“To my taste the main characteristic of intelligent thinking is that one is willing and able to study in depth an aspect of one's subject matter in isolation, for the sake of its own consistency, all the time knowing that one is occupying oneself with only one of the aspects. ...

- Dijkstra, *A discipline of programming*, 1976
last chapter, **In retrospect**

… The other aspects have to wait their turn, because our heads are so small that we cannot deal with them simultaneously without getting confused. This is what I mean by ‘focussing one's attention upon a certain aspect’; it does not mean completely ignoring the other ones, but temporarily forgetting them to the extent that they are irrelevent for the current topic. ...

- Dijkstra, *A discipline of programming*, 1976
last chapter, **In retrospect**

… Such separation, even if not perfectly possible, is yet the only available technique for effective ordering of one's thoughts that I know of. ...

- Dijkstra, *A discipline of programming*, 1976
last chapter, **In retrospect**

… I usually refer to it as ‘separation of concerns’, because one tries to deal with the difficulties, the obligations, the desires, and the constraints one by one. ...

- Dijkstra, *A discipline of programming*, 1976
last chapter, **In retrospect**

… When this can be achieved successfully, we have more or less partitioned the reasoning that had to be done — and this partitioning may find its reflection in the resulting partitioning of the program into ‘modules’ — but I would like to point out that this partitioning of the reasoning to be done is only the result, and not the purpose. ...

- Dijkstra, *A discipline of programming*, 1976
last chapter, **In retrospect**

… The purpose of thinking is to reduce the detailed reasoning needed to a doable amount, and a separation of concerns is the way we hope to achieve this reduction. ...

- Dijkstra, *A discipline of programming*, 1976
last chapter, **In retrospect**

… The crucial choice is, of course, what aspects to study 'in isolation', how to disentangle the original amorphous knot of obligations, constraints and goals into a set of 'concerns' that admit a reasonably effective separation. ...

- Dijkstra, *A discipline of programming*, 1976
last chapter, **In retrospect**

… To arrive at a successful separation of concerns for a new, difficult problem area will nearly always take a long time of hard work; it seems unrealistic to expect otherwise. ...

- Dijkstra, *A discipline of programming*, 1976
last chapter, **In retrospect**

… The knowledge of the goal of 'separation of concerns' is a useful one: we are at least beginning to understand what we are aiming at."

- Dijkstra, *A discipline of programming*, 1976
last chapter, **In retrospect**

goal of this talk

- discuss the implementation of complex software systems
- focusing on issues of modularity
- how existing tools help achieve it
- propose a new tool to help improve modularity in some cases where existing tools are inadequate

slides, papers and system at www.parc.xerox.com/aop

format of this talk

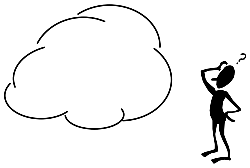
- sharing context
- a problem and an idea
- our current instantiation of the idea
- implementation
- summary and hopes

part i -- sharing context

I sharing context

the engineering challenge

- extremely complex systems
- more than our mind can handle all at once
- must manage the complexity

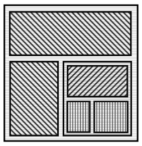


problem decomposition

- break the problem into sub-problems
- address those relatively independently

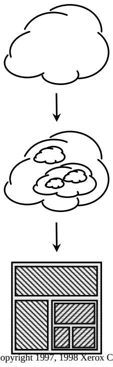
solution construction & composition

- construct complete systems from the designs by
  - implementing the sub-parts, and
  - composing them to get the whole



design & implementation

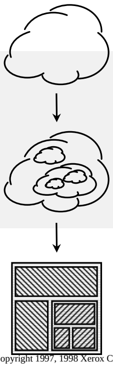
- decomposition breaks big problems into smaller ones
- composition builds big solutions out of smaller ones



“clean separation of concerns”

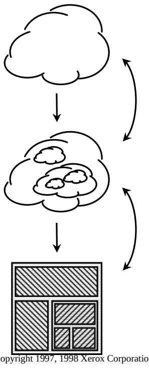
we want:

- – natural decomposition
- – concerns to be localized
- – explicit handling of design decisions
- – in both design and implementation



achieving this requires...

- synergy among
  - problem structure and
  - design concepts and
  - language mechanisms



“natural design”

“the program looks like the design”

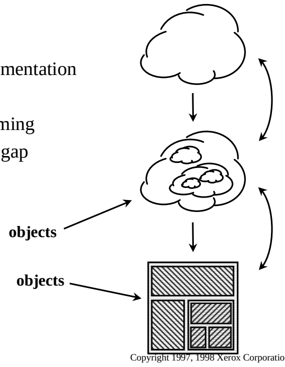
the “component”[1] concept

- a modular unit of functionality
- fits many natural design concerns
- well-supported by existing programming technology
- a rich collection of
  - design principles, conventions and notations
  - programming mechanisms

object-orientation

“objects”

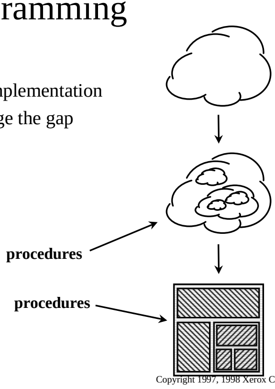
- used in design and implementation
- object-oriented design
- object-oriented programming
- many tools to bridge the gap



procedural programming

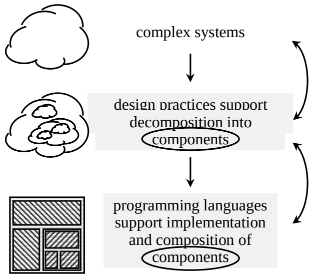
“procedures”

- used in design and implementation
- some tools even bridge the gap



summary so far

good separation of
concerns in both design
and implementation

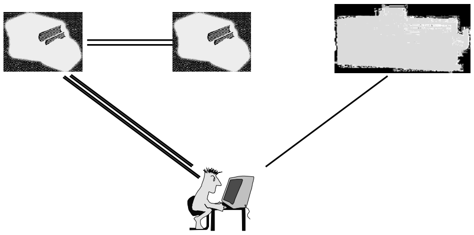

complex systems

design practices support decomposition into components

programming languages support implementation and composition of components

II a problem and an idea

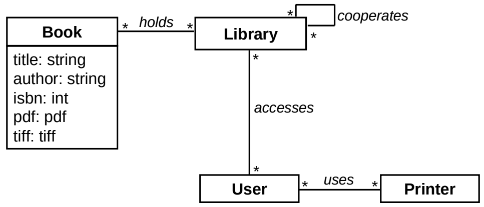
a distributed digital library



the component structure

- use objects
  - objects are a natural fit for this system
- so…
  - the design breaks down into component objects
  - implement using OOP

the class graph



the code

Book

```
class Book {
  private String      title;
  private String      author;
  private String      isbn;
  private PostScript  ps;
  private User        borrower;

  public Book(String t, String a, String i, PostScript p) {
    title = t;
    author = a;
    isbn = i;
    ps = p;
  }

  public User get_borrower() {return borrower;}
  public void set_borrower(User u) {borrower = u;}
  public PostScript get_ps() { return ps; }
}
```

User

```
class User {
  private String name;
  Library theLibrary;
  Printer thePrinter;

  public User(String n) { name = n; }

  public boolean getBook (String title) {
    Book aBook = theLibrary.getBook(this, title);
    thePrinter.print(this,aBook);
    return true;
  }
}
```

Library

```
class Library  {
  Hashtable books;
  Library(){
    books = new Hashtable(100);
  }
  public Book getBook(User u, String title) {
    System.out.println("REQUEST TO GET BOOK " + title);
    if(books.containsKey(title)) {
      Book b = (Book)books.get(title);
      System.out.println("getBook: Found it:" + b);
      if (b != null) {
        if (b.get_borrower() == null) {
          b.set_borrower(u);
          return b;
        }
      }
    }
    return null;
  }
}
```

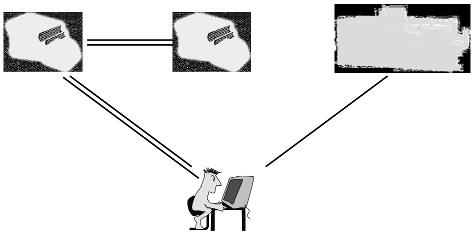
Printer

```
public class Printer {
  String status = "Idle";
  Vector jobs;

public boolean print (User u, Book b) {
    PostScript ps=get_ps(b);
    Job newJob = new Job (ps, u.get_name());
    return queue(newJob);
  }
  boolean queue(Job j) {
  //...
  return true;
  }
}
```

all is well

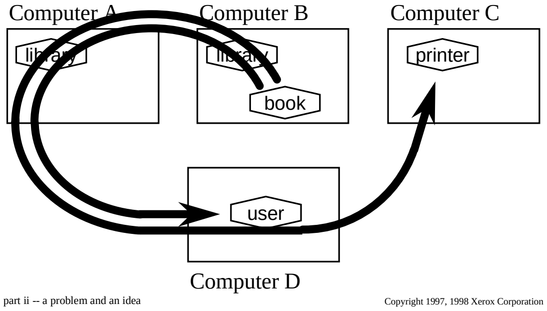
- design is natural
- code looks like the design
- good separation of concerns
  - localized in the design
  - localized in the code
  - handled explicitly

a distributed digital library



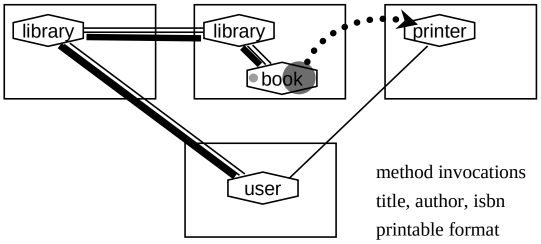
minimizing network load

dataflow patterns



minimizing network load

controlling slot copying



method invocations

title, author, isbn

printable format

revised
the ^ code

Book

```
class Book {
  private BookID        id;
  private PostScript    ps;
  private UserID        borrower;

  public Book(String t, String a, String i, PostScript p) {
    id = new BookID(t,a,i);
    ps = p;
  }

  public UserID get_borrower() {return borrower;}
  public void set_borrower(UserID u) {borrower = u;}
  public PostScript get_ps() { return ps; }
  public BookID get_bid() { return id; }
}

class BookID {
  private String    title;
  private String    author;
  private String    isbn;

  public BookID(String t, String a, String i) {
    title = t;
    author = a;
    isbn = i;
  }
  public String get_title() {return title;}
}
```

User

```
class User {
  private UserID id;
  Library theLibrary;
  Printer thePrinter;

  public User(String n) { id = new UserID(n); }

  public boolean getBook (String title) {
    BookID aBook=null;
    try{
      aBook = theLibrary.getBook(id, title);
    } catch (RemoteException e) {}
    try {
      thePrinter.print(id, aBook);
    } catch (RemoteException e) {}
    return true;
  }
  public UserID get_uid() { return id; }
}

class UserID {
  private String name;

  public UserID(String n) { name = n; }
  public String get_name() { return name; }
}
```

Library

```
interface LibraryInterface extends Remote {
  public BookID getBook(UserID u, String title) throws RemoteException;

  public PostScript getBookPS(BookID bid) throws RemoteException;
}

class Library extends UnicastRemoteObject implements LibraryInterface  {
  Hashtable books;
  Library() throws RemoteException {
    books = new Hashtable(100);
  }
  public BookID getBook(UserID u, String title)
  throws RemoteException {
    System.out.println("REQUEST TO GET BOOK " + title);
    if(books.containsKey(title)) {
      Book b = (Book)books.get(title);
      System.out.println("getBook: Found it:" + b);
      if (b != null) {
        if (b.get_borrower() == null) {
          b.set_borrower(u);
          return b.get_bid();
        }
      }
    }
    return null;
  }
  public PostScript getBookPS(BookID bid)
  throws RemoteException {
    if (books.containsKey(bid.get_title())) {
      Book b = (Book)books.get(bid.get_title());
      if (b != null)
        return b.get_ps();
    }
    return null;
  }

}
```

Printer

```
interface PrinterInterface extends Remote {
  public boolean print (UserID u, BookID b) throws RemoteException;
}

class Printer extends UnicastRemoteObject
              implements PrinterInterface {
  String status = "Idle";
  Vector jobs;
  private Library theLibrary;

  public Printer() throws RemoteException{}
  public boolean print (UserID u, BookID b) throws RemoteException{
    PostScript ps=null;
    try{ps = theLibrary.getBookPS(b);}
      catch (RemoteException e) {}
    Job newJob = new Job (ps, u.get_name());
    return queue(newJob);
  }
  boolean queue(Job j) {
  //...
  return true;
  }
}
```

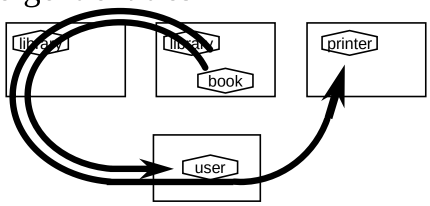
why?

- why did so much code change?
- why wasn't this concern well localized?
- why didn't this "fit" the component structure?

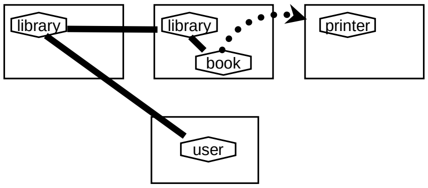
because…

- we are working with "emergent entities", and
- the component concept, and its associated implementation mechanisms, fundamentally don't provide adequate support for working with emergent entities

emergent entities



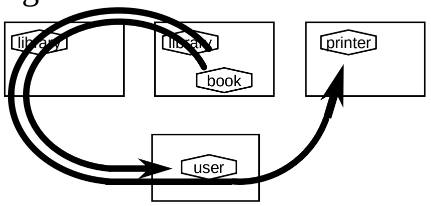
emergent entities



- emerge[1] during program execution
  - from (possibly non-local) interactions of the components
- are not components
  - do not exist explicitly in the component model or code

[1] emerge: to become manifest; to rise from or as if from an enveloping fluid; come out into view

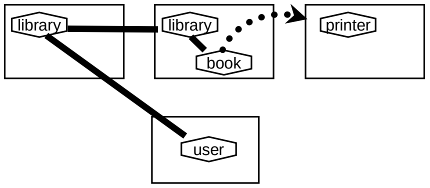
emergent entities



- emerge[1] during program execution
  - from (possibly non-local) interactions of the components
- are not components
  - do not exist explicitly in the component model or code

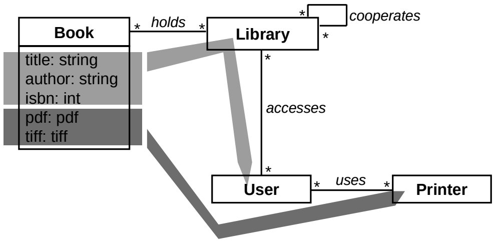
[1] emerge: to become manifest; to rise from or as if from an enveloping fluid; come out into view

are tough to handle because...



- they are not explicit in the component model or code
- they have non-localized origins and interactions
- they cross-cut the component structure...

cross-cutting the components



- the sub-parts of the objects are not existing classes
- the desired dataflows are not existing message sends

~~but, but, but...~~

~~the code can be remodularized to “fit” better...~~

~~<imagine your own alternative class diagram here>~~

violates separation of concerns
leads to tangled code

claim

- remodularizing isn’t good enough!
  - it ruins the separation of concerns
- the functionality and the network optimization concern are fundamentally different
- would like different “carvings”[1] of the system
  - in terms of component structure,
  - and in terms of emergent entities,
    - with support for the cross-cutting modularities

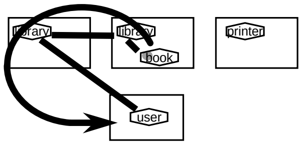
[1] carve: to cut with care or precision, to cut into pieces or slices, to work as a sculptor or engraver

just try it

```
dataflow Book {Library to User}
  {copy: title, author, isbn};


dataflow Book {Library to Printer}
  {direct: pdf, tiff};
```

what it says

```
dataflow Book {Library to User}
  {copy: title, author, isbn};
```

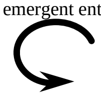


the dataflow of books, from library objects to user objects, should be implemented by copying the title, author and isbn slots only

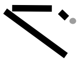
how it says it

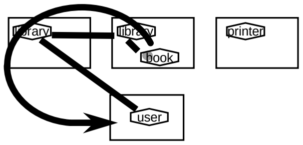
```
dataflow Book {Library to User}
  {copy: title, author, isbn};
```

identifies emergent entity



controls its implementation



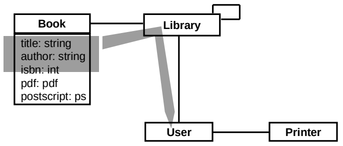


cross-cutting

```
dataflow Book {Library to User}
  {copy: title, author, isbn};
```

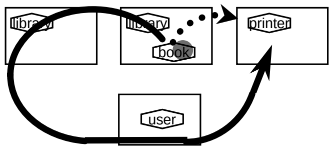
emergent

static

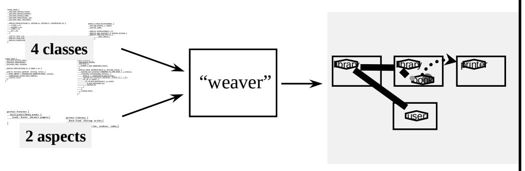


and...

```
dataflow Book {Library to Printer}
  {direct: pdf, tiff};
```



assume a…



- a "language processor" that
  - accepts two kinds of code as input;
  - produces "woven" output code, or
  - directly implements the computation

general claim

- remodularizing the component structure is not a satisfactory way of dealing with emergent entities
- want different carvings of the system:
  - keep the clean component structure
  - control emergent entities in "natural terms"
    - in terms of the emergent entity
    - with support for cross-cutting

emergent entities

- an entity that does not exist explicitly in the component model or code, but rather arises during execution
  - – data flows
    - all the places this value goes...
  - – control states
    - two methods running concurrently
    - one method blocked on another
    - all the callers of this function
    - history of calls up to this point (aka the stack)...

the “aspect” concept

- components are modular units of functionality
- aspects are modular units of control over emergent entities
- in the distributed digital library:

– library component
– book component
– user component
– printer component
– …

– lookup dataflow aspect
– printing dataflow aspect
– …

“aspect languages”

- aspect languages

  connect to a component language, and provide:

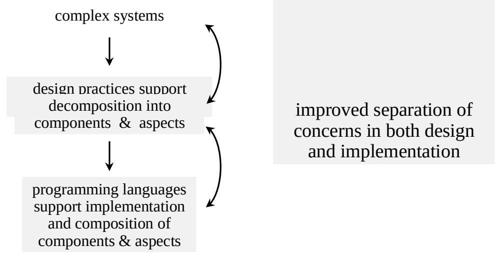
  – a mechanism for referring to emergent entities

  – a mechanism for exercising some control over the implementation of the emergent entities

  – support for using cross-cutting modularities

```
dataflow Book {Library to Printer}
  {direct: pdf, tiff};
```

summary so far


complex systems
design practices support decomposition into components & aspects
programming languages support implementation and composition of components & aspects
improved separation of concerns in both design and implementation

III

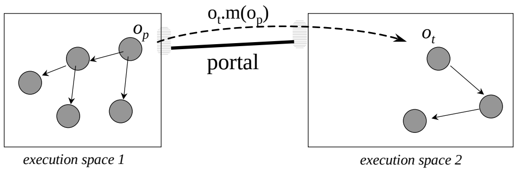
The AspectJ™ languages

AspectJ is…

- an extension to Java™
- targeted at distributed and/or concurrent applications
- several general-purpose aspect languages
  - – remote data transfer aspect language
  - – computation migration aspect language
  - – coordination aspect language
- a weaver for those languages

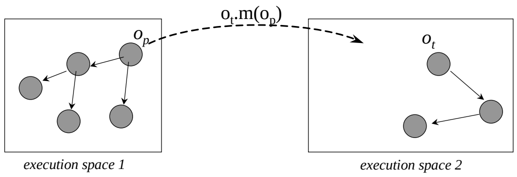
a data transfer aspect language

- provides control over data transfers between execution spaces
  - transfer of arguments and/or return values
  - control over sub-fields, sub-sub-fields etc.



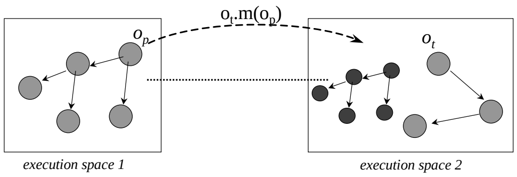
referring to the emergent entity

```
portal Library {
 Book find (String title){
 return:
   Book: {copy title, author, isbn;}
 }
}
```



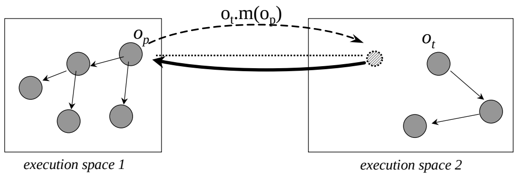
copy transfer mode

```
portal Library {
 Book find (String title){
 return:
   Book: {copy title, author, isbn;}
 }
}
```



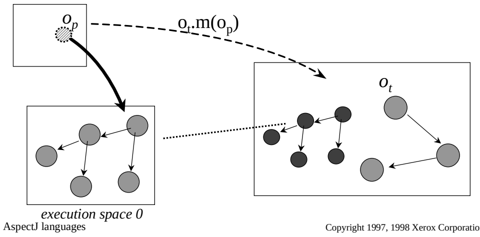
gref transfer mode

```
portal Library {
Book find (String title){
 return:
   Book: gref;
 }
}
```



direct transfer mode

```
portal Printer {
  void print(Book book) {
    book: Book: {direct pages;}
  }
}
```



the aspect language cross-cuts OOP

```
portal Printer {
  void print(Book book) {
    book: Book: {direct pages;}
  }
}
```

when you send:

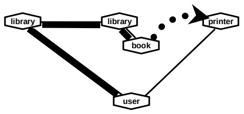
- this kind of object, as
- this argument of
- this method, send
- this field
- this way

aspect composition cross-cuts too

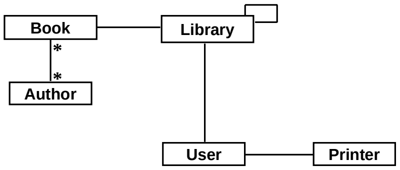
- these aspects compose along dataflows
- not along normal class/method composition

```
portal Library {
 Book find (String title){
 return:
   Book: {copy title, author, isbn;}
 }
}
```

```
portal Printer {
  void print(Book book) {
    book: Book: {direct pages;}
  }
}
```



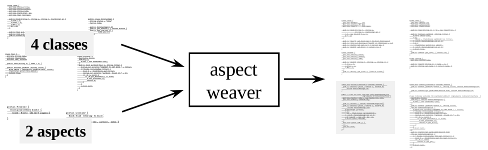
more on cross-cutting



```
portal Library {
  Book find(String title) {
    return: {copy title, author, isbn;
              Author bypass books;}
  }
}
```

what this is and isn’t

- weaver combines two kinds of code
- equivalent effect of complex tangled code
- equivalent elegance of original clean code
  - component code is unchanged
  - natural modularity of aspects



a coordination aspect language

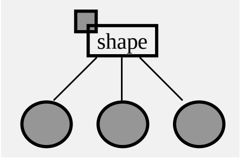
```
public class Shape {
  protected int x = 0;
  protected int y = 0;
  protected int w = 0;
  protected int h = 0;

  int getX() { return x; }
  int getY() { return y; }
  int getWidth(){ return w; }
  int getHeight(){ return h; }
  void adjustLocation() {
    x = longCalculation1();
    y = longCalculation2();
  }
  void adjustSize() {
    w = longCalculation3();
    h = longCalculation4();
  }
}
```

```
coordinator Shape {
  selfex adjustLocation;
  selfex adjustSize;
  mutex {adjustLocation, getX};
  mutex {adjustLocation, getY};
  mutex {adjustSize, getWidth};
  mutex {adjustSize, getHeight};
}
```

fits object-oriented modularity

```
static coordinator Shape {
  selfex adjustLocation,
         adjustSize;
  mutex {adjustLocation, getX};
  mutex {adjustLocation, getY};
  mutex {adjustSize, width};
  mutex {adjustSize, height};
}
```

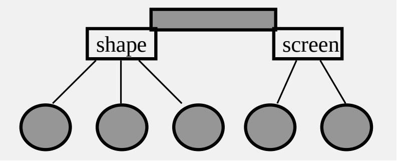
- per-object
- per-class



cross-cuts object-oriented modularity

```
static coordinator Shape, Screen {
  selfex adjustLocation,
         adjustSize;
  mutex {adjustLocation, getX};
  mutex {adjustLocation, getY};
  mutex {adjustSize, width};
  mutex {adjustSize, height};
}
```

- per-object
- per-class
- multi-class
- any methods



status of AspectJ

- some preliminary user studies complete
  - results promising, not yet conclusive
- first public release to go on web-site shortly
  - free use (including in products)
  - weaver, documentation, example programs
  - coordination aspect language only
- next release early June
  - remote data transfer aspect language
- later releases
  - other aspect languages, operate directly on class files…

IV implementing aspect weavers

jump to conclusion

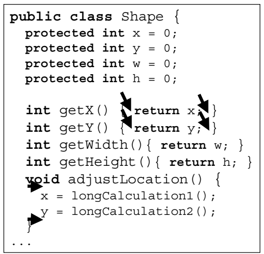
what aspect weavers do

- implement one or more aspect languages
- allow us to program in alternate modularity
  - in the modularity of the emergent entity
  - help with cross-cutting
- aspect weaver must "gather up the roots and contact points of emergent entities"
  - places spread around the OO program
  - this can appear difficult...

for example

```
coordinator Shape, Screen {
  mutex {adjustLocation, getX};
  mutex {adjustLocation, getY};
}
```

requires coordinated code in these places

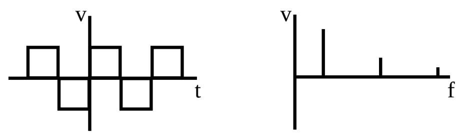


```
public class Shape {
  protected int x = 0;
  protected int y = 0;
  protected int w = 0;
  protected int h = 0;

  int getX() { return x; }
  int getY() { return y; }
  int getWidth(){ return w; }
  int getHeight(){ return h; }
  void adjustLocation() {
    x = longCalculation1();
    y = longCalculation2();
  }
...
```

"frob every method call"

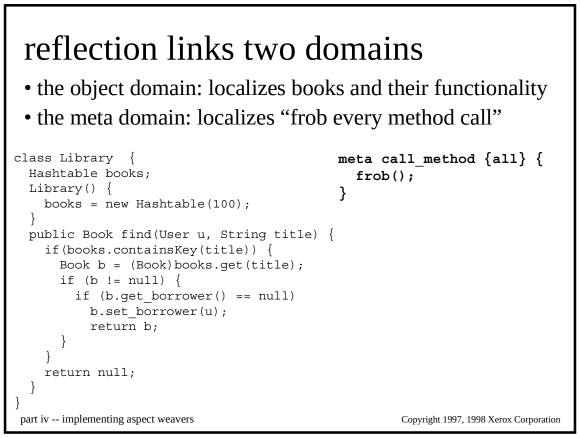
```
class Library  {
  Hashtable books = new Hashtable(100);
  }
  public Book find(User u, String title) {
    frob();
    if(books.containsKey(title)) {
      frob();
      Book b = (Book)books.get(title);
      if (b != null) {
        frob();
        if (b.getBorrower() == null)
          {frob();
           b.setBorrower(u);}
          return b;
      }
    }
    return null;
  }
}
```

domain transforms



time domain *frequency domain*

- what is diffuse in one domain is local in another
- the Fourier transform moves between the two
  - it localizes what was non-local and vice-versa

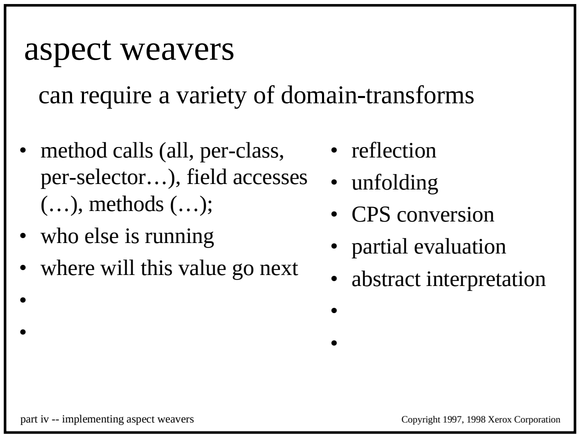


reflection links two domains

- the object domain: localizes books and their functionality
- the meta domain: localizes “frob every method call”

```
class Library  {
  Hashtable books;
  Library() {
    books = new Hashtable(100);
  }
  public Book find(User u, String title) {
    if(books.containsKey(title)) {
      Book b = (Book)books.get(title);
      if (b != null) {
        if (b.get_borrower() == null)
          b.set_borrower(u);
          return b;
      }
    }
    return null;
  }
}
```

```
meta call_method {all} {
  frob();
}
```

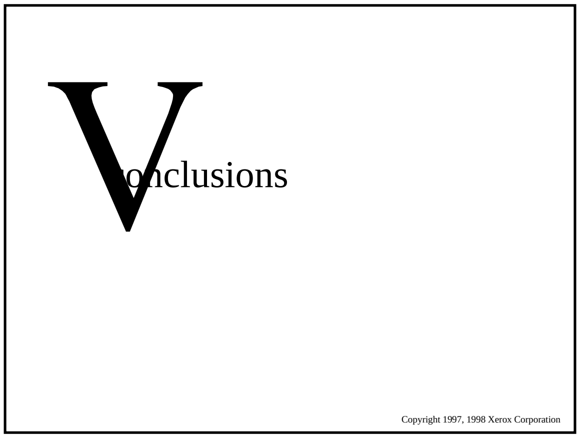


aspect weavers

can require a variety of domain-transforms

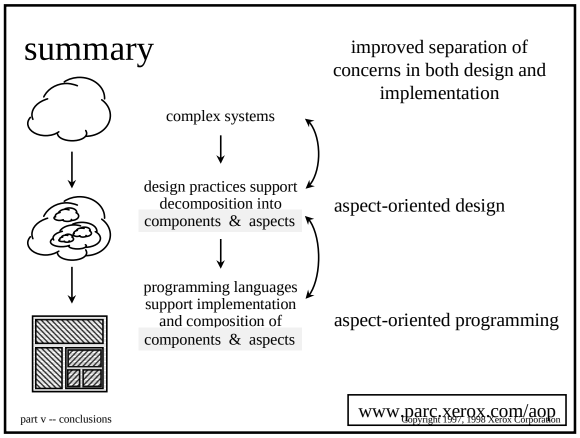
- method calls (all, per-class, per-selector…), field accesses (…), methods (…);
- who else is running
- where will this value go next
-
-

- reflection
- unfolding
- CPS conversion
- partial evaluation
- abstract interpretation
-
-



V

onclusions



summary

improved separation of concerns in both design and implementation

complex systems

design practices support decomposition into components & aspects

aspect-oriented design

programming languages support implementation and composition of components & aspects

aspect-oriented programming

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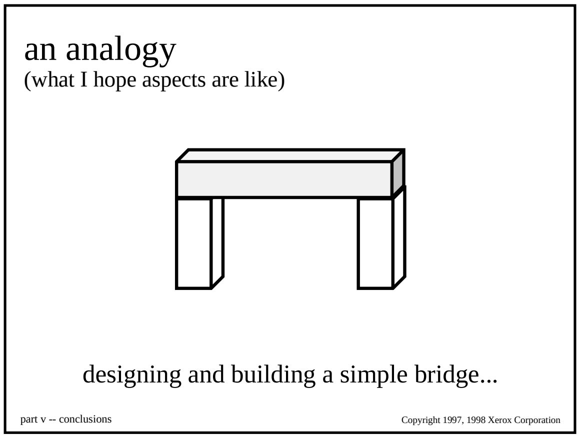
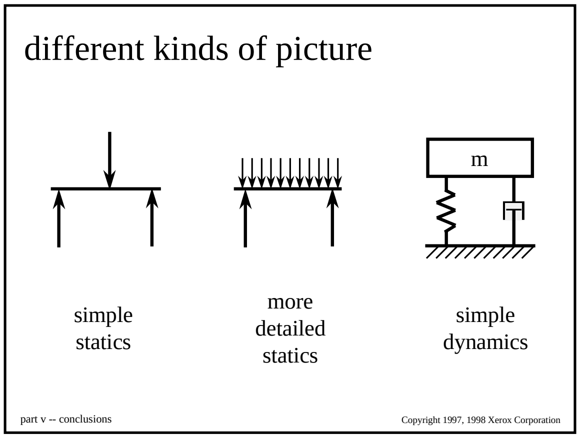


an analogy

(what I hope aspects are like)

designing and building a simple bridge...

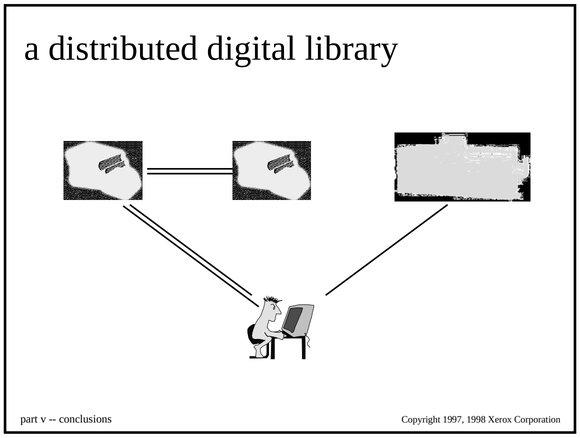


different kinds of picture

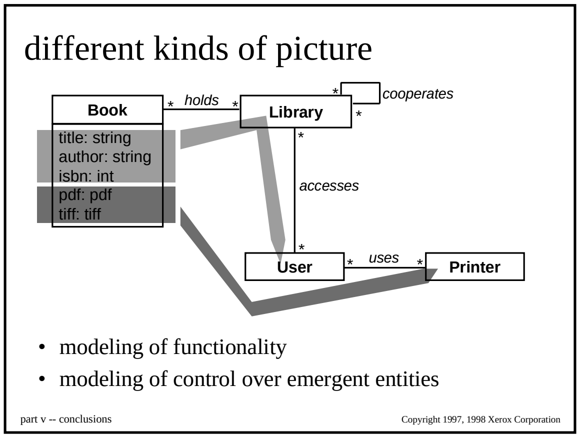
simple statics

more detailed statics

simple dynamics



a distributed digital library



different kinds of picture

Book
title: string
author: string
isbn: int
pdf: pdf
tiff: tiff

Library

User

Printer

holds

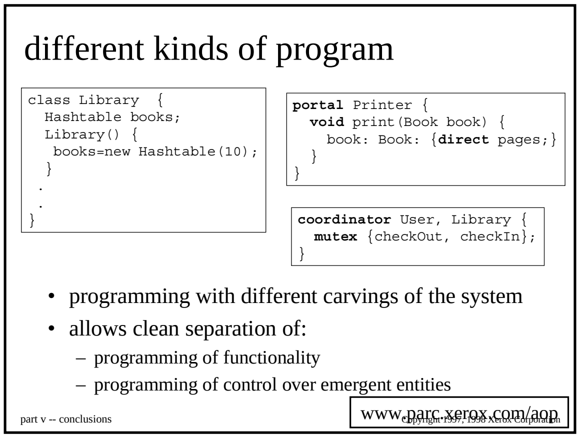
cooperates

accesses

uses

*

- modeling of functionality
- modeling of control over emergent entities



different kinds of program

```
class Library  {
  Hashtable books;
  Library() {
   books=new Hashtable(10);
  }
 .
 .
}
```

```
portal Printer {
  void print(Book book) {
    book: Book: {direct pages;}
  }
}
```

```
coordinator User, Library {
  mutex {checkOut, checkIn};
}
```

- programming with different carvings of the system
- allows clean separation of:
  - programming of functionality
  - programming of control over emergent entities

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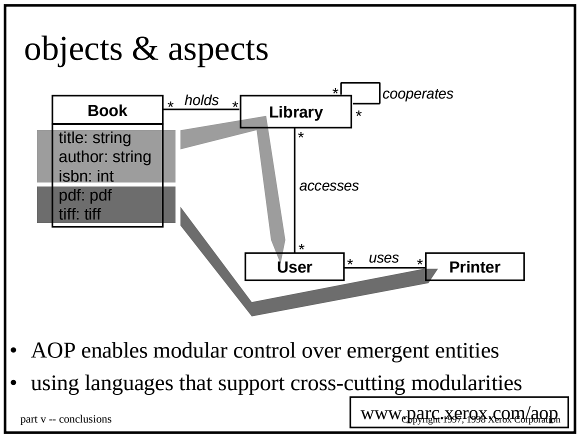

objects & aspects

Book
title: string
author: string
isbn: int
pdf: pdf
tiff: tiff

Library

User

Printer

holds

cooperates

accesses

uses

*

- AOP enables modular control over emergent entities
- using languages that support cross-cutting modularities

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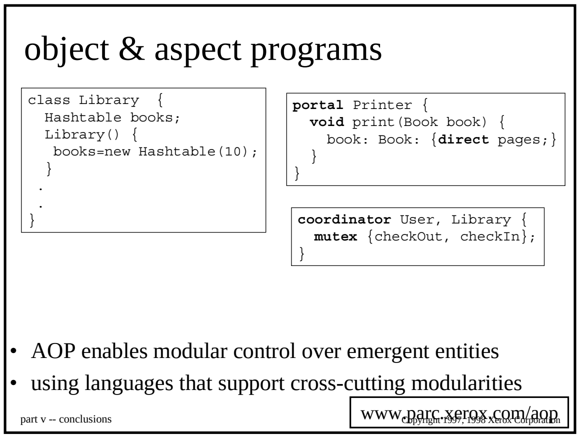

object & aspect programs

```
class Library  {
  Hashtable books;
  Library() {
   books=new Hashtable(10);
  }
 .
 .
}
```

```
portal Printer {
  void print(Book book) {
    book: Book: {direct pages;}
  }
}
```

```
coordinator User, Library {
  mutex {checkOut, checkIn};
}
```

- AOP enables modular control over emergent entities
- using languages that support cross-cutting modularities

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