

Agenda

Agenda

Static Configurability with the CPP?



I4WeatherMon example from last lecture

Case Study eCos [4]

- The **e**mbedded **C**onfigurable **o**perating **s**ystem
  - Operating system for embedded applications
  - Open source, maintained by eCosCentric Inc.
  - Many 16-bit and 32-bit platforms supported
  - Broadly accepted real-world system
- More than **750** configuration options (kernel)
  - Feature-based selection
  - **Preprocessor-based** implementation

Static Configurability with the CPP?

```
Cyg_Mutex::Cyg_Mutex() {
  CYG_REPORT_FUNCTION();
  locked      = false;
  owner       = NULL;
#if defined(CYGSEM_KERNEL_SYNCH_MUTEX_PRIORITY_INVERSION_PROTOCOL_DEFAULT) && \
  defined(CYGSEM_KERNEL_SYNCH_MUTEX_PRIORITY_INVERSION_PROTOCOL_DYNAMIC)
#ifdef CYGSEM_KERNEL_SYNCH_MUTEX_PRIORITY_INVERSION_PROTOCOL_DEFAULT_INHERIT
  protocol    = INHERIT;
#endif
#ifdef CYGSEM_KERNEL_SYNCH_MUTEX_PRIORITY_INVERSION_PROTOCOL_DEFAULT_CEILING
  protocol    = CEILING;
  ceiling     = CYGSEM_KERNEL_SYNCH_MUTEX_PRIORITY_INVERSION_PROTOCOL_DEFAULT_PRIORITY;
#endif
#ifdef CYGSEM_KERNEL_SYNCH_MUTEX_PRIORITY_INVERSION_PROTOCOL_DEFAULT_NONE
  protocol    = NONE;
#endif
#else // not (DYNAMIC and DEFAULT defined)
#ifdef CYGSEM_KERNEL_SYNCH_MUTEX_PRIORITY_INVERSION_PROTOCOL_CEILING
#ifdef CYGSEM_KERNEL_SYNCH_MUTEX_PRIORITY_INVERSION_PROTOCOL_DEFAULT_PRIORITY
  // if there is a default priority ceiling defined, use that to initialize
  // the ceiling.
  ceiling = CYGSEM_KERNEL_SYNCH_MUTEX_PRIORITY_INVERSION_PROTOCOL_DEFAULT_PRIORITY;
#else
  // Otherwise set it to zero.
  ceiling = 0;
#endif
#endif
#endif // DYNAMIC and DEFAULT defined
  CYG_REPORT_RETURN();
}
```

Mutex options: PROTOCOL, CEILING, INHERIT, DYNAMIC

Kernel policies: Tracing, Instrumentation, Synchronization

Static Configurability with the CPP?

```
Cyg_Mutex::Cyg_Mutex() {
  CYG_REPORT_FUNCTION();
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#ifdef CYGSEM_KERNEL_SYNCH_MUTEX_PRIORITY_INVERSION_PROTOCOL_DEFAULT_INHERIT
  protocol    = INHERIT;
#endif
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  protocol    = CEILING;
  ceiling     = CYGSEM_                    N_PROTOCOL_DEFAULT_PRIORITY;
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#ifdef CYGSEM_KERNEL_SY                    _DEFAULT_NONE
  protocol    = NONE;
#endif
#else // not (DYNAMIC a
#ifdef CYGSEM_KERNEL_SY                    _CEILING
#ifdef CYGSEM_KERNEL_SYNCH_MUTEX_PRIORITY_INVERSION_PROTOCOL_DEFAULT_PRIORITY
  // if there is a default priority ceiling defined, use that to initialize
  // the ceiling.
  ceiling = CYGSEM_KERNEL_SYNCH_MUTEX_PRIORITY_INVERSION_PROTOCOL_DEFAULT_PRIORITY;
#else
  // Otherwise set it to zero.
  ceiling = 0;
#endif
#endif
#endif // DYNAMIC and DEFAULT defined
  CYG_REPORT_RETURN();
}
```

```
Cyg_Mutex::Cyg_Mutex() {
  locked      = false;
  owner       = NULL;
}
```

Mutex options:

PROTOCOL

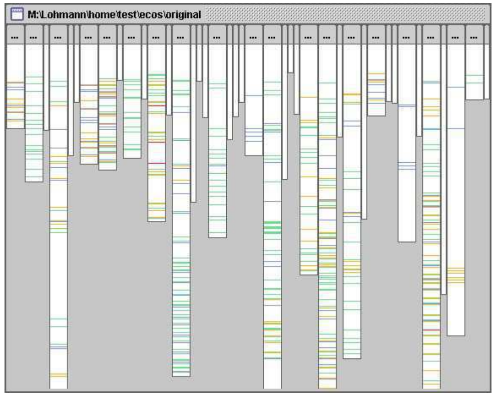
CEILING

INHERIT

DYNAMIC

Kernel policies: Tracing | Instrumentation | Synchronization

Static Configurability with the CPP?



Mutex options:

PROTOCOL

CEILING

INHERIT

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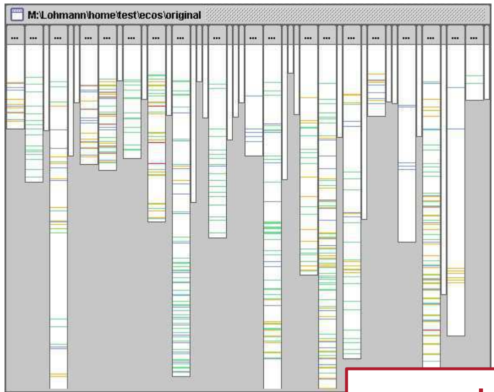
Kernel policies: Tracing | Instrumentation | Synchronization

Static Configurability with the CPP?



Mutex options:

PROTOCOL

CEILING

INHERIT

DYNAMIC

Issue

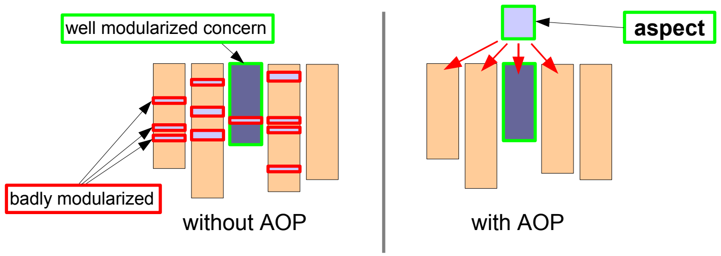
Crosscutting Concerns

Kernel policies: Tracing | Instrumentation | Synchronization

Aspect-Oriented Programming (AOP) [2]

Aspect-Oriented Programming

- AOP is about modularizing crosscutting concerns



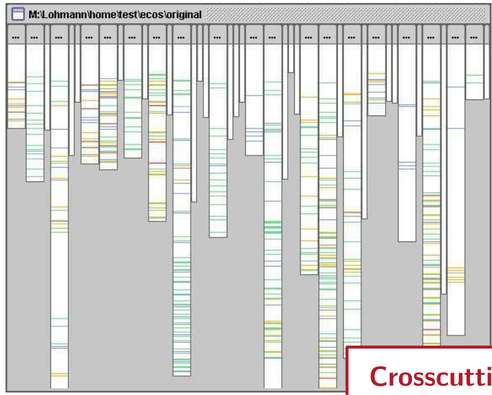
- Examples: tracing, synchronization, security, buffering, error handling, constraint checks, ...

AOP: The Basic Idea

Separation of **what** from **where**:

- **Join Points** ↦ **where**
  - positions in the static structure or dynamic control flow (event)
  - given declaratively by pointcut expressions
- **Advice** ↦ **what**
  - additional elements (members, ...) to introduce at join points
  - additional behavior (code) to superimpose at join points

Static Configurability with the CPP?



Mutex options:

PROTOCOL

CEILING

INHERIT

DYNAMIC

Crosscutting Concerns
Can we do better with aspects?

Kernel policies: Tracing Instrumentation Synchronization

Implementation of Crosscutting Concerns with AOP

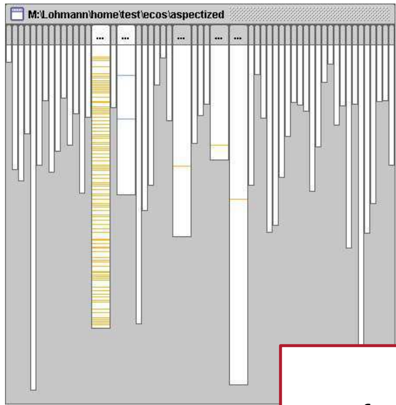
```
aspect int_sync {

  pointcut sync() = execution(...) // kernel calls to sync
          || construction(...)
          || destruction(...);

  // advise kernel code to invoke lock() and unlock()
  advice sync() : before() {
    Cyg_Scheduler::lock();
  }
  advice sync() : after() {
    Cyg_Scheduler::unlock();
  }

  // In eCos, a new thread always starts with a lock value of 0
  advice execution(
  "%Cyg_HardwareThread::thread_entry(...)") : before() {
    Cyg_Scheduler::zero_sched_lock();
  }
  ...
};
```

where

what

Synchronization

Static Configurability with the CPP?



Result
after refactoring into aspects [4]

Kernel policies: Tracing Instrumentation Synchronization

AspectC++ [5, 6]

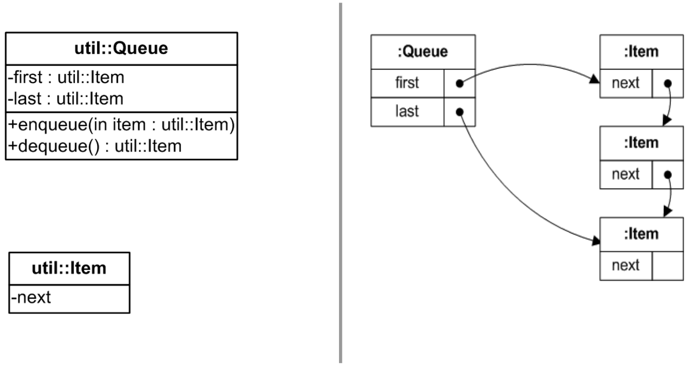
- AspectC++ is an AOP language extension for C++
  - superset of ISO C++ 98 [1]
    ⇝ every C++ program is also an AspectC++ program
  - additionally supports AOP concepts
- Technical approach: source-to-source transformation
  - `ac++` *weaver* transforms AspectC++ code into C++ code
  - resulting C++ code can be compiled with any standard-compliant compiler (especially gcc)
  - `ag++` *weaver wrapper* works as replacement for `g++` in makefiles
- Language and weaver are open source (GPL2)

`http://www.aspectc.org`

Agenda

Scenario: A Simple Queue

Scenario: A Queue utility class



Scenario: A Simple Queue

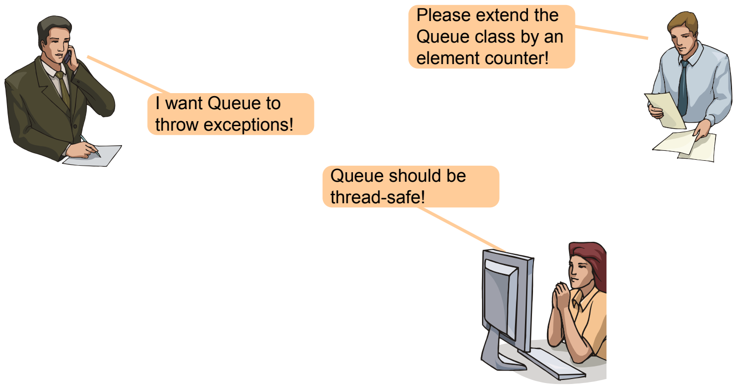
The Simple Queue Class

```
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();
  }
```

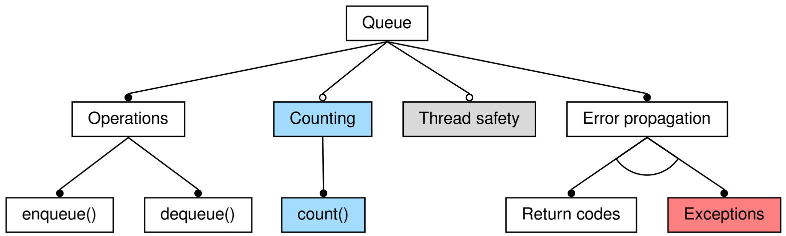
```
  Item* dequeue() {
    Item* res;
    lock.enter();
    try {
      res = first;
      if (first == last)
        first = last = 0;
      else first = first->next;
      if (counter > 0) -counter;
      if (res == 0)
        throw QueueEmptyError();
    } catch (...) {
      lock.leave();
     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

Goal: A configurable Queue



Goal: A configurable Queue

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
  }
```

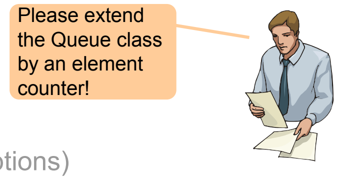
```
  Item* dequeue() {
    Item* res;
#ifdef LOCKING_ASPECT
    lock.enter();
    try {
#endif
      res = first;
      if (first == last)
        first = last = 0;
      else first = first->next;
#ifdef COUNTING_ASPECT
      if (counter > 0) --counter;
#endif
#ifdef ERRORHANDLING_ASPECT
      if (res == 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
```


Agenda

Queue: Element Counting

Queue: Demanded Extensions

I. Element counting



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

```
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 );
  }
};
```

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

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 {

  advice "util::Queue" : slice class {
    int counter;
  public:
    int count() const { return counter; }
  };
  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 {

  advice "util::Queue" : slice class {
    int counter;
  public:
    int count() const { return counter; }
  };
  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 slice of members into all classes denoted by the pointcut "util::Queue"

ElementCounter2.ah

ElementCounter2 - Elements


```
aspect ElementCounter {

  advice "util::Queue" : slice class {
    int counter;
  public:
    int count() const { return counter; }
  };
  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 introduce a private *counter* element and a public method to read it

ElementCounter2.ah

ElementCounter2 - Elements

```
aspect ElementCounter {

  advice "util::Queue" : slice class {
    int counter;
  public:
    int count() const { return counter; }
  };
  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 {

  advice "util::Queue" : slice class {
    int counter;
  public:
    int count() const { return counter; }
  };
  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 {

  advice "util::Queue" : slice class {
    int counter;
  public:
    int count() const { return counter; }
  };
  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

- A *slice* of additional methods, types, etc. is 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

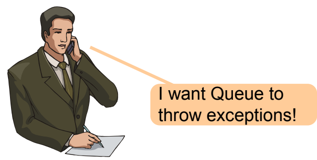
advice “ClassA” : **slice class** {
element to introduce

public:
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();
  }
};
```

ErrorException.ah

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

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();
  }
};
```

ErrorException.ah

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

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();
  }
};
```

ErrorException.ah

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

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)

III. Thread safety
(synchronization by mutex variables)

Queue should be thread-safe!

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" : slice class { 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" : slice class { 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" : slice class { 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" : slice class { 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();
  }
};
```

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

LockingMutex.ah

LockingMutex - Elements

```
aspect LockingMutex {
  advice "util::Queue" : slice class { 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();
  }
};
```

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

LockingMutex.ah

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();
  }
};
```

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

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

  advice sync_classes() : slice class {
    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 abstract locking aspect declares two **pure virtual pointcuts** and uses the **joinpoint API** for an context-independent advice implementation.

```
#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() : slice class {
    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(...)";
};
```

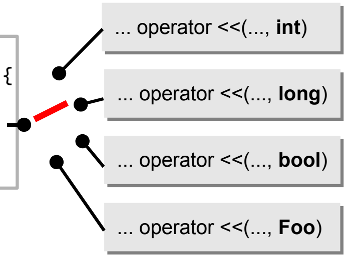
LockingQueue.ah

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();
  }
};
```



Generic Advice

Uses static JP-specific type information in advice code

- in combination with C++ overloading
- …mplate 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++)

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

Aspects are transformed into **ordinary classes**

```
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

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

```
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

Advice becomes a **member function**

```
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

```
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'

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

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

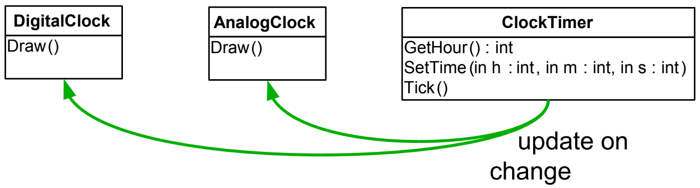
```
int main() {
  struct __call_main_0_0 {
    static inline void invoke (){
      AC::..._a0_before ();
      ::foo();
    }
  };
  __call_main_0_0::invoke ();
  return 0;
}
```

main.cc'

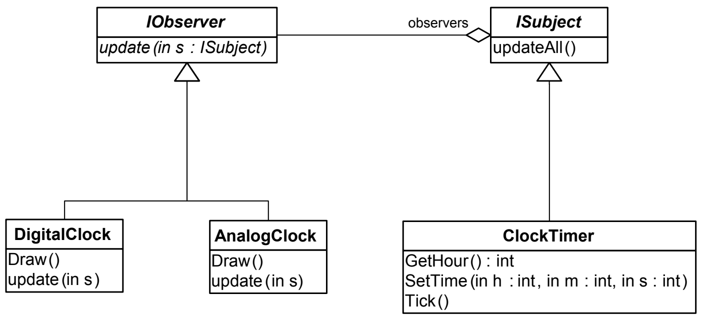
Translation Modes

- 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

Observer Pattern: Scenario

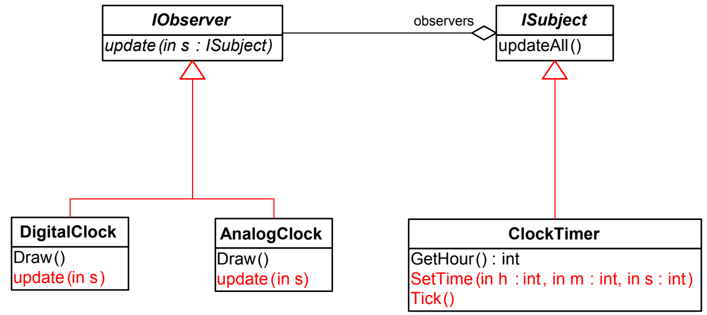


Observer Pattern: Implementation



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 () : slice class : public ObserverPattern::IObserver;
  advice subjects()   : slice class : public ObserverPattern::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

Interfaces for the subject/observer roles

```
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 () : slice class : public ObserverPattern::IObserver;
  advice subjects()   : slice class : public ObserverPattern::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

abstract pointcuts that define subjects/observers

(need to be overridden by a derived 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 () : slice class : public ObserverPattern::IObserver;
  advice subjects()   : slice class : public ObserverPattern::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 () : slice class : public ObserverPattern::IObserver;
  advice subjects()   : slice class : public ObserverPattern::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 () : slice class : public ObserverPattern::IObserver;
  advice subjects()   : slice class : public ObserverPattern::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( "% ...::%(...)"
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  advice observers () : slice class : public ObserverPattern::IObserver;
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  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() : slice class {
  public:
    void update( ObserverPattern::ISubject* s ) {
      Draw();
    }
  };
};
```

Errorhandling in Legacy Code: Scenario

```
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;
}
```

A typical Win32 application

Errorhandling in Legacy Code: Scenario

```
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;
}
```

These Win32 API functions may fail!

Win32 Errorhandling: Goals

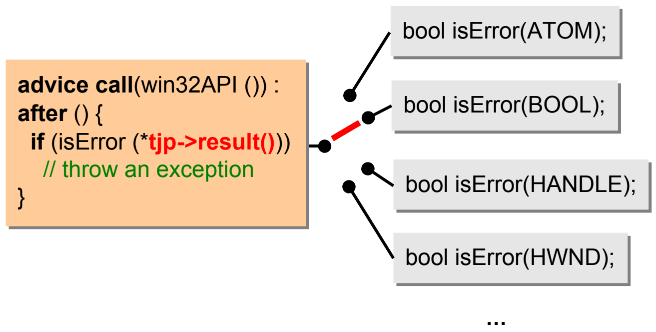
- Detect failed calls of Win32 API functions
  - by giving after advice for any call to a Win32 function
- Throw a *helpful* exception in case of a failure
  - describing the exact circumstances and reason of the failure

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

Detecting the failure: Generic Advice



Further Examples

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() );
}
```


Further Examples

Reporting the Error

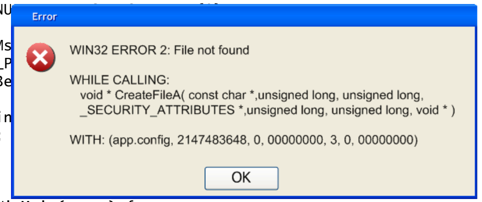
```
LRESULT WINAPI WndProc( HWND hWnd, UINT nMsg, WPARAM wParam, LPARAM lParam ) {
  HDC dc = NU

  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;
}
```



Agenda

Aspect-Oriented Programming: Summary

- AOP aims at a better separation of crosscutting concerns
  - Avoidance of code tangling
    ↦ implementation of optional features
  - Avoidance of code scattering
    ↦ implementation of nonfunctional features
- Basic idea: separation of **what** from **where**
  - **Join Points** ↦ **where**
    - positions in the static structure or dynamic control flow (event)
    - given declaratively by pointcut expressions
  - **Advice** ↦ **what**
    - additional elements (members, ...) to introduce at join points
    - additional behavior (code) to superimpose at join points
- AspectC++ brings AOP concepts to the C++ world
  - Static source-to-source transformation approach

Aspect-Oriented Programming: Summary

- AOP aims at a better separation of crosscutting concerns
  - Avoidance of code tangling
    ↦ implementation of optional features
  - Avoidance of code scattering
    ↦ implementation of nonfunctional features

> **Next Lecture:**
> How to use AOP to achieve loose coupling, granularity and variability for feature implementations in configurable system software
> ⇝ **aspect-aware design**

- Basic idea: separation of **what** from **where**
  - **Join Points** ↦ **where**
    - positions in the static structure or dynamic control flow (event)
    - given declaratively by pointcut expressions
  - **Advice** ↦ **what**
    - additional elements (members, ...) to introduce at join points
    - additional behavior (code) to superimpose at join points
- AspectC++ brings AOP concepts to the C++ world
  - Static source-to-source transformation approach

Referenzen

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[6] Olaf Spinczyk, Daniel Lohmann, and Matthias Urban. "AspectC++: An AOP Extension for C++". In: *Software Developers Journal* 5 (May 2005), pp. 68–76. URL: `http://www.aspectc.org/fileadmin/publications/sdj-2005-en.pdf`.

AspectC++ Quick Reference

Concepts

aspect
: Aspects in AspectC++ implement in a modular way crosscutting concerns and are an extension to the class concept of C++. Additionally to attributes and methods, aspects may also contain *advice declarations*.

advice
: An advice declaration is used either to specify code that should run when the *join points* specified by a *pointcut expression* are reached or to introduce a new method, attribute, or type to all *join points* specified by a *pointcut expression*.

slice
: A slice is a fragment of a C++ element like a class. It may be used by introduction advice to implemented static extensions of the program.

join point
: In AspectC++ join points are defined as points in the component code where aspects can interfere. A join point refers to a method, an attribute, a type (class, struct, or union), an object, or a point from which a join point is accessed.

pointcut
: A pointcut is a set of join points described by a *pointcut expression*.

pointcut expression
: Pointcut expressions are composed from *match expressions* used to find a set of join points, from pointcut functions used to filter or map specific join points from a pointcut, and from algebraic operators used to combine pointcuts.

match expression
: Match expressions are strings containing a search pattern.

order declaration
: If more than one *aspect* affects the same *join point* an *order declaration* can be used to define the order of advice code execution.

Aspects

Writing aspects works very similar to writing C++ class definitions. Aspects may define ordinary class members as well as advice.

aspect *A* **{ ... };**
: defines the aspect *A*

aspect *A* **:** *public B* **{ ... };**
: *A* inherits from class or aspect *B*

Advice Declarations

advice *pointcut* : **before**(...) {...}
: the advice code is executed before the join points in the pointcut

advice *pointcut* : **after**(...) {...}
: the advice code is executed after the join points in the pointcut

advice *pointcut* : **around**(...) {...}
: the advice code is executed in place of the join points in the pointcut

advice *pointcut* : **order**(*high*, *...low*)**;**
: *high* and *low* are pointcuts, which describe sets of aspects. Aspects on the left side of the argument list always have a higher precedence than aspects on the right hand side at the join points, where the order declaration is applied.

advice *pointcut* : **slice class** : **public** *Base* {...}
: introduces a new base class *Base* and members into the target classes matched by *pointcut*.

advice *pointcut* : **slice** *ASlice* **;**
: introduces the slice *ASlice* into the target classes matched by *pointcut*.

Pointcut Expressions

Type Matching

`"int"`
: matches the C++ built-in scalar type `int`

`"% *"`
: matches any pointer type

Namespace and Class Matching

`"Chain"`
: matches the class, struct or union *Chain*

`"Memory%"`
: matches any class, struct or union whose name starts with "Memory"

Function Matching

`"void reset()"`
: matches the function *reset* having no parameters and returning `void`

`"% printf(...)"`
: matches the function *printf* having any number of parameters and returning any type

`"% ...::%(...)"`
: matches any function, operator function, or type conversion function (in any class or namespace)

`"% ...::Service::%(...) const"`
: matches any const member-function of the class `Service` defined in any scope

`"% ...::operator %(...)"`
: matches any type conversion function

`"virtual %C::%(...)"`
: matches any virtual member function of `C`

Template Matching†

`"std::set<...>"`
: matches all template instances of the class *std::set*

`"std::set<int>"`
: matches only the template instance *std::set<int>*

`"% ...::%<...>::%(...)"`
: matches any member function from any template class instance in any scope

Predefined Pointcut Functions

Functions

call(*pointcut*) $N \to C_C$ ‡‡
: provides all join points where a named entity in the *pointcut* is called.

execution(*pointcut*) $N \to C_E$
: provides all join points referring to the implementation of a named entity in the *pointcut*.

construction(*pointcut*) $N \to C_{Cons}$
: all join points where an instance of the given class(es) is constructed.

destruction(*pointcut*) $N \to C_{Des}$
: all join points where an instance of the given class(es) is destructed.

pointcut may contain function names or class names. A class name is equivalent to the names of all functions defined within its scope combined with the || operator (see below).

Control Flow

cflow(*pointcut*) $C \to C$
: captures join points occuring in the dynamic execution context of join points in the *pointcut*. The argument pointcut is forbidden to contain context variables or join points with runtime conditions (currently cflow, that, or target).

Types

base(*pointcut*) $N \to N_{C,F}$
: returns all base classes resp. redefined functions of classes in the *pointcut*

derived(*pointcut*) $N \to N_{C,F}$
: returns all classes in the *pointcut* and all classes derived from them resp. all redefined functions of derived classes

Scope

within(*pointcut*) N→C
: filters all join points that are within the functions or classes in the *pointcut*

Context

that(*type pattern*) N→C
: returns all join points where the current C++ `this` pointer refers to an object which is an instance of a type that is compatible to the type described by the *type pattern*

target(*type pattern*) N→C
: returns all join points where the target object of a call is an instance of a type that is compatible to the type described by the *type pattern*

result(*type pattern*) N→C
: returns all join points where the result object of a call/execution is an instance of a type described by the *type pattern*

args(*type pattern*, ...) (N,...)→C
: a list of *type patterns* is used to provide all joinpoints with matching argument signatures

Instead of the *type pattern* it is possible here to pass the name of a **context variable** to which the context information is bound. In this case the type of the variable is used for the type matching.

Algebraic Operators

pointcut **&&** *pointcut* (N,N)→N, (C,C)→C
: intersection of the join points in the *pointcuts*

pointcut || *pointcut* (N,N)→N, (C,C)→C
: union of the join points in the *pointcuts*

! *pointcut* N→N, C→C
: exclusion of the join points in the *pointcut*

JoinPoint-API

The JoinPoint-API is provided within every advice code body by the built-in object **tjp** of class **JoinPoint**.

Compile-time Types and Constants

That [type]
: object type (object initiating a call)

Target [type]
: target object type (target object of a call)

Result [type]
: type of the object, which is used to *store* the result of the affected function

Res::Type, Res::ReferredType [type]
: result type of the affected function

Arg<i>::Type, Arg<i>::ReferredType [type]
: type of the i^{th} argument of the affected function (with $0 \leq i < ARGS$)

ARGS [const]
: number of arguments

JPID [const]
: unique numeric identifier for this join point

JPTYPE [const]
: numeric identifier describing the type of this join point (*AC::CALL, AC::EXECUTION*, AC::CONSTRUCTION, or AC::DESTRUCTION)

Runtime Functions and State

static const char ***signature**()
: gives a textual description of the join point (function name, class name, ...)

static const char ***filename**()
: returns the name of the file in which the joinpoint shadow is located

static int **line**()
: the source code line number that is associated with the joinpoint shadow

That ***that**()
: returns a pointer to the object initiating a call or 0 if it is a static method or a global function

Target ***target**()
: returns a pointer to the object that is the target of a call or 0 if it is a static method or a global function

Result ***result**()
: returns a typed pointer to the result value or 0 if the function has no result value

Arg<i>::ReferredType ***arg**<*i*>()
: returns a typed pointer to the i^{th} argument value (with $0 \leq i < ARGS$)

void ***arg**(*int* i)
: returns a pointer to the memory position holding the argument value with index *i*

void **proceed**()
: executes the original code in an around advice (should be called at most once in around advice)

AC::Action &**action**()
: returns the runtime action object containing the execution environment to execute (*trigger()*) the original code encapsulated by an around advice

Runtime Type Information

static AC::Type **resulttype**()
static AC::Type **argtype**(*int* i)
: return a C++ ABI V3 conforming string representation of the result type / argument type of the affected function

---

Example

A reusable tracing aspect.

```
aspect Trace {
  pointcut virtual functions() = 0;
  advice execution(functions()) : around() {
    cout << "before " << JoinPoint::signature() << "(";
    for (unsigned i = 0; i < JoinPoint::ARGS; i++)
      cout << (i ? ", " : "") << JoinPoint::argtype(i);
    cout << ")" << endl;
    tjp->proceed();
    cout << "after" << endl;
  }
};
```

In a derived aspect the pointcut *functions* may be redefined to apply the aspect to the desired set of functions.

```
aspect TraceMain : public Trace {
  pointcut functions() = "% main(...)";
};
```

This is a reference sheet corresponding to AspectC++ 1.0.
Version 1.12, April 18, 2011.

† support for template instance matching is an experimental feature

†† `http://www.codesourcery.com/cxx-abi/abi.html#mangling`

‡‡ C, C_C, C_E, C_{Cons}, C_{Des}: Code (any, only *Call*, only *Execution*, only object *Construction*, only object *Destruction*); N, N_N, N_C, N_F, N_T: Names (any, only *Namespace*, only *Class*, only *Function*, only *Type*)