CS 6156

Program Instrumentation (with ASM and AspectJ)

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Slides based in part on lectures by Klaus Havelund at CalTech

Some logistics

- Reading 3 to be assigned
  - due 11:59pm AoE 3/2
- Feedback on your project proposal was provided on CMSX on 2/14
  - Work on your phase 1, due 3/8

What is instrumentation?

- "By program instrumentation here we mean the process of inserting additional statements into a program for information gathering purposes."[1]

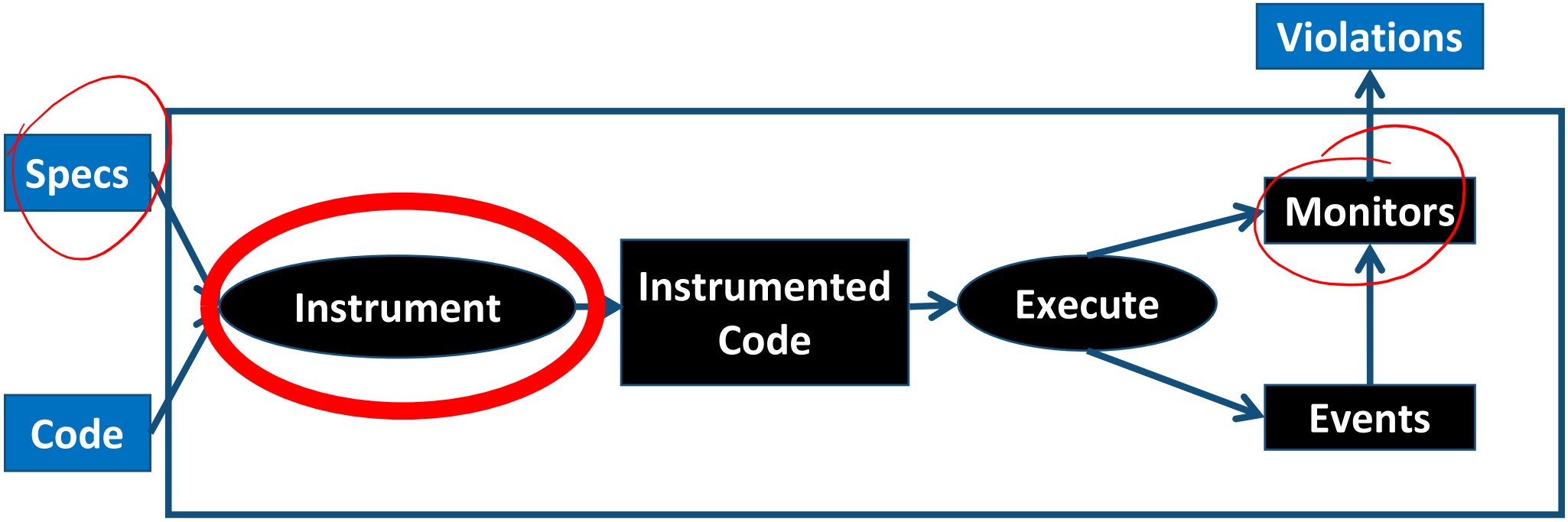
- "Program instrumentation is a way of learning about the effect individual tests have on a program."[2]

[1]J.C. Huang, Detection of Data Flow Anomaly Through Program Instrumentation, TSE 1979
[2]E. F. Miller, Program Testing, IEEE Computer 1978

Instrumentation in practice

- How do debuggers know what code to step through?
- How does your code coverage tool know what statements, blocks, methods, etc., are covered?
- Did you ever write "printf" statements to know what (parts of) your code does?

Recall: what you'll learn in CS 6156



- How to instrument code to obtain runtime events?
- Compile-time vs. runtime instrumentation
- Problems and challenges of instrumentation

Why instrumentation in CS6156

- At 57% of student projects will need perform instrumentation

- No instrumentation, no RV

Some instrumentation frameworks

- ASM
- Javassist
- BCEL
- AspecJ, AspectC, AspectWerkz, etc.
- JVMTI
- JMX
- Spring AOP
- …

Demo

- Maven
- Visitor Pattern
- ASM
- AspectJ

Why AspectJ?

- RV requires instrumentation and specification
- AspectJ can provide both elements[3]
- AspectJ is probably the most popular aspect-oriented programming (AOP) framework

[3]Bodden et al., Collaborative Runtime Verification with Tracematches, RV 2007

http://fsl.cs.illinois.edu/index.php/JavaMOP_Syntax

JavaMOP syntax extends AspectJ

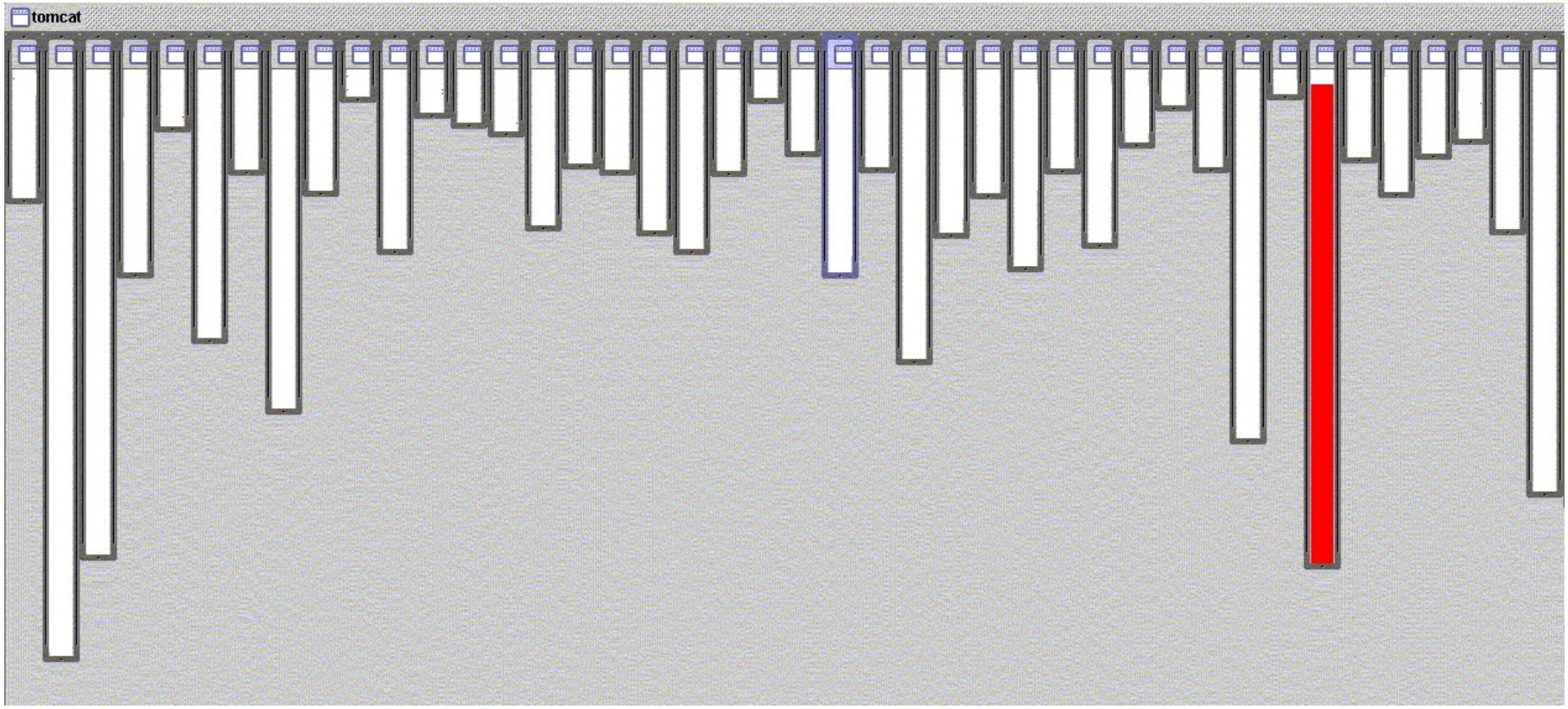
```
// BNF below is extended with {p} for zero or more and [p] for zero or one repetitions of p

   <Specification>         ::= {<Modifier>} <Id> <Parameters> "{"
                                  {<Declaration>}
                                  {<Event>}
                                  {  <Property>
                                    {<Property Handler>}
                                  }
                               "}"
   <Modifier>              ::= "unsynchronized" | "decentralized" | "perthread" | "suffix"
   <Event>                 ::= "event" <Id> <Event Definition> <Action>
   <Property>              ::= <Logic Name> ":" <Logic Syntax>
   <Property Handler>      ::= "@" <Logic State> <Action>
   <Event Definition>      ::= <Advice Specification> ":" <Extended Pointcut>
   <Action>                ::= "{" [ <Statements> ] "}"
   <Extended Pointcut>     ::= <Pointcut>
                             | <Extended Pointcut> "&&" <Extended Pointcut>
                             | "thread" "(" <Id> ")"
                             | "condition" "(" <Boolean Expression> ")"

   <Parameters>            ::= "(" [ <Parameter> { "," <Parameter> } ] ")"
   <Parameter>             ::= <Type Pattern> <Id>
   <Type Pattern>          ::= <!-- AspectJ Type Pattern                -->
   <Id>                    ::= <!-- Java Identifier                     -->
   <Declaration>           ::= <!-- Java variable declaration            -->
   <Advice Specification>  ::= <!-- AspectJ AdviceSpec                   -->
   <Pointcut>              ::= <!-- AspectJ Pointcut                     -->
   <Statements>            ::= <!-- Java statements                      -->
   <Boolean Expression>    ::= <!-- Java boolean expressions             -->
```

AspectJ implements AOP

- AOP modularizes programs differently than OOP
- Separates out cross-cutting concerns: code for one *aspect* of the program is collected in one place
- We will not delve into AOP as a paradigm
  - But we briefly explain the more general purpose of AOP
  - Focus: enough AspectJ to understand/write JavaMOP specs

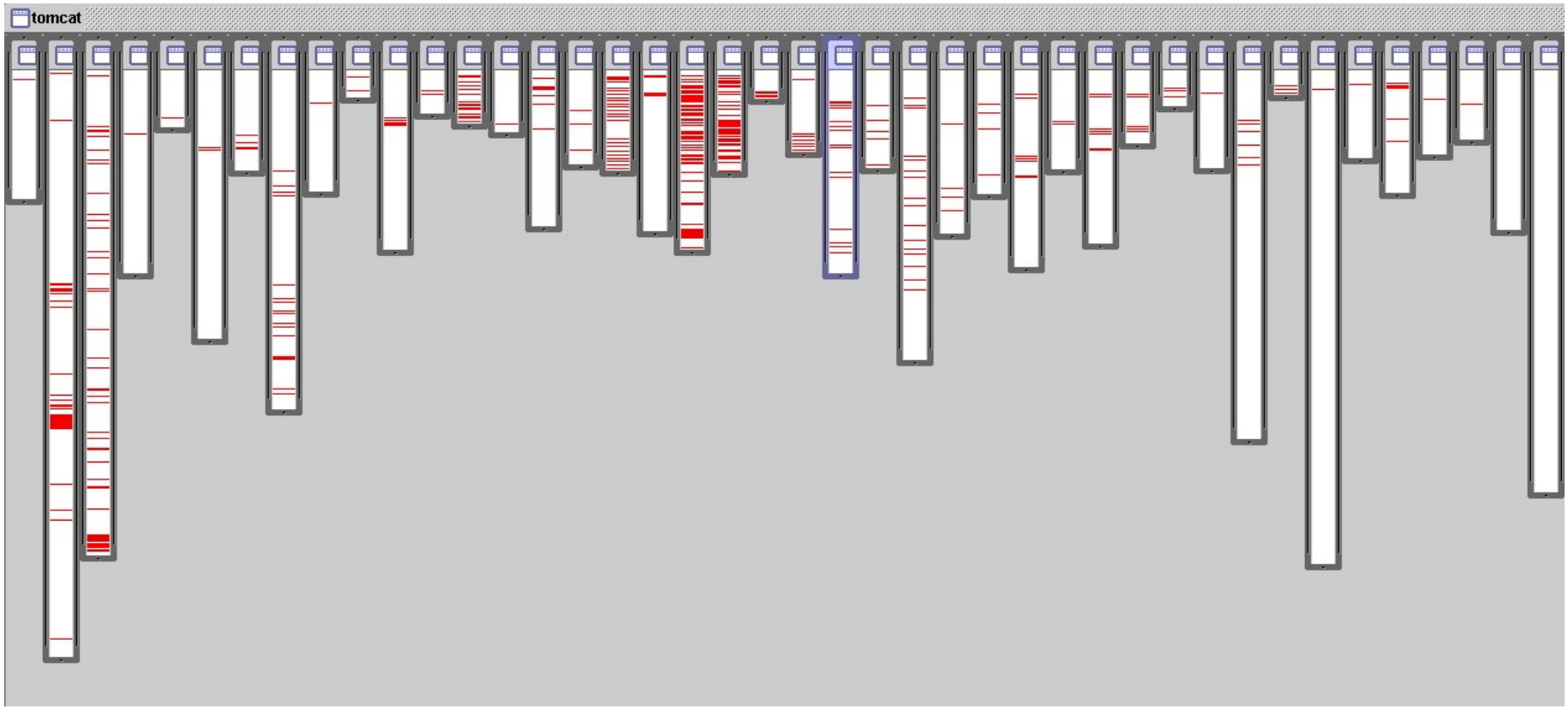
XML parsing

Good modularity



- XML parsing in org.apache.tomcat circa 2009(?)
  - red shows relevant lines of code
  - nicely fits in one box (object)

Bad modularity

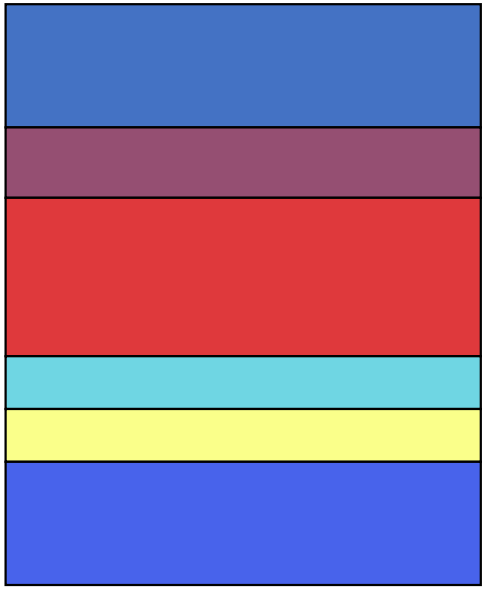


- Where is logging in org.apache.tomcat?
  - red shows lines of code that handle logging
  - not in just one place
  - not even in a small number of places

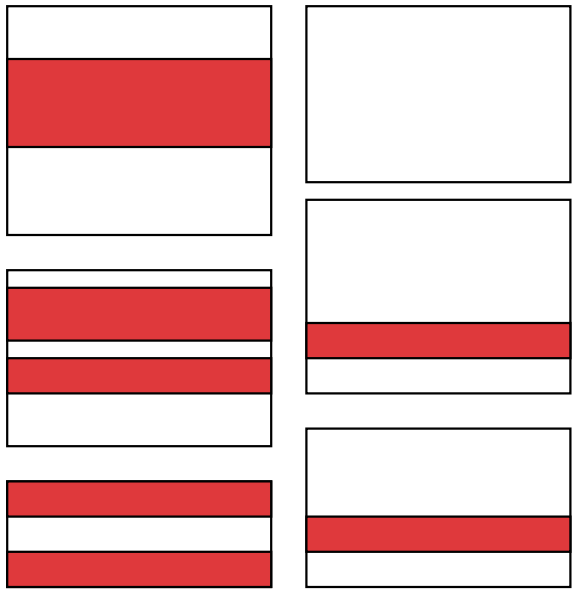
Two problems AOP tries to solve

code tangling:
one module
many concerns

example:
logging



code scattering:
one concern
many modules



Discuss: what are the effects of tangling and scattering?

The effects of the two problems

- Core logic becomes harder to comprehend when it is tangled with other code

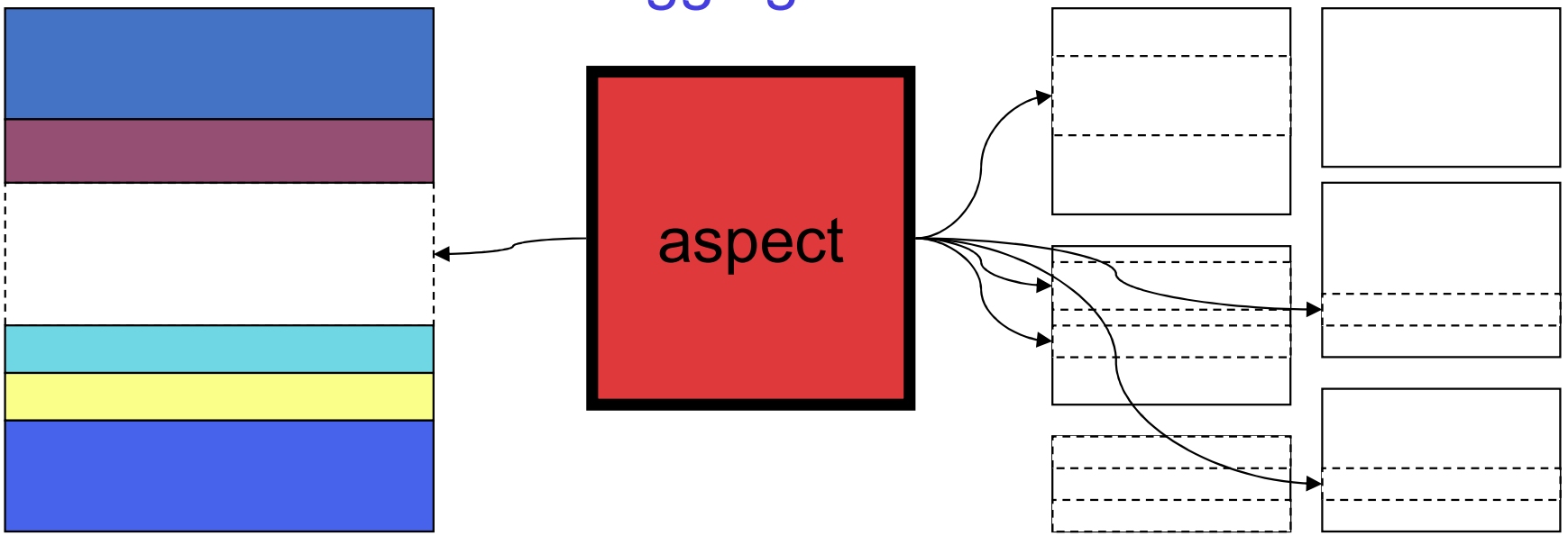
- Scattering similar logic in the code base results in
  - lots of typing, difficult to change code
  - missing the big picture (in one place)
  - increased probability of consistency errors

How AOP solves the two problems

code tangling:
one module
many concerns

code scattering:
one concern
many modules

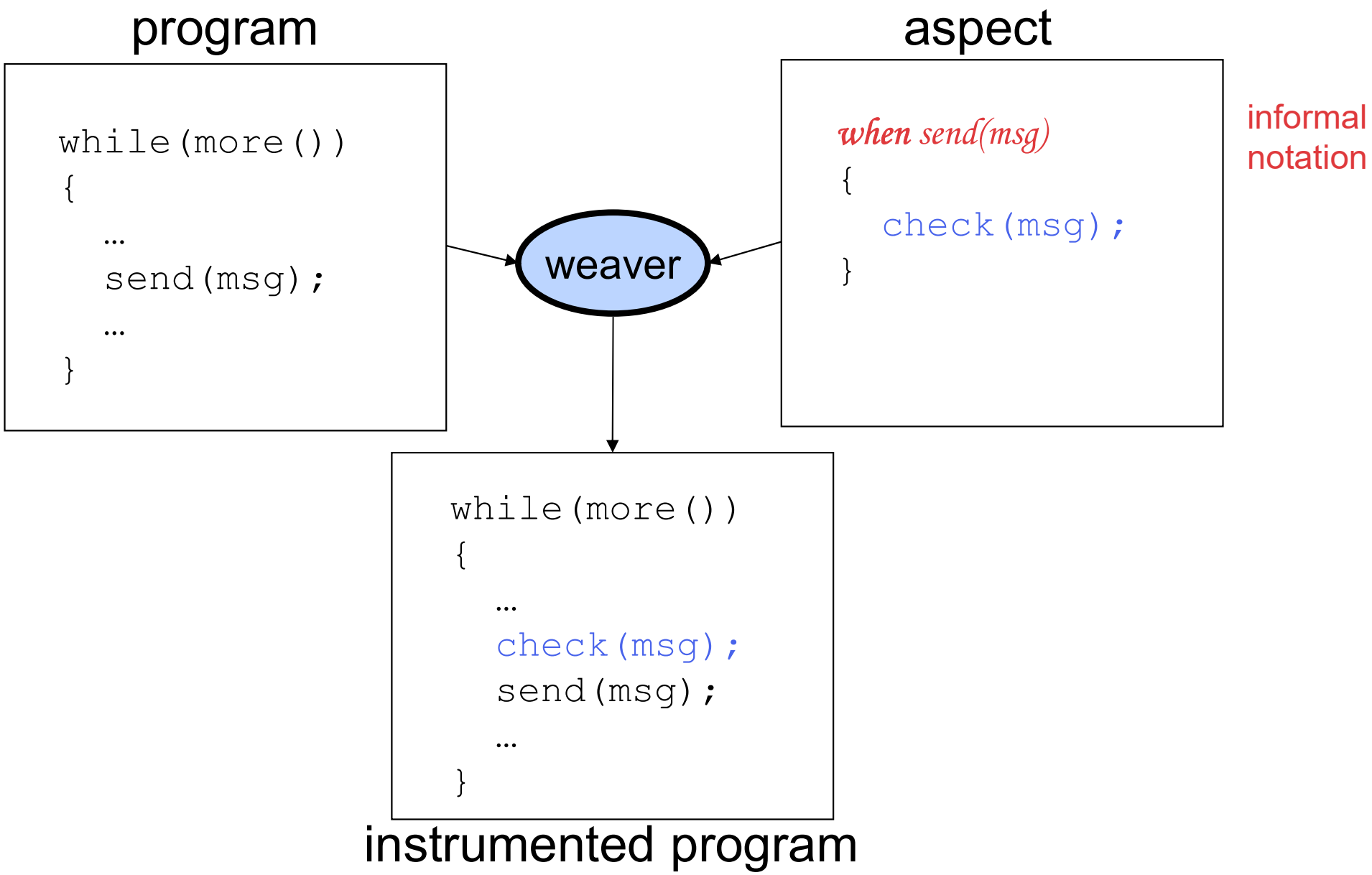
example:
logging



Cross-cutting concerns are common

- logging (tracking program behavior)
- verification (checking program behavior)
- policy enforcement (correcting behavior)
- security management (preventing attacks)
- profiling (exploring where programs spend time)
- memory management
- visualization of program executions
- …

A very simplified view of AOP



That’s it

except for notation, all the details, usage, …

Basic mechanisms

- Join points
  - points in a Java program

- Three main additions to Java
  - **Pointcut:** picks out join points and values at those points (primitive and user-defined pointcuts)
  - **Advice:** additional action to take at join points matching a pointcut
  - **Aspect:** a modular unit of crosscutting behavior (normal Java declarations, pointcut definitions, advice)

AspectJ terminology

Joinpoint = well-defined point in the program

Pointcut = Joinpoint-set

Advice = Kind × Pointcut × Code
`where` Kind = {before, after, around}

Aspect = Advice-list

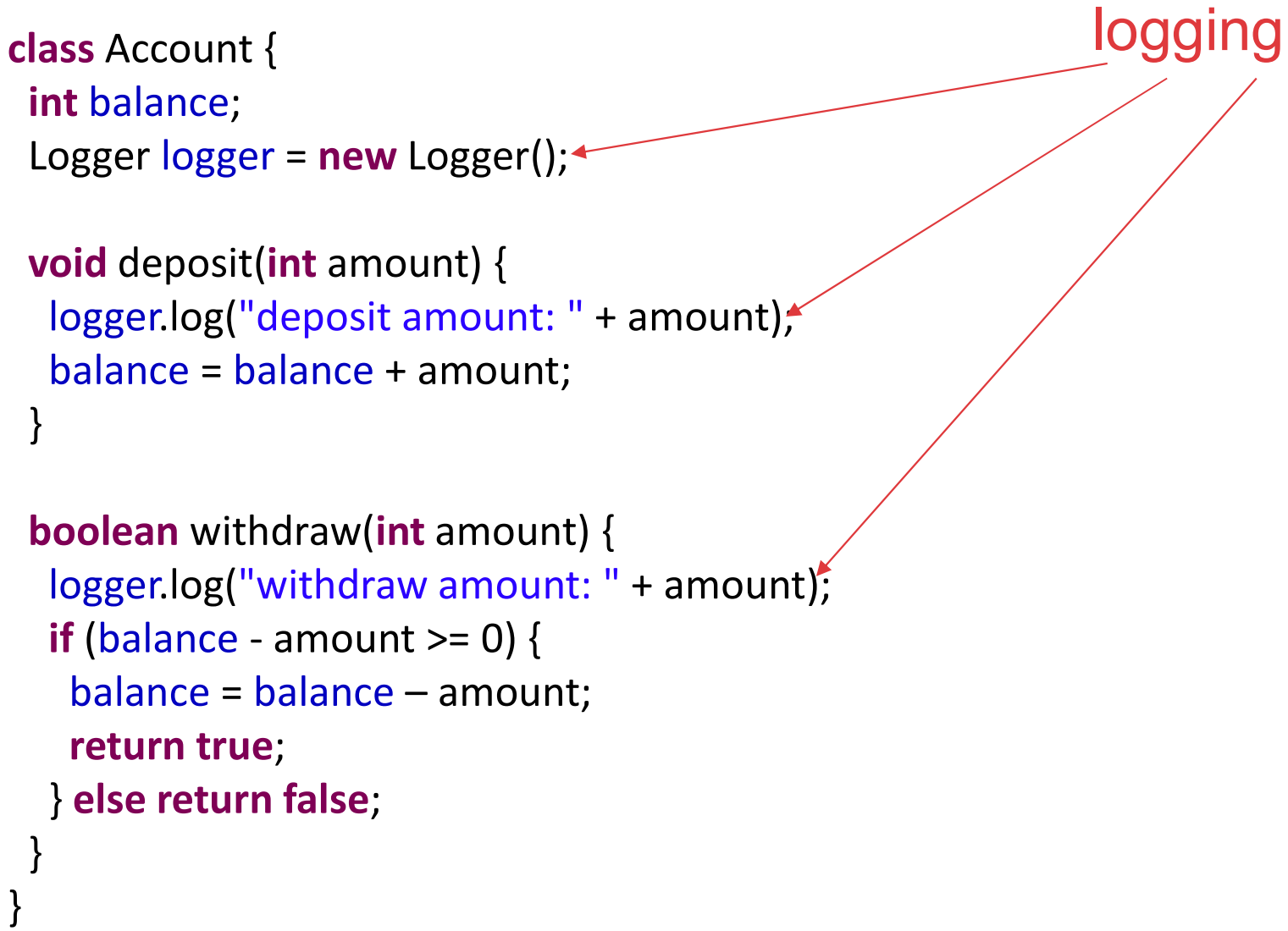
Example code

```
class Account {
  int balance;

  void deposit(int amount) {
    balance = balance + amount;
  }

  boolean withdraw(int amount) {
    if (balance - amount > 0) {
      balance = balance - amount;
      return true;
    } else return false;
  }
}
```

Logger class

```
class Logger {
  private PrintStream stream;

  Logger() {
    … create stream
  }

  void log(String message) {
    stream.println(message);
  }
}
```

Logging without AOP

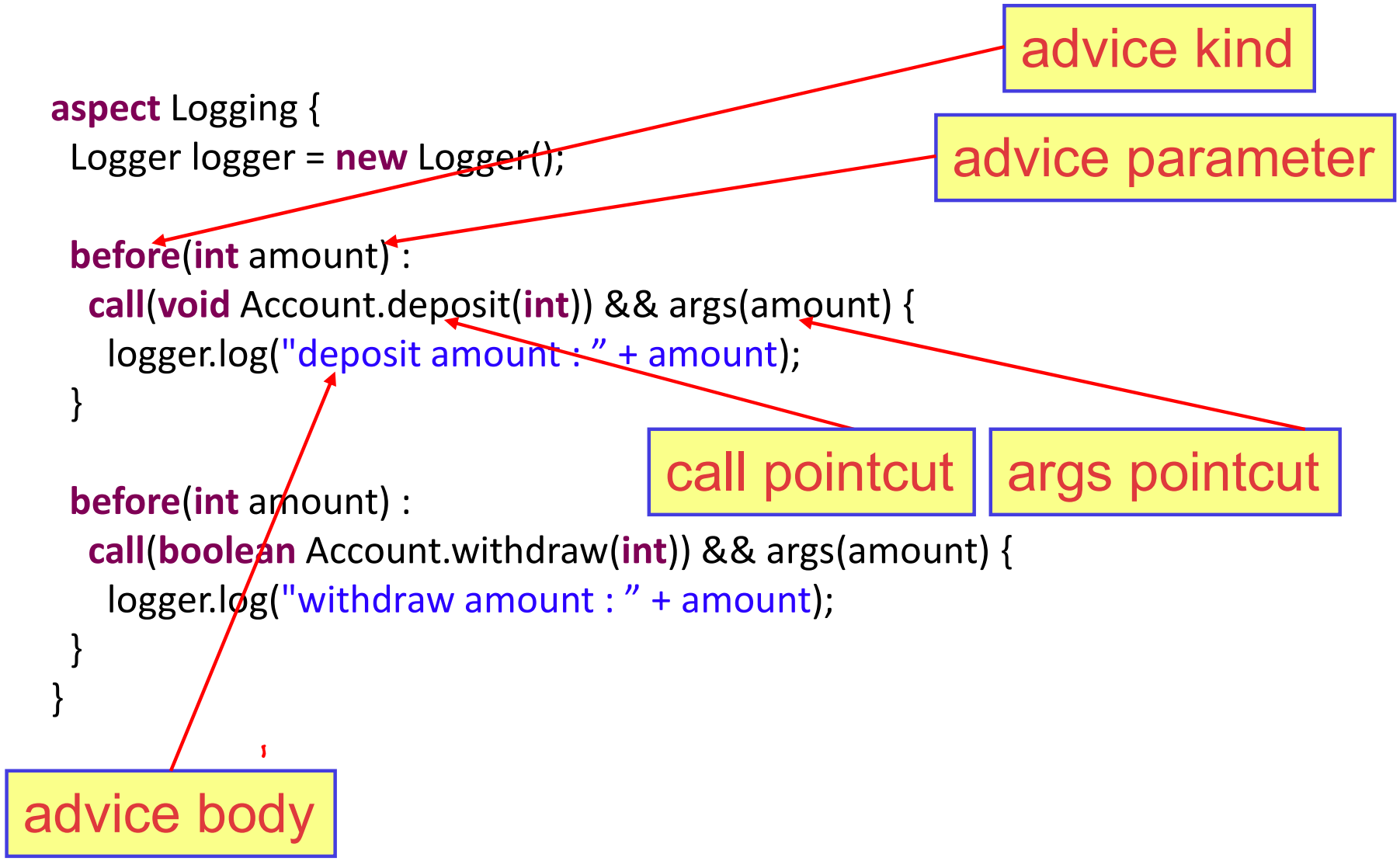


Logging with AOP

```
aspect Logging {
  Logger logger = new Logger();

  when deposit(amount){
    logger.log("deposit amount : " + amount);
  }

  when withdraw(amount){
    logger.log("withdraw amount : ” + amount);
  }
}
```

Logging code is in exactly one place

Logging in AspectJ



Primitive pointcuts

- A pointcut is a predicate on join points that:
  - can match or not match any given join point
  - can extract some values at matching join points

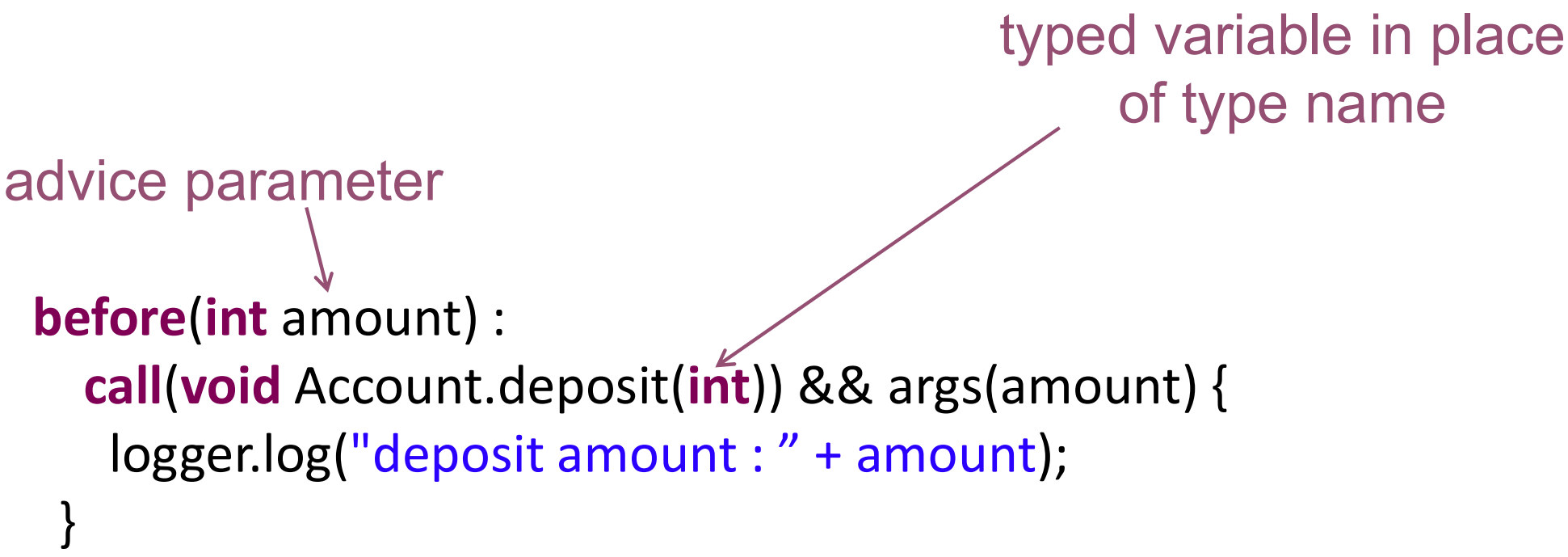
Example:

```
call(void Account.deposit(int))
```

matches any join point that is a call of a method with this signature

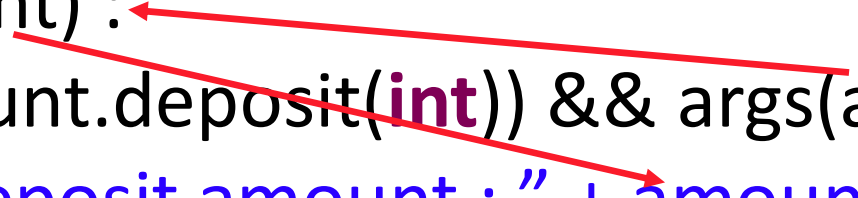
Explaining advice parameters

- Variables are bound by advice declaration
- Pointcuts supply values for variable
- Values are available in the advice body



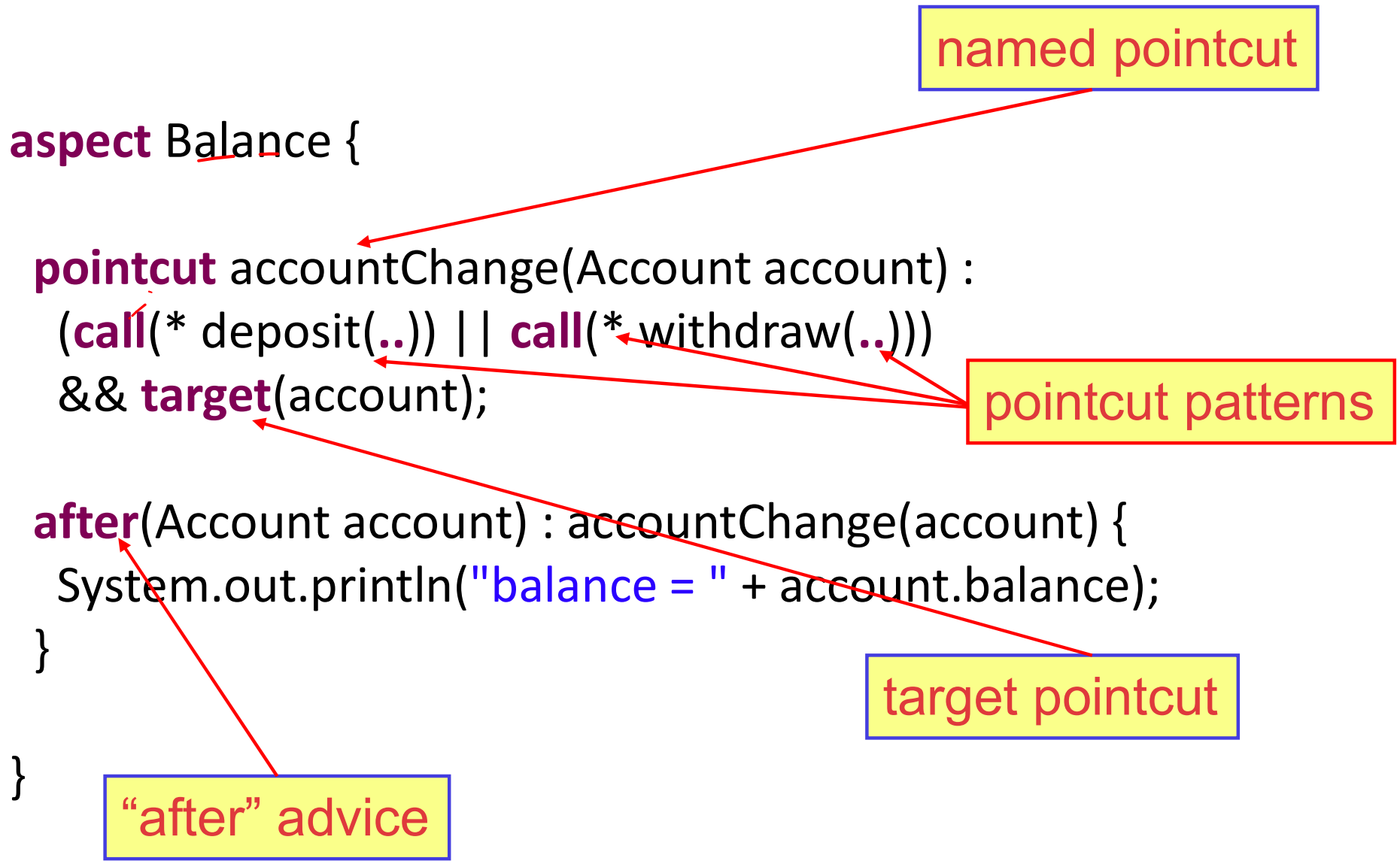
Advice parameter data flow

- Value is ‘pulled’
  - right to left across ‘**:**’ from pointcuts to advice
  - and then to advice body



```
before(int amount) :
    call(void Account.deposit(int)) && args(amount) {
      logger.log("deposit amount : ” + amount);
  }
```

Pointcut naming and patterns



Privileged aspects

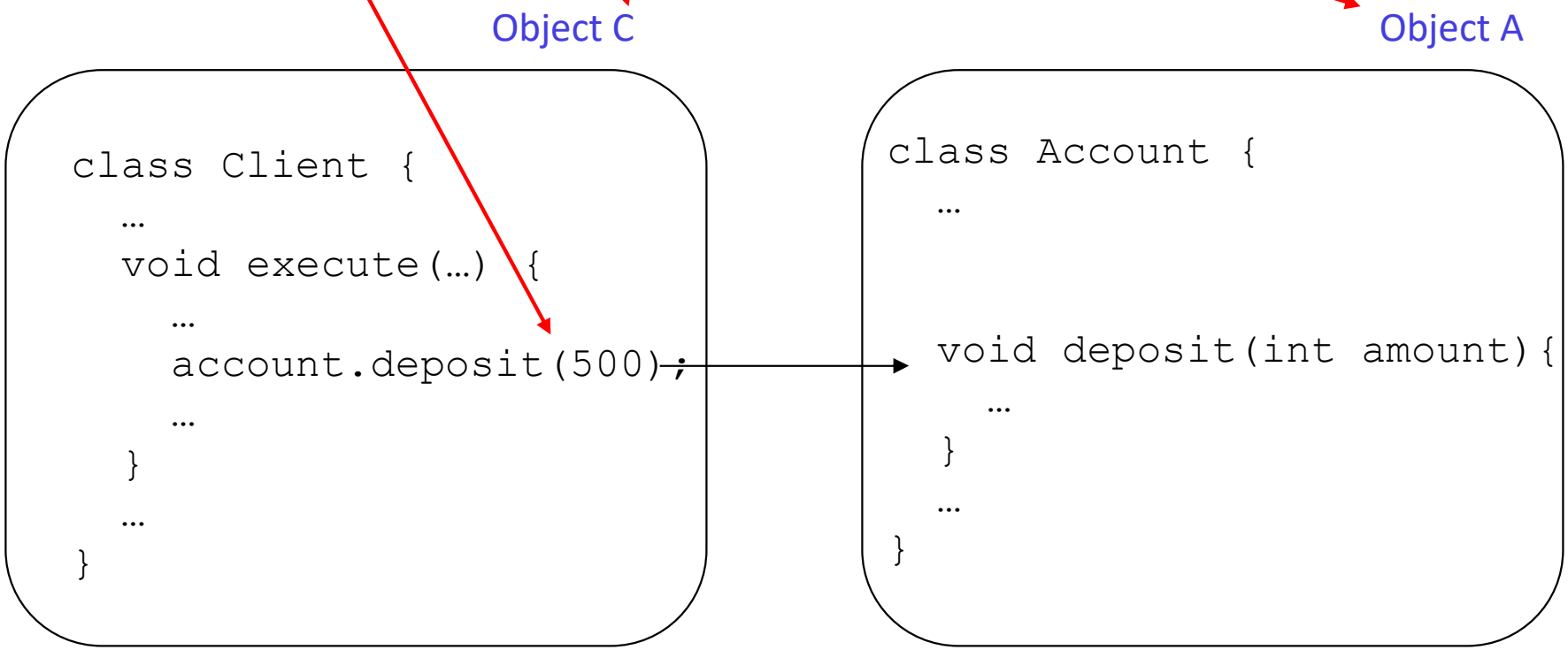
- Aspects that can access private fields and methods

```
privileged aspect Balance {

  pointcut accountChange(Account account) :
    (call(* deposit(..)) || call(* withdraw(..)))
    && target(account);

  after(Account account) : accountChange(account) {
    System.out.println("balance = " + account.balance);
  }
}
```

suppose account.balance is a private variable. Then the aspect must be privileged.

args, this and target pointcuts

```
before(Client client, Account account, int amount) :
   call(void Account.deposit(int))
   && args(amount) && this(client) && target(account) {…}
```



target pointcut

target(*TypeName* | *VariableName*)

Does two things:
- predicate on join points - any join point at which target object is an instance of *TypeName* or of same type as *VariableName*.
- exposes target if argument is a variable name

target(Account) :
- matches when target object is of type Account

`Account` is a type

target(account) :
- matches too, since account is of type Account
- in addition, it binds the target object to account

`account` is a variable

Parameter data flow again

- Value is ‘pulled’
  - right to left from pointcuts to user-defined pointcuts
  - from pointcuts to advice
  - and then to advice body

```
pointcut accountChange(Account account) :
  (call(* deposit(..)) || call(* withdraw(..)))  && target(account);

 after(Account account) : accountChange(account) {
  System.out.println("balance = " + account.balance);
 }
```

The proceed “method”

- **For each around advice with the signature:**

  ***T* around(*T1* arg1, *T2* arg2, …)**

- **There is a special method with the signature:**

  ***T* proceed(*T1*, *T2*, …)**

- **Calling “proceed” means:**

  “run what would have been run if this around advice had not been defined”

Reflexive information available at all joinpoints

- thisJoinPoint
  - getArgs() : Object[]
  - getTarget() : Object
  - getThis() : Object
  - getStaticPart() : JoinPointStaticPart

- thisJoinPointStaticPart
  - getKind() : String
  - getSignature() : Signature
  - getSourceLocation() : SourceLocation

Fun activity: implement a code coverage tool in AspectJ

Examples of patterns

Type names:

Command
*Command
java.*.Date
Java..*
Javax..*Model+

Combined Types:

!Vector
Vector || HashTable
java.util.RandomAccess+ && java.util.List+

Method Signatures:

public void Account.set*(*)
boolean Account.withdraw(int)
bo* Po*.wi*w(i*)
!static * *.*(..)
rover..command.Command+.check(int,..)

Challenges in instrumentation

- Cost: instrumentation can slow programs down
- Heisenbugs[4]: slowing program execution can introduce hard-to-debug timing-related bugs
- Can produce hard to read (binary) code
- Instrumentation tools can conflict

[4]Recall “Heisenberg’s” uncertainty principle in physics

Food for thought (take home)

Is AspectJ/AOP the best way to instrument code for RV?

AspectJ Resources

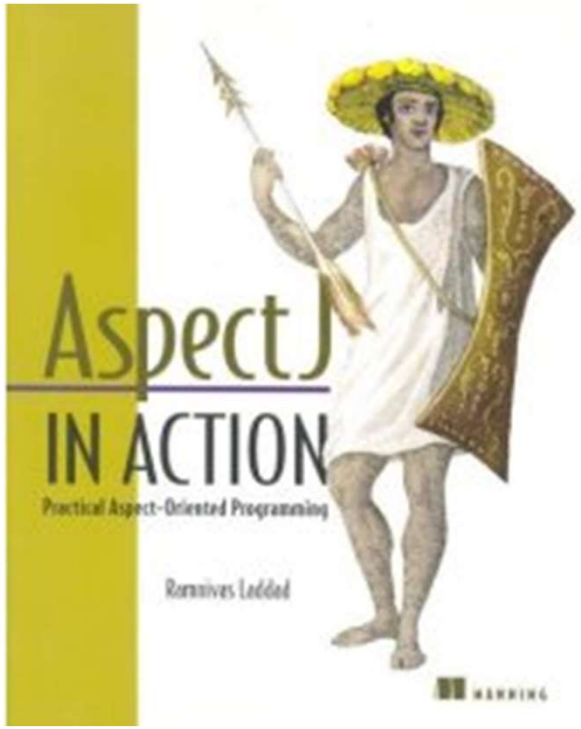
- http://www.eclipse.org/aspectj

AspectJ Quick Reference

Aspects *at top-level (or* **static** *in types)*

aspect *A* { … }
defines the aspect *A*
privileged aspect *A* { … }
A can access private fields and methods
aspect *A* **extends** *B* **implements** *I, J* { … }
B is a class or abstract aspect, *I* and *J* are interfaces
aspect *A* **percflow**(*call(void Foo.m())*) { … }
an instance of *A* is instantiated for every control flow through calls to *m()*

general form:
[**privileged**] [*Modifiers*] **aspect** *Id*
[**extends** *Type*] [**implements** *TypeList*] [*PerClause*]
{ *Body* }
where *PerClause* is one of
pertarget (*Pointcut*)



ICAOSDDP 2020: 14. International Conference on Aspect-Oriented Software Development, Design and Programming

September 24-25, 2020 in London, United Kingdom

What we covered in this class

- Instrumentation is important in many software engineering tasks, including RV
- We learned the basics of two instrumentation tools
- An introduction to aspect-oriented programming
- Hands-on exposure to AspectJ