Principles of Software Construction: Objects, Design and Concurrency

Design Goals

15-214

toad

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with slides from Klaus Ostermann

Learning Goals

- Discuss alternative designs in terms of design goals
  - Design for division of labor
  - Design for understandability and maintenance
  - Design for change
  - Design for reuse
  - Design for robustness
- Characterize modularity and its benefits
- Apply design strategies to achieve design goals
  - Explicit interfaces (clear boundaries)
  - Information hiding (hide likely changes)
  - Low coupling (reduce dependencies)
  - High cohesion (one purpose per class)
  - Low repr. gap (align requirements and impl.)
- Understand how strategies support goals
- Explain tradeoffs in designs with design goals and strategies

Goal of Software Design

- For each desired program behavior there are infinitely many programs that have this behavior
  - What are the differences between the variants?
  - Which variant should we choose?
- Since we usually have to synthesize rather than choose the solution…
  - How can we design a variant that has the desired properties?

Tradeoffs

```
void sort(int[] list, String order) {
   …
  boolean mustswap;
  if (order.equals("up")) {
    mustswap = list[i] < list[j];
  } else if (order.equals("down")) {
    mustswap = list[i] > list[j];
  }
  …
}
```

```
void sort(int[] list, Comparator cmp) {
   …
  boolean mustswap;
  mustswap = cmp.compare(list[i], list[j]);
  …
}
interface Comparator {
  boolean compare(int i, int j);
}
class UpComparator implements Comparator {
  boolean compare(int I, int j) { return i<j; }}

class DownComparator implements Comparator {
  boolean compare(int I, int j) { return i>j; }}
```

it depends

(see context)

depends on what?
what are scenarios?
what are tradeoffs?

The design process

1. Object-Oriented Analysis
   - Understand the problem
   - Identify the key **concepts** and their relationships
   - Build a (visual) vocabulary
   - Create a **domain model** (aka conceptual model)
2. Object-Oriented Design
   - Identify **software classes** and their relationships with *class diagrams*
   - Assign responsibilities (attributes, methods)
   - Explore **behavior** with *interaction diagrams*
   - Explore design alternatives
   - Create an **object model** (aka design model and design class diagram) and **interaction models**
3. Implementation
   - Map designs to code, implementing classes and methods

Object-Oriented Design

- “After identifying your requirements and creating a domain model, then add methods to the software classes, and define the messaging between the objects to fulfill the requirements.”
- But how?
  - How should concepts be implemented by classes?
  - What method belongs where?
  - How should the objects interact?
  - This is a critical, important, and non-trivial task

Software Quality

Source: Braude, Bernstein, Software Engineering. Wiley 2011

- Sufficiency / Functional Correctness
  - Fails to implement the specifications … Satisfies all of the specifications
- Robustness
  - Will crash on any anomalous even … Recovers from all anomalous events
- Flexibility
  - Will have to be replaced entirely if specification changes … Easily adaptable to reasonable changes
- Reusability
  - Cannot be used in another application … Usable in all reasonably related applications without modification
- Efficiency
  - Fails to satisfy speed or data storage requirement … satisfies speed or data storage requirement with reasonable margin
- Scalability
  - Cannot be used as the basis of a larger version … is an outstanding basis…
- Security
  - Security not accounted for at all … No manner of breaching security is known

Object-Design Challenges

Design for Change

Software Change

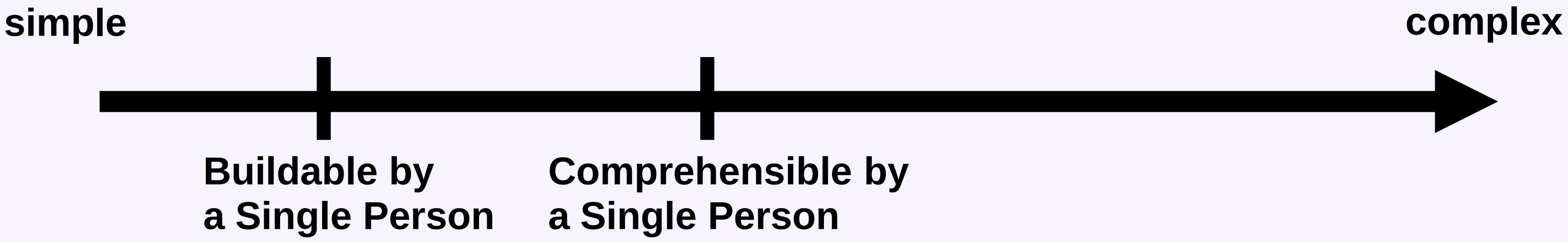
- …accept the fact of change as a way of life, rather than an untoward and annoying exception.
  —Brooks, 1974

- Software that does not change becomes useless over time.
  —Belady and Lehman

- For successful software projects, most of the cost is spent evolving the system, not in initial development
  - Therefore, reducing the cost of change is one of the most important principles of software design

Design for Division of Labor

Building Complex Systems



- Division of Labor
- Division of Knowledge and Design Effort
- Reuse of Existing Implementations

Design for Change

Design for Division of Labor

Design for Understandability

Design for Reuse

Design for Robustness

Design for Enabling Innovation

Design for Security

...

Modularity

A History of Modularity

IBM System/360

announced 1964

(cc 2.0) Dave Ross

Before System/360

- 7070
  - 7074
- 7090
- 1401
  - 1410
- 1620
- 7080
- 7030

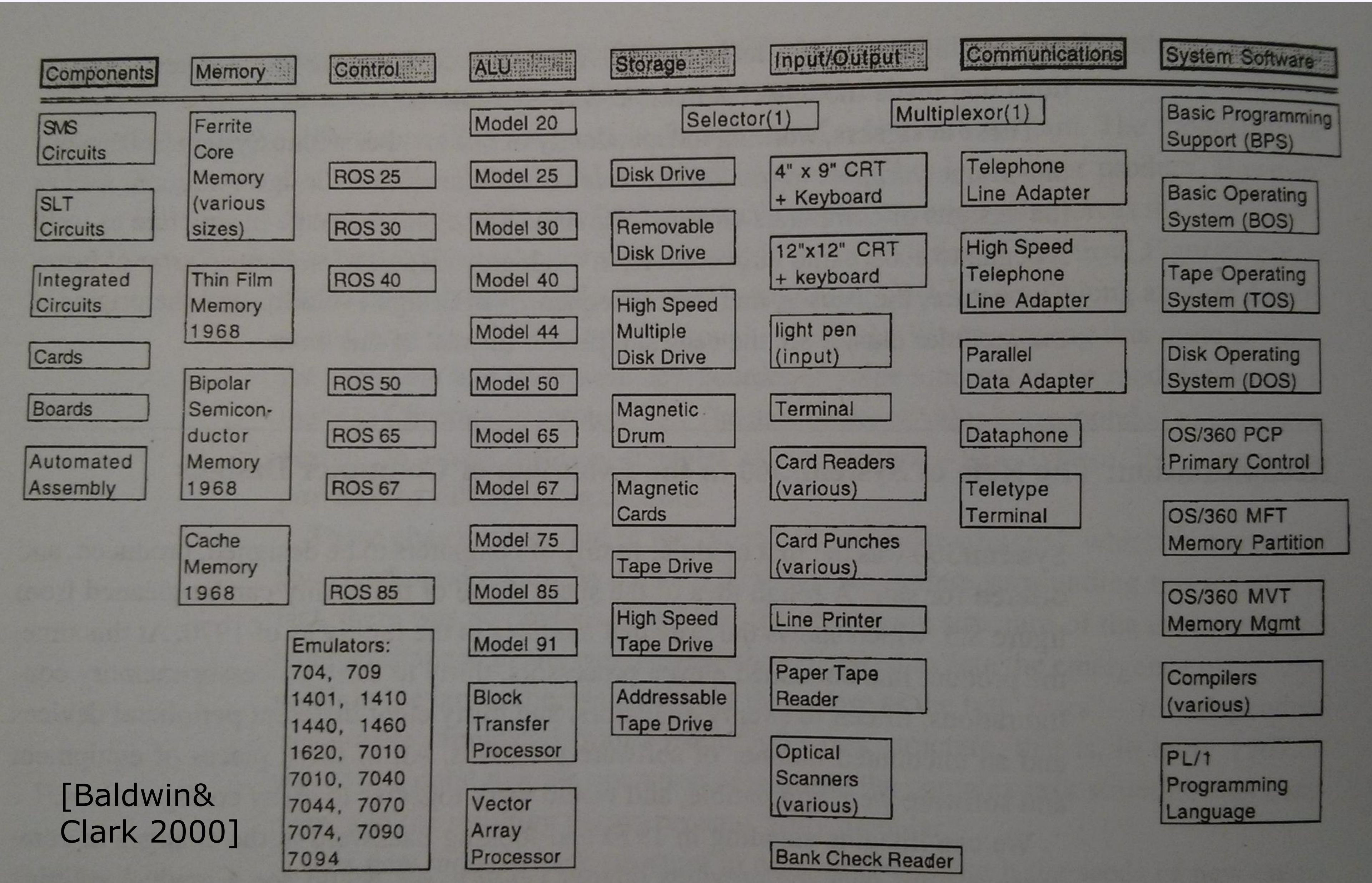
- 8 different processors
- 6 different data formats and instruction sets
- each designed from scratch
- each with their own hardware connections
  - memory
  - I/O
  - disks

Modular System/360

- Family of similar processors
- Standardized communication with I/O devices (except for data rate)
- A single memory-CPU coupling
- A single I/O control system
- Compatible binary representations
  - compiled on one machine, executed on another

- => Interchangeable hardware
- => Separate design of hardware

System/360 in 1970



Components
- SMS Circuits
- SLT Circuits
- Integrated Circuits
- Cards
- Boards
- Automated Assembly

Memory
- Ferrite Core Memory (various sizes)
- Thin Film Memory 1968
- Bipolar Semicon-ductor Memory 1968
- Cache Memory 1968

Control
- ROS 25
- ROS 30
- ROS 40
- ROS 50
- ROS 65
- ROS 67
- ROS 85
- Emulators: 704, 709 1401, 1410 1440, 1460 1620, 7010 7010, 7040 7044, 7070 7074, 7090 7094

ALU
- Model 20
- Model 25
- Model 30
- Model 40
- Model 44
- Model 50
- Model 65
- Model 67
- Model 75
- Model 85
- Model 91
- Block Transfer Processor
- Vector Array Processor

Storage
- Disk Drive
- Removable Disk Drive
- High Speed Multiple Disk Drive
- Magnetic Drum
- Magnetic Cards
- Tape Drive
- High Speed Tape Drive
- Addressable Tape Drive

Selector(1)

Multiplexor(1)

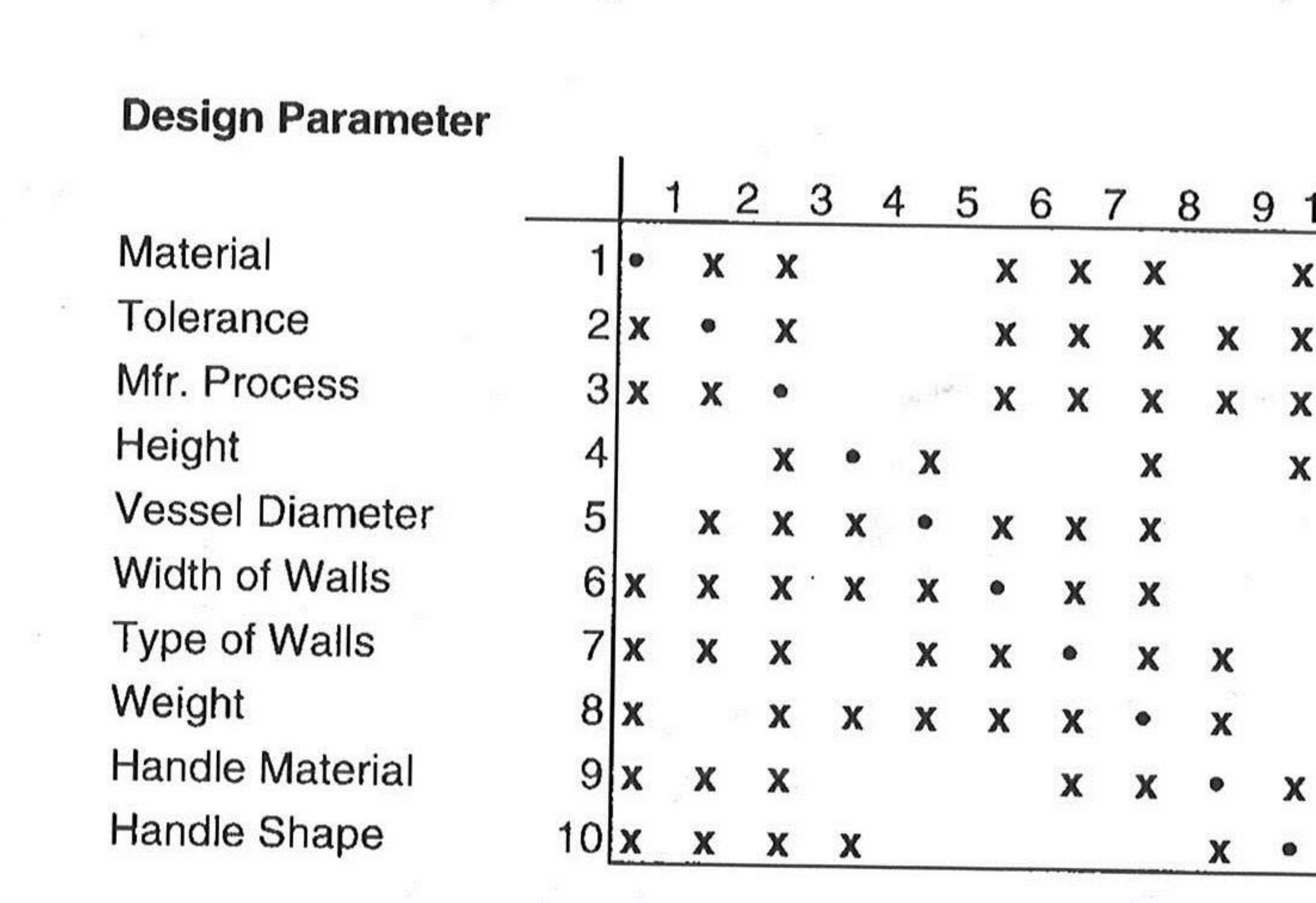
Input/Output
- 4" x 9" CRT + Keyboard
- 12"x12" CRT + keyboard
- light pen (input)
- Terminal
- Card Readers (various)
- Card Punches (various)
- Line Printer
- Paper Tape Reader
- Optical Scanners (various)
- Bank Check Reader

Communications
- Telephone Line Adapter
- High Speed Telephone Line Adapter
- Parallel Data Adapter
- Dataphone
- Teletype Terminal

System Software
- Basic Programming Support (BPS)
- Basic Operating System (BOS)
- Tape Operating System (TOS)
- Disk Operating System (DOS)
- OS/360 PCP Primary Control
- OS/360 MFT Memory Partition
- OS/360 MVT Memory Mgmt
- Compilers (various)
- PL/1 Programming Language

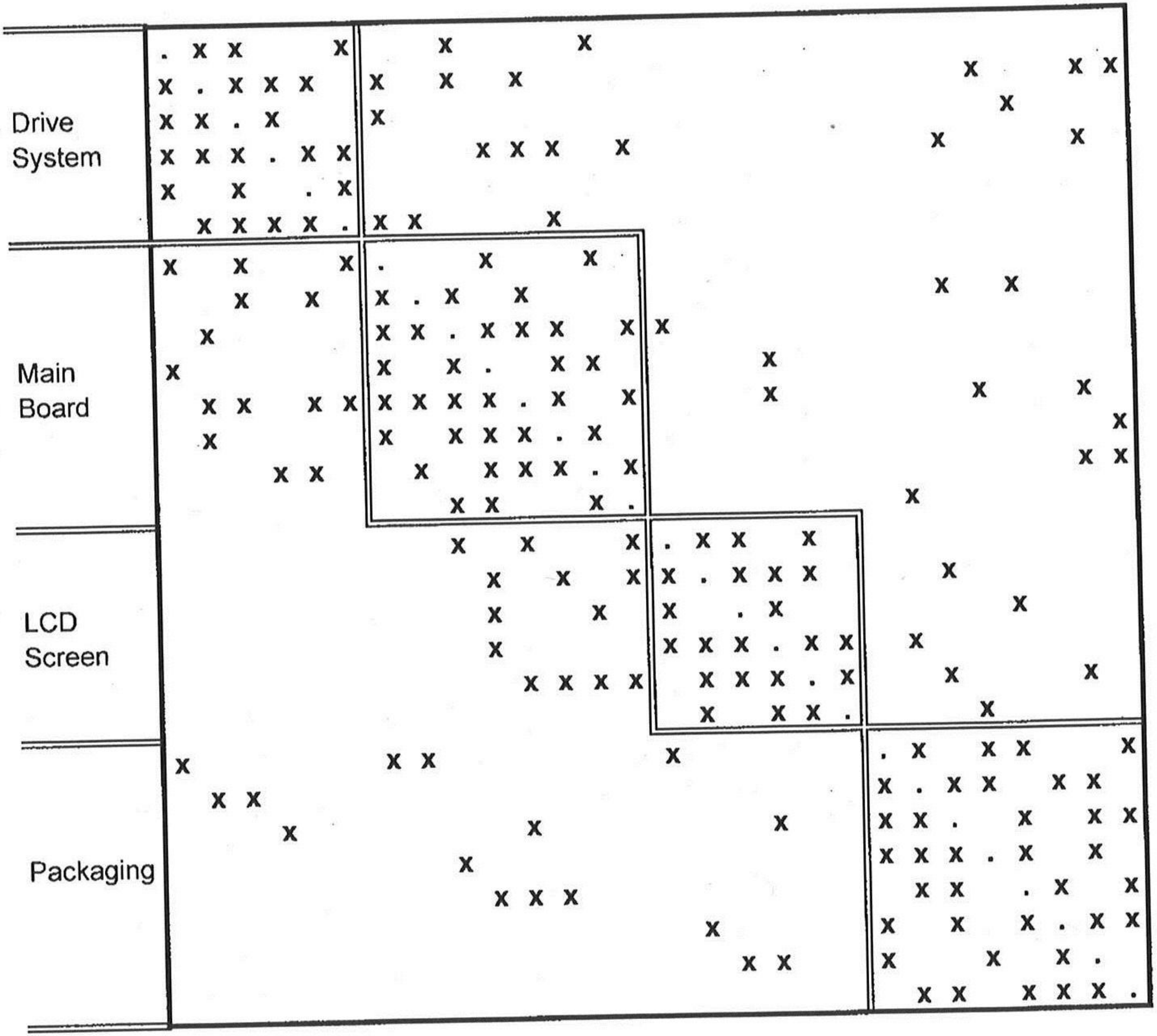
[Baldwin& Clark 2000]

Design Structure Matrix

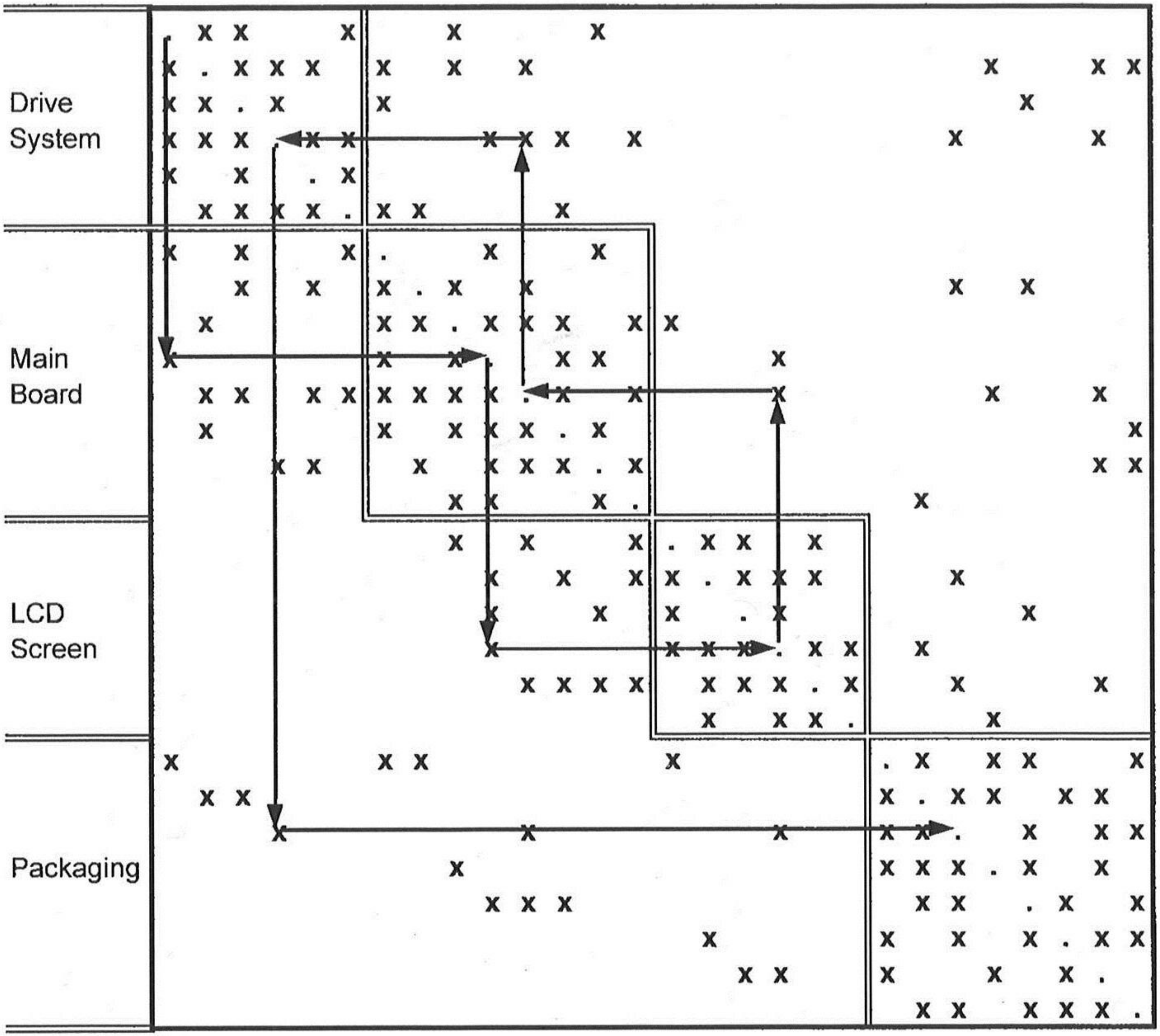


Design Parameter		1	2	3	4	5	6	7	8	9	10
Material	1	•	x	x			x	x	x		x
Tolerance	2	x	•	x			x	x	x	x	x
Mfr. Process	3	x	x	•			x	x	x	x	x
Height	4			x	•	x			x		x
Vessel Diameter	5		x	x	x	•	x	x	x		
Width of Walls	6	x	x	x	x	x	•	x	x		
Type of Walls	7	x	x	x		x	x	•	x	x	
Weight	8	x		x	x	x	x	x	•	x	
Handle Material	9	x	x	x				x	x	•	x
Handle Shape	10	x	x	x	x					x	•

[Baldwin&Clark 2000]



[Baldwin&Clark 2000]



Drive System	.	x	x			x			x				x															
	x	.	x	x	x		x		x		x													x			x	x
	x	x	.	x			x																		x			
	x	x	x	.	x	x				x	x	x		x									x				x	
	x		x		.	x																						
		x	x	x	x	.	x	x				x																
Main Board	x		x			x	.			x			x															
			x		x		x	.	x		x												x		x			
		x					x	x	.	x	x	x		x	x													
	x						x		x	.		x	x					x										
		x	x		x	x	x	x	x	x	.	x		x				x						x			x	
		x					x		x	x	x	.	x															x
				x	x			x		x	x	x	.	x													x	x
									x	x			x	.								x						
LCD Screen									x		x			x	.	x	x		x									
										x		x		x	x	.	x	x	x				x					
										x			x		x		.	x							x			
										x					x	x	x	.	x	x		x						
											x	x	x	x		x	x	x	.	x			x				x	
																x		x	x	.				x				
Packaging	x						x	x							x						.	x		x	x			x
		x	x																		x	.	x	x		x	x	
				x							x							x			x	x	.		x		x	x
									x												x	x	x	.	x		x	
										x	x	x										x	x		.	x		x
																x					x		x		x	.	x	x
																	x	x			x			x		x	.	
																						x	x		x	x	x	.

[Baldwin&Clark 2000]

Modularity

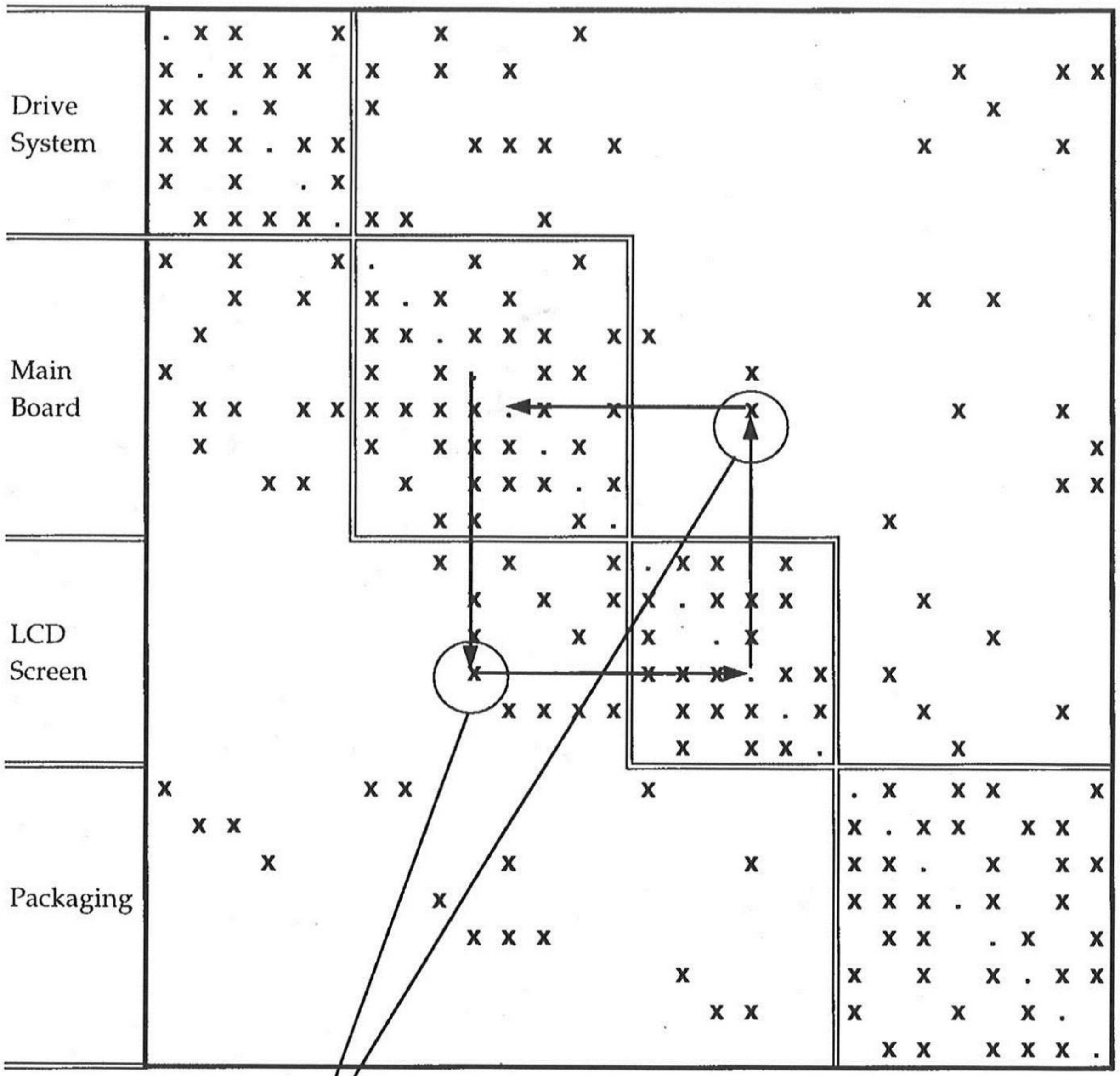
- Interdependence within and independence across modules

- “A module is a unit whose structural elements are powerfully connected among themselves and relatively weakly connected to elements in other units. Clearly there are degrees of connection, thus there are gradations of modularity.”

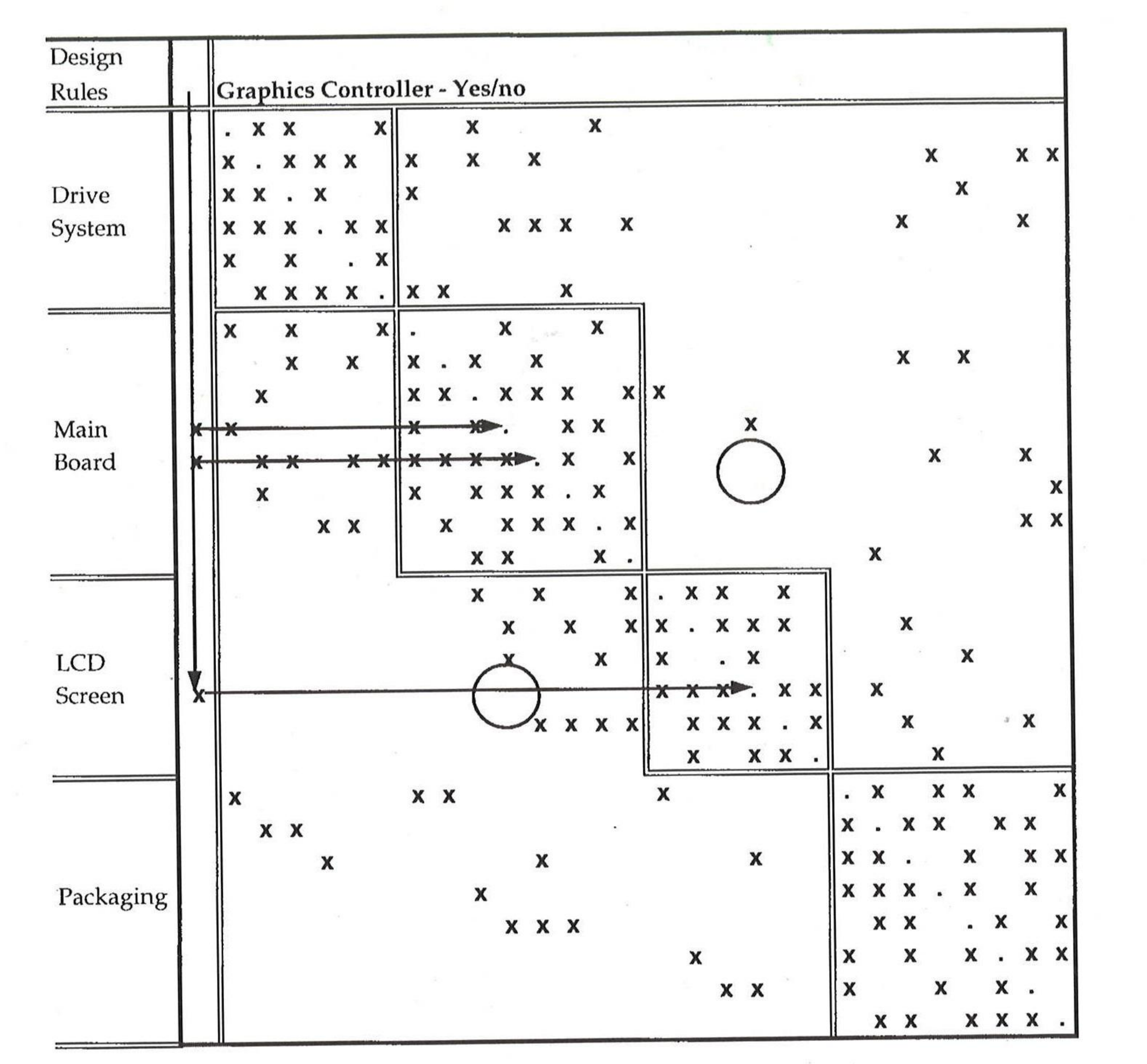
Modularity

- Abstraction, Information Hiding, and Interface

- “A complex system can be managed by dividing it up into smaller pieces and looking at each one separately. When the complexity of one of the elements crosses a certain threshold, that complexity can be isolated by defining a separate abstraction that has a simple interface. The abstraction hides the complexity of the element; the interface indicates how the element interacts with the larger system.”

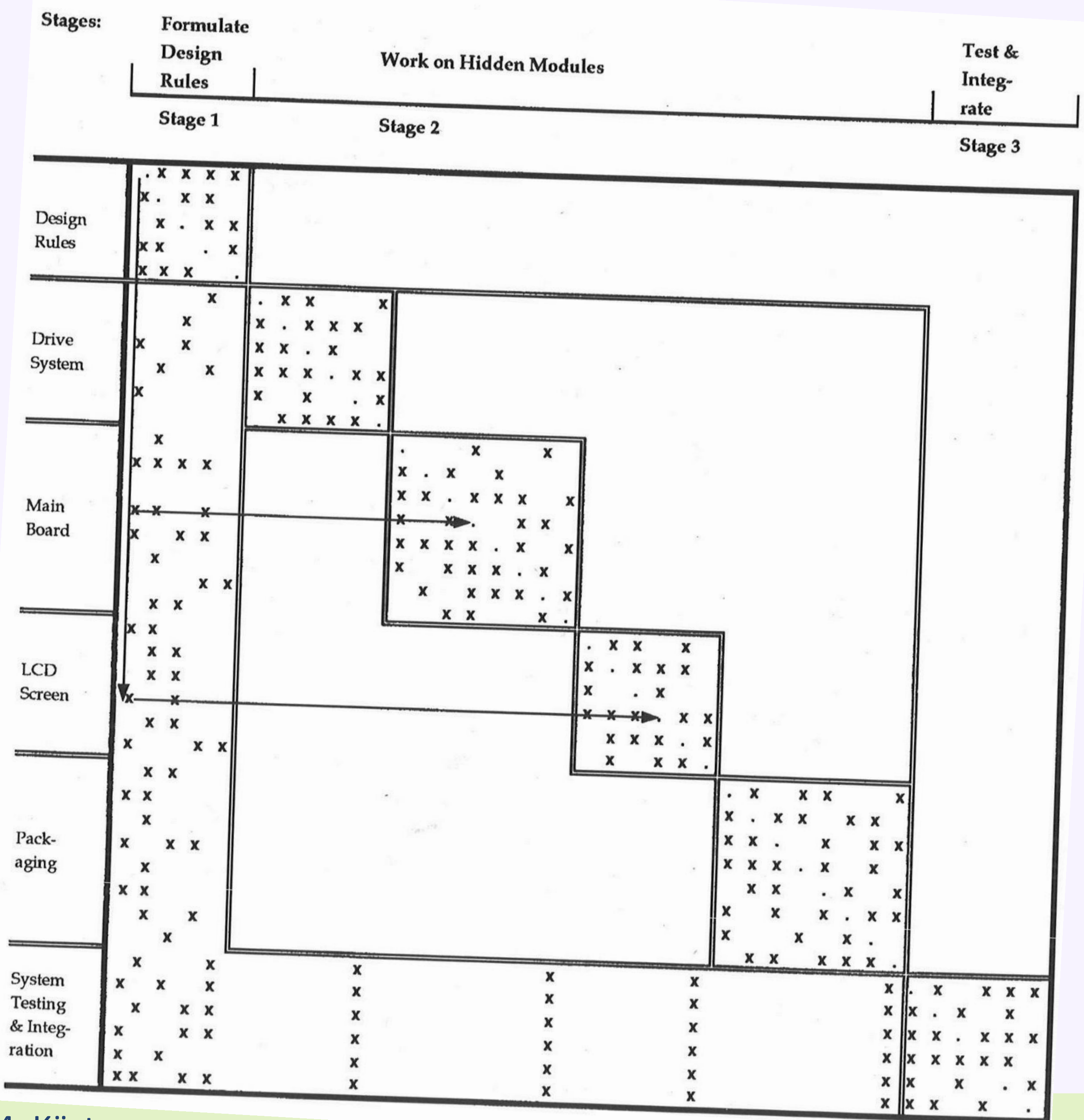


Graphics controller on Main Board or not?
If yes, screen specifications change;
If no, CPU must process more; adopt different interrupt protocols


Design Rules
Graphics Controller - Yes/no
Drive System
Main Board
LCD Screen
Packaging

Interface (or Design Rule)

- Establishing a stable contract/interface
- Benefit:
  - Efficiency; independent decisions
- Costs:
  - Eliminates a choice
  - Interface may not change (evolution)
  - Interface may prevent superior design (opportunity costs)


Stages:
Formulate Design Rules
Stage 1
Work on Hidden Modules
Stage 2
Test & Integrate
Stage 3
Design Rules
Drive System
Main Board
LCD Screen
Packaging
System Testing & Integration

Understanding the Domain (OO Analysis + Design)

- Poorly Understood
  - Unforeseen Interdependencies
  - High Risk; Integration and Testing Problems
  - High Opportunity Costs
- Well Understood
  - Clear Design Rules
  - Standards
  - Testing and Integration can be done by Users

Consequences

- Modularity increases the range of "manageable" complexity
- Modularity allows concurrent (design) work
- Modularity accommodates uncertainty
  - Isolate risks
  - Isolate parts that will likely change
- Modularity allows decentralized improvements
- Modularity as an investment (~stock option)

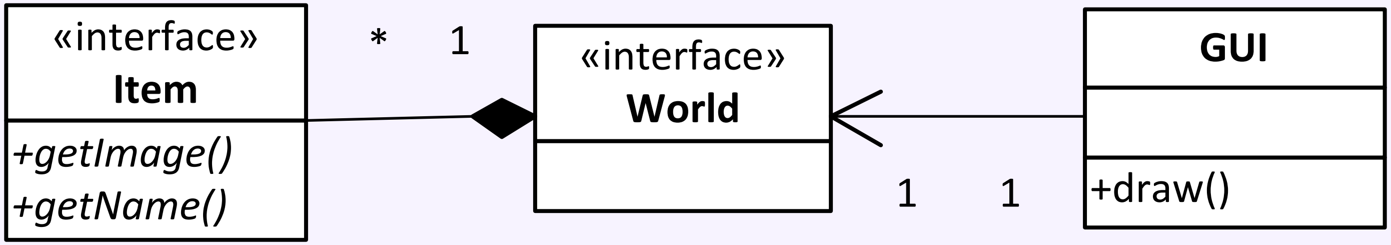
Design Goals and Design Strategies

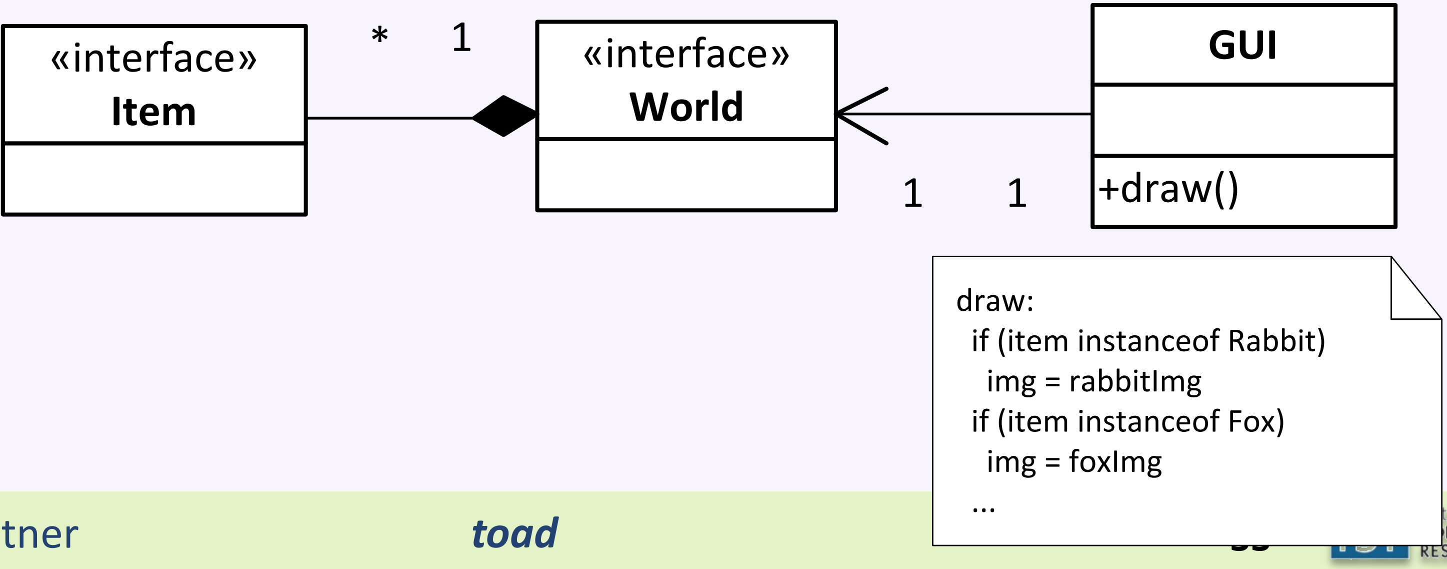
Overview

- 5 design goals
  - Design for division of labor
  - Design for understandability
  - Design for change
  - Design for reuse
  - Design for robustness
- 5 design strategies (for now)
  - Explicit interfaces (clear boundaries)
  - Information hiding(hide likely changes)
  - Low coupling (reduce dependencies)
  - High cohesion (one purpose per class)
  - Low repr. gap (align requirements and impl.)

Design for Division of Labor

- Modular Decomposition
  - decomposing both design and implementation!
- Limit interactions in design process





```
draw:
  if (item instanceof Rabbit)
    img = rabbitImg
  if (item instanceof Fox)
    img = foxImg
  ...
```

Discussion Virtual World

- In the first design GUI and Item are independent
  - New items can be added without changing the GUI
  - A different GUI can be implemented without changing items
- Items have an interface describing how they can be drawn
  - Only this data available to GUI
- In the second design the GUI needs to know the possible items
  - GUI designer and Item designer need to communicate

Design Strategy: Explicit Interfaces

- Whenever two modules communicate, it should be obvious from their interfaces
- Make interfaces between modules explicit
  - Public methods
  - Documentation, contracts
  - Import of classes and libraries
- Avoid global state (e.g., static fields)
- Avoid hidden interactions through side channels (data, files, network, …)

- Keep interfaces small and exchange as little information as possible

Design for Reuse

- Modular Composability, compose modules from different sources

- Good modules contain well-defined tasks reusable in many contexts
  - (Module may be a class, a package, a subsystem, …)
  - **Explicit interfaces** how others can use a module
  - Limited dependencies on other modules (**low coupling**)
  - Useful **cohesive** functionality that’s worth reusing

- Examples
  - GUI reuses Swing GUI elements
  - World reuses collection libraries
  - JUnit reusable in many projects
  - Rabbits potentially reusable in different virtual world
  - GUI reusable for arbitrary other simulations with items
  - HW 1 reuses stack implementation from HW 0

Design Strategies: Coupling and Cohesion

Coupling

- Modules should depend on as few other modules as possible
  - Easier to understand (little context to understand)
  - Independent modules easier to modify without rippling effects (Design for Change)
  - Easier to reuse in different context

Cohesion

- All responsibilities of a module should be related and well defined – one purpose per class
  - A module with lots of unrelated functionality is unlikely to be reusable as it (or unnecessarily large)
  - A cohesive module is easier to understand

Chose design alternatives with lower coupling and higher cohesion

Key principles to evaluate designs

Coupling and Cohesion

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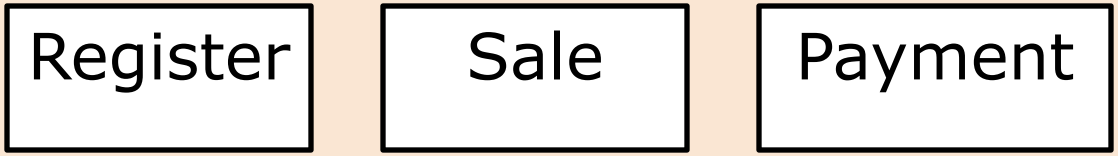
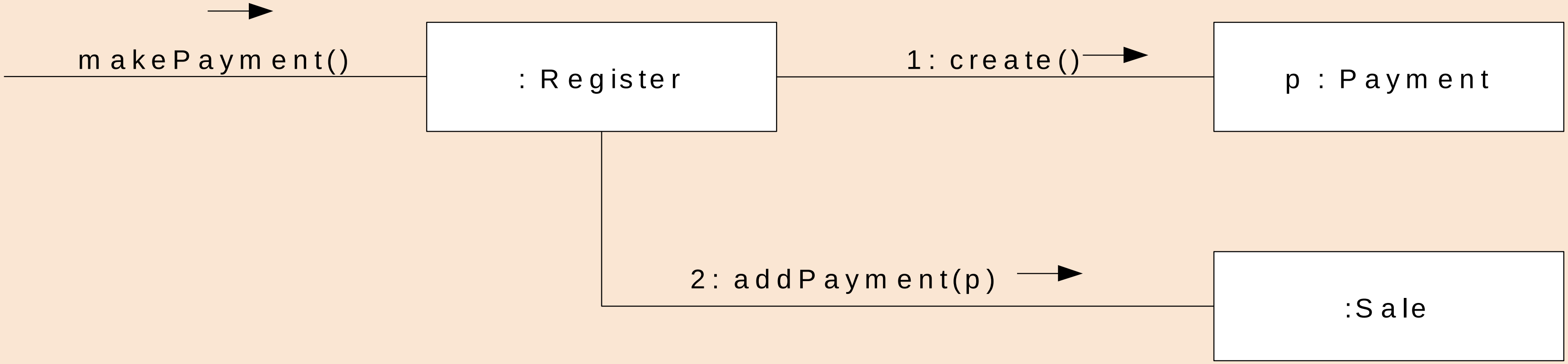
Key principles to evaluate designs

Example

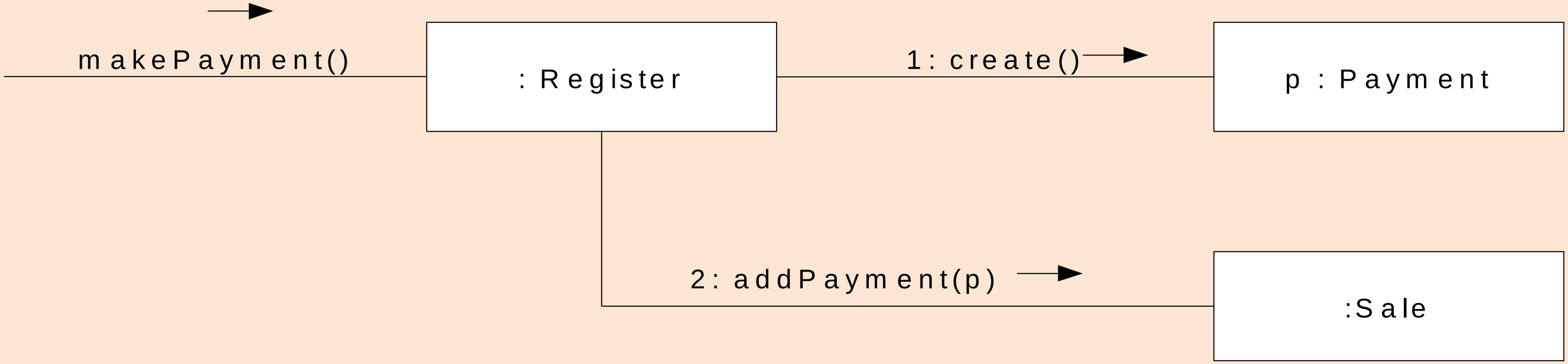
- Create a Payment and associate it with the Sale.



Example


makePayment()
: Register
1: create()
p : Payment
2: addPayment(p)
:Sale

Example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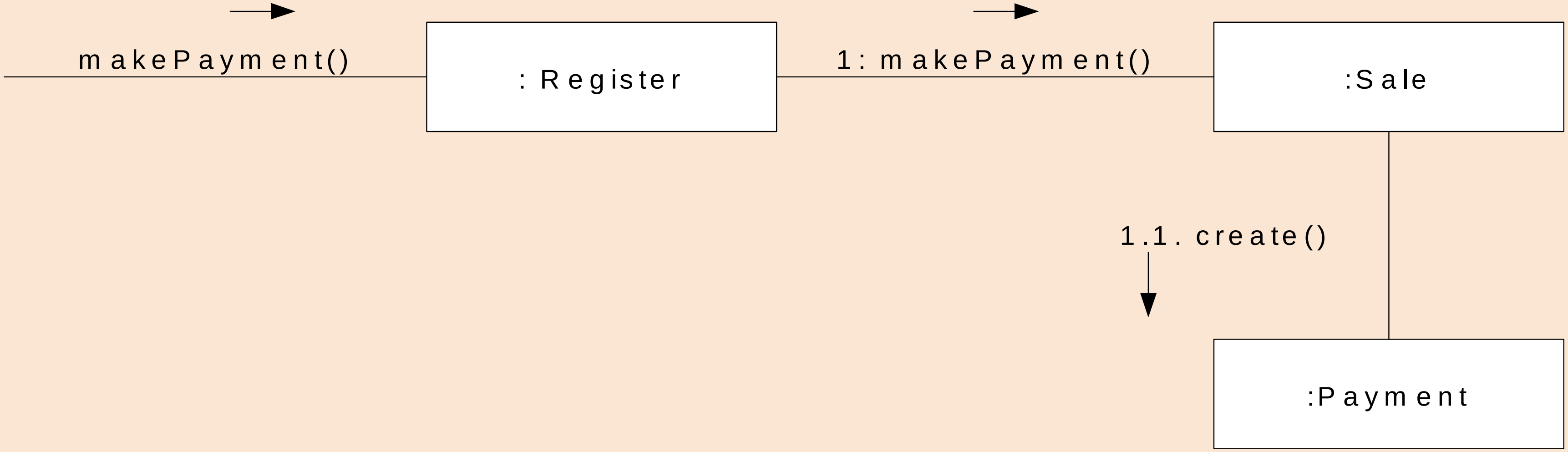
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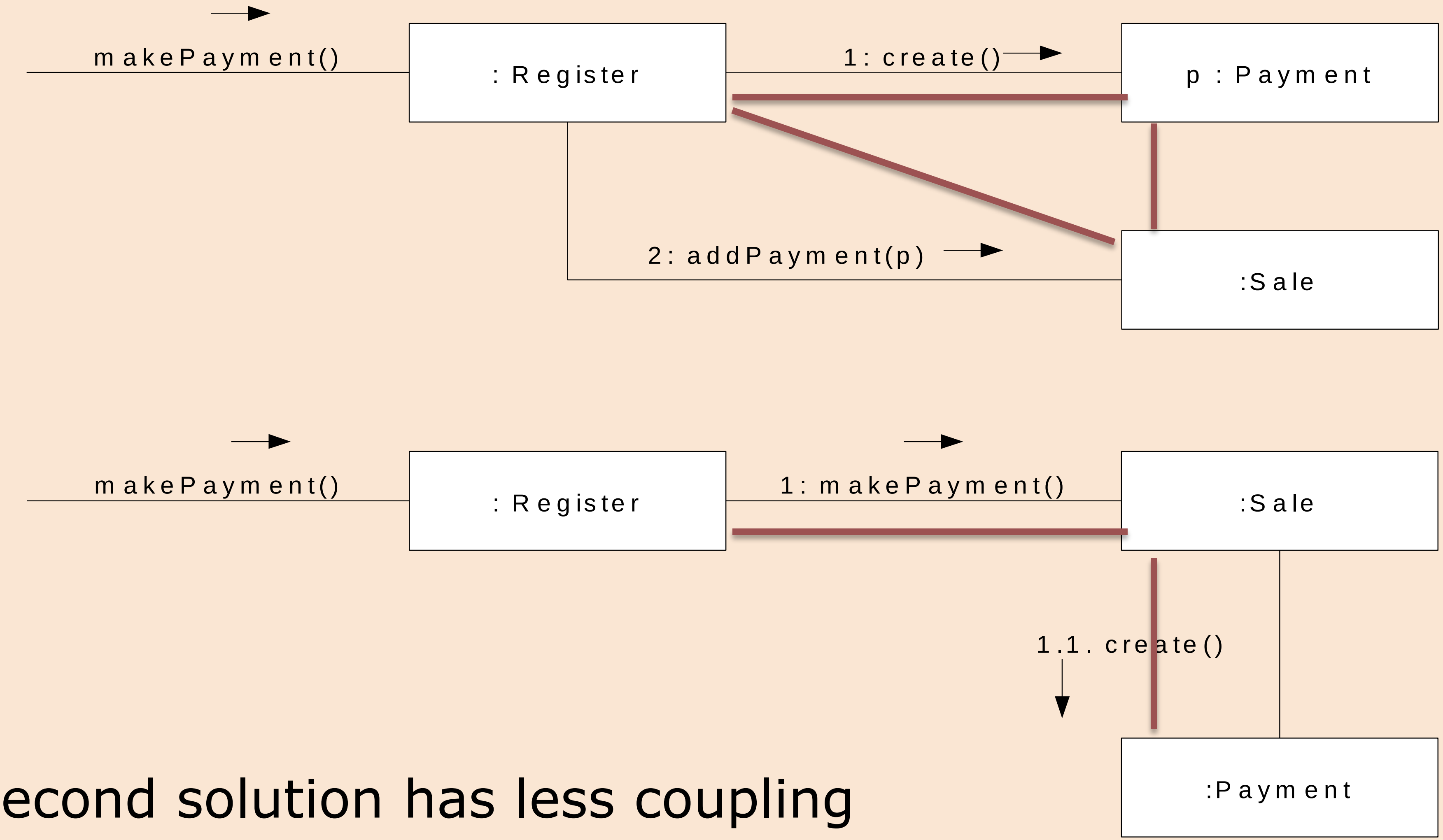
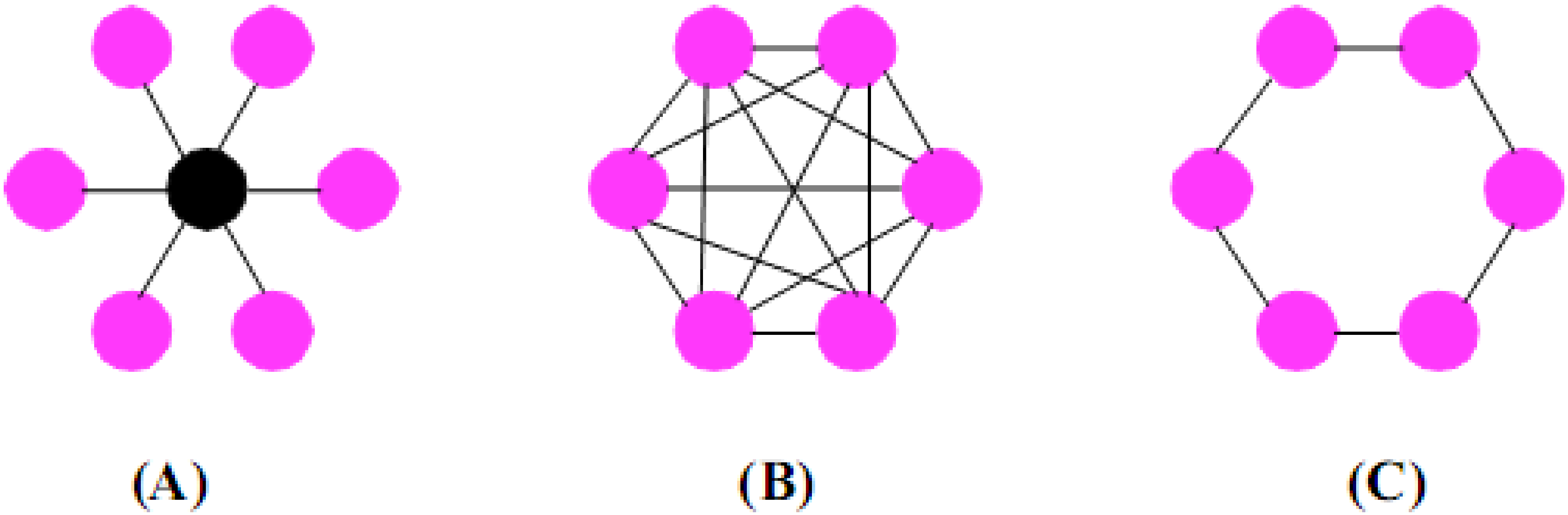
Coupling



Second solution has less coupling
Register does not know about Payment class

Topologies with different coupling



Why High Coupling is undesirable

- Element with low coupling depends on only few other elements (classes, subsystems, …)
  - “few" is context-dependent
- A class with high coupling relies on many other classes
  - Changes in related classes force local changes; changes in local class forces changes in related classes (brittle, rippling effects)
  - Harder to understand in isolation.
  - Harder to reuse because requires additional presence of other dependent classes
  - Difficult to extend – changes in many places

Common Forms of Coupling in OO Languages

- TypeX has an attribute (data member or instance variable) that refers to a TypeY instance, or TypeY itself.
- TypeX has a method which references an instance of TypeY, or TypeY itself, by any means.
  - Typically include a parameter or local variable of type TypeY, or the object returned from a message being an instance of TypeY.
- TypeX is a direct or indirect subclass of TypeY.
- TypeY is an interface, and TypeX implements that interface.

Low Coupling: Discussion

- Low Coupling is a principle to keep in mind during all design decisions
- It is an underlying goal to continually consider.
- It is an evaluative principle that a designer applies while evaluating all design decisions.
- Low Coupling supports design of more independent classes; reduces the impact of change.
- Context-dependent; should be considered together with cohesion and other principles and patterns
- Prefer coupling to interfaces over coupling to implementations

Low Coupling: Discussion

- Subclassing produces a particularly problematic form of high coupling
  - Dependence on implementation details of superclass
  - -> Prefer composition over inheritance
- Extremely low coupling may lead to a poor design
  - Few incohesive, bloated classes do all the work; all other classes are just data containers
- High coupling to very stable elements is usually not problematic

Coupling to “non-standards”

- Libraries or platforms may include non-standard features or extensions
- Example: JavaScript support across Browsers

<div id=“e1”>old content</div>

W3C-compliant DOM standard

In JavaScript…

MSIE: e1.innerText = “new content”

Firefox: e1.textContent = “new content”

Coupling and Cohesion

Key principles to evaluate designs

Coupling

- Modules should depend on as few other modules as possible
  - Easier to understand (little context to understand)
  - Independent modules easier to modify without rippling effects (Design for Change)
  - Easier to reuse in different context

Cohesion

- All responsibilities of a module should be related and well defined – one purpose per class
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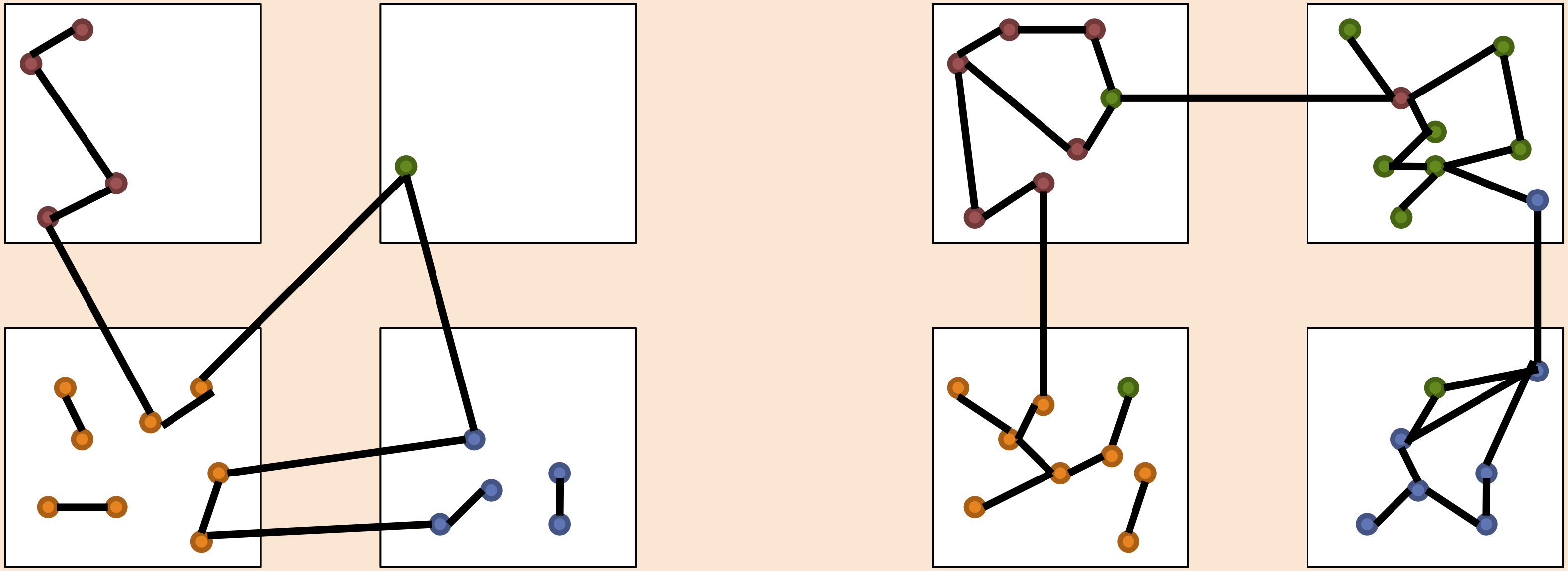
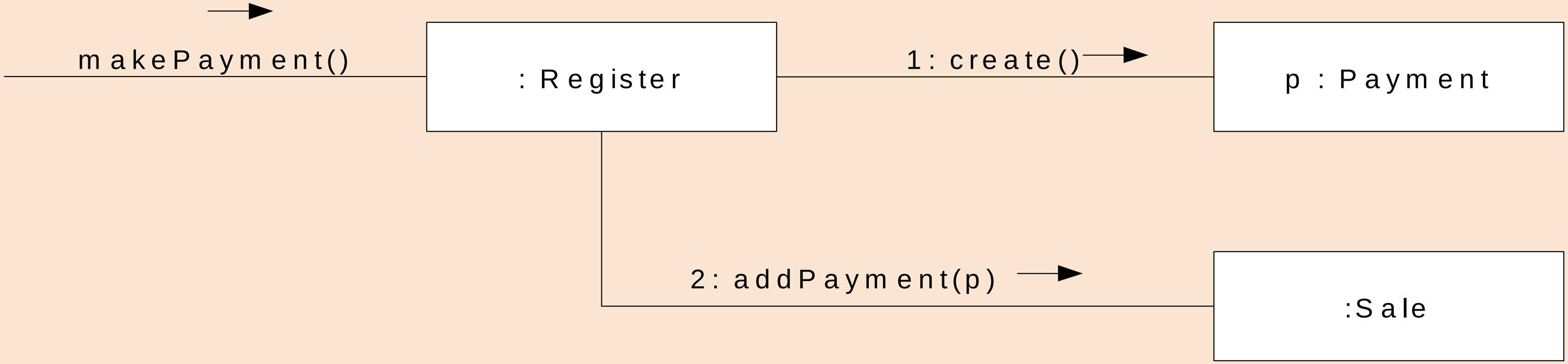
Chose design alternatives with lower coupling and higher cohesion

High cohesion



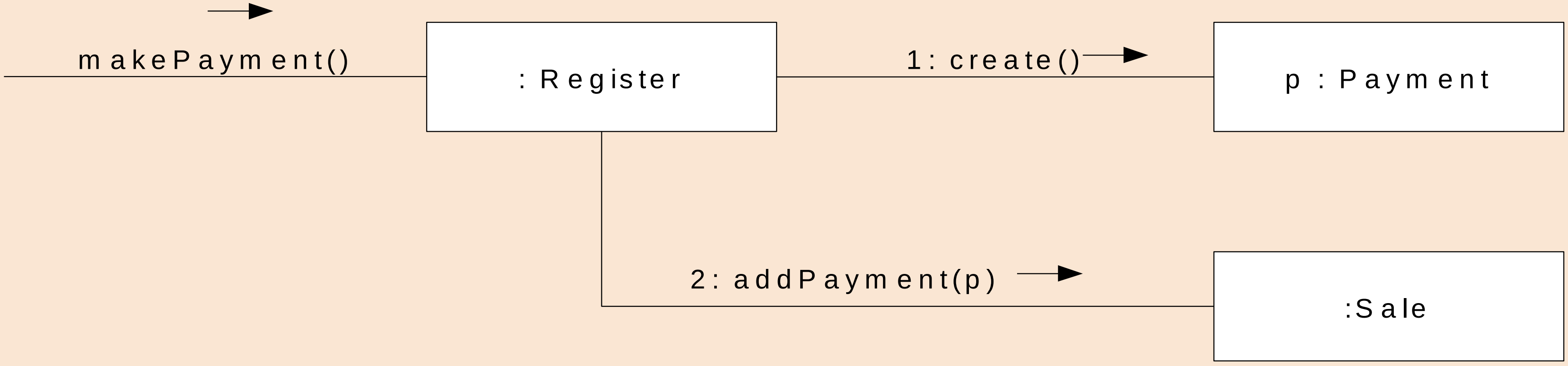
- Classes are easier to maintain
- Easier to understand
- Often support low coupling
- Supports reuse because of fine grained responsibility

Example



(except for coupling), looks OK if *makePayement* considered in isolation, but adding more system operations, *Register* would take on more and more responsibilities and become less cohesive.

Example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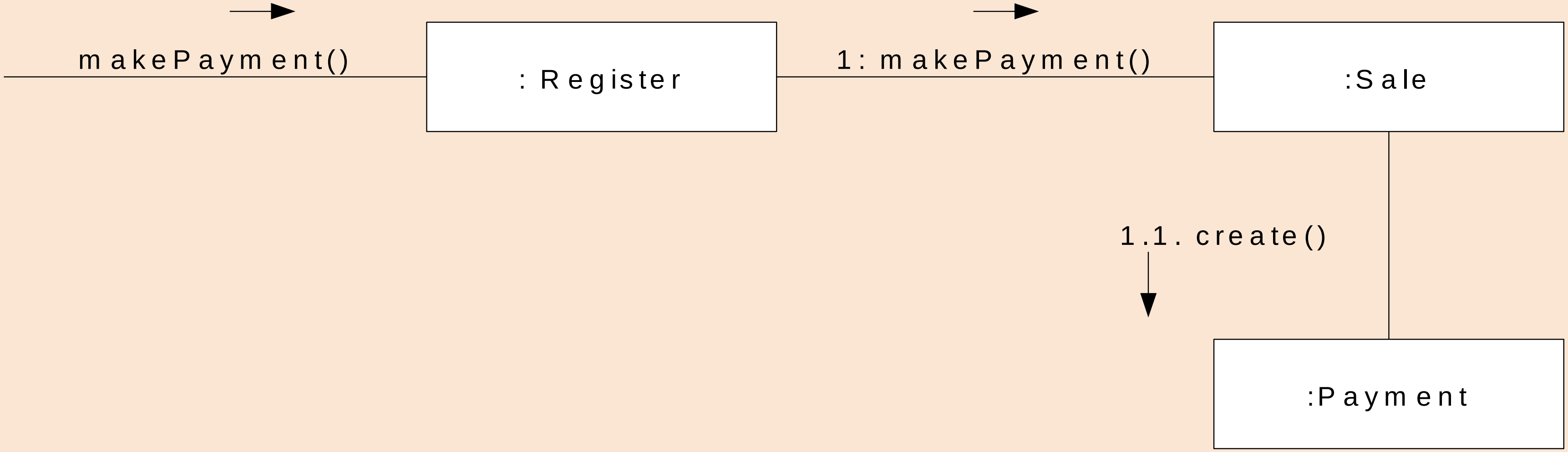
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Cohesion in Graph Implementations

```
class Graph {
        Node[] nodes;
        boolean[] isVisited;
}
class Algorithm {
        int shortestPath(Graph g, Node n, Node m) {
                for (int i; …)
                        if (!g.isVisited[i]) {
                                …
                                g.isVisited[i] = true;
                        }
                }
                return v;
        }
}
```

Cohesion: Discussion

- Very Low Cohesion: A Class is solely responsible for many things in very different functional areas
- Low Cohesion: A class has sole responsibility for a complex task in one functional area
- High Cohesion: A class has moderate responsibilities in one functional area and collaborates with classes to fulfil tasks
- Advantages of high cohesion
  - Classes are easier to maintain
  - Easier to understand
  - Often support low coupling
  - Supports reuse because of fine grained responsibility
- Rule of thumb: a class with high cohesion has relatively few methods of highly related functionality; does not do too much work

Monopoly Example

```
class Player {
        Board board;
        Square getSquare(String name) {
                for (Square s: board.getSquares())
                        if (s.getName().equals(name))
                                return s;
                return null;
}}
```

```
class Player {
        Board board;
        Square getSquare(String n) { board.getSquare(n); }
}
class Board{
        List<Square> squares;
        Square getSquare(String name) {
                for (Square s: squares)
                        if (s.getName().equals(name))
                                return s;
                return null;
}}
```

Aside: Law of Demeter (LoD)

- LoD (or Principle of Least Knowledge): Each module should have only limited knowledge about other units: only units "closely" related to the current unit
- In particular: Don’t talk to strangers!
- For instance, no a.getB().getC().foo()

Design for Understandability

- Understand (maintain, debug, test) modules locally, ideally in isolation
- Good modules are self-contained and understandable with little context
  - **Explicit interfaces**, well-defined and well-documented
  - **Low coupling**, **high cohesion**
  - Self-documenting implementations
- Examples:
  - GUI can be understood without knowing how Rabbits load their icons
  - Graphs can be understood without knowing how they are used; graph algorithms can be understood without knowing how graphs are implemented

Design for Change

- Anticipate change where possible
  - Identify risks
  - Identify instable requirements
  - Identify opportunities for future innovation
  - Identify stable parts
  - Anticipate future trends, customers, …
- Design modules such that:
  - Interfaces correspond to stable parts
  - Internal implementations hide unstable parts
  - Allows changing module implementation locally without affecting remaining system
- Example:
  - Initialization of virtual world encapsulated in single class
  - Common behavior of rabbits, foxes codified in interfaces, AI implementation hidden for change

Design for Change: Continuity

- Continuity: Small changes in the requirements should require only small changes in the implementation
- Design for change
  - **Low coupling** and **high cohesion** prevent ripple effects
  - Anticipate likely changes, extensions, and risk; hide behind an interface (**information hiding**, polymorphism)
- Heuristic **Low Representational Gap**: Align object model with domain model
- Examples:
  - New language editor in Eclipse should not require modification of Eclipse’s platform
  - Changing what Travis CI executes: change travis.yml file
  - Separate GUI from core implementation
  - Avoid replicating code (one change instead of many)

Continuity (details)

- Poor continuity
  - Major requirements change = minor change
  - Minor requirements change = months of work
- Good continuity
  - Major requirements change = major overhaul
  - Minor requirements change = change a config file
- Some crosscutting usually not avoidable
- Client is less likely to change purpose of the application
  - …but more likely to change how a dialog appears
- Design with an expectation of change
  - …but make it less costly to make changes
- Clients will pay for what they see
  - …but no one will pay $1000 to make text bold

OO Design Strategy: Low Representational Gap

- Align object model with domain model
  - Map problem-space abstractions to solution-space abstractions
  - Model solution-space relationships after problem-space relationships
  - May even start with one class per concept
  - Name classes corresponding to real-world concepts
- Supports *design for change*: if problem structure and solution structure similar, problem changes should correspond to solution changes
- Supports *design for division of labor*: knowing the decomposition of the problem, may help decomposing the solution
- Supports *design for understandability* and *reuse*: …

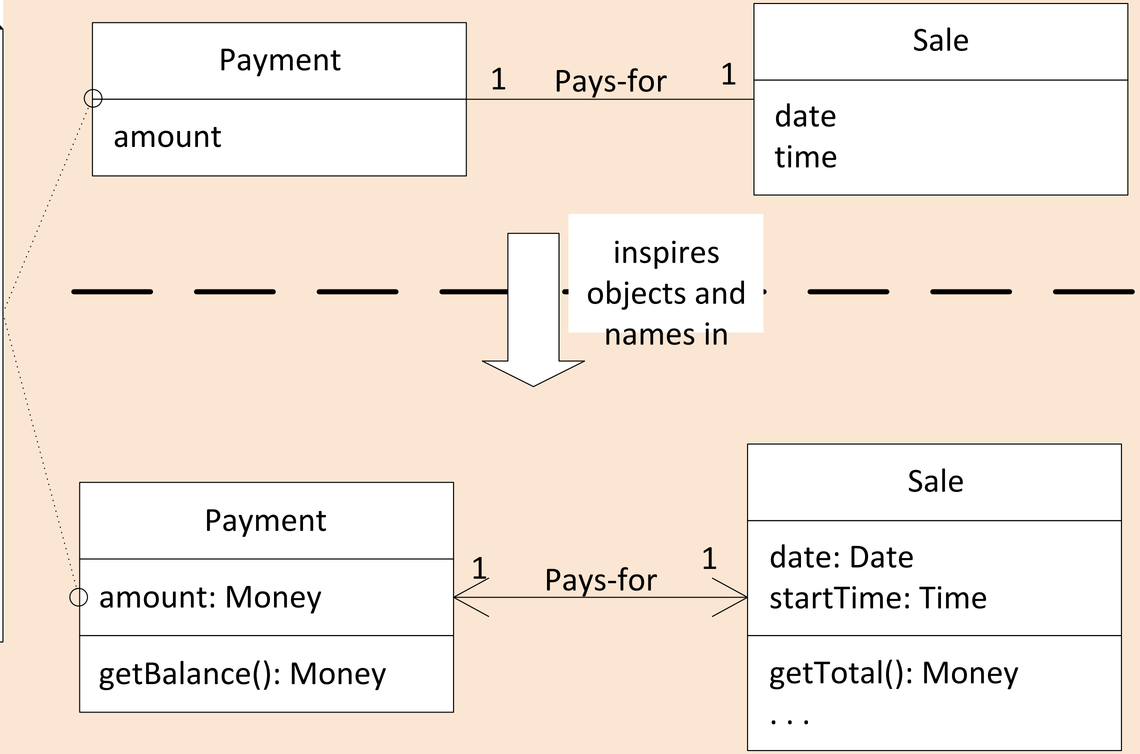
Low Representational Gap

Domain Model
Noteworthy concepts in the domain.

A Payment in the Domain Model is a concept, but a Payment in the Object Model is a software class. They are not the same thing, but the former inspired the naming and definition of the latter.

This reduces the representational gap.

This is one of the big ideas in object technology.



Object Model
The object-oriented developer has taken inspiration from the real world domain in creating software classes.

Therefore, the representational gap between how stakeholders conceive the domain, and its representation in software, has been lowered.

Design Strategy: Information Hiding

- A module exposes the interface, but hides how it implements it
  - Interface must remain stable (or else rippling changes)
  - Implementation may change freely
- Each interface represents a design decision and modules hide remaining ones
  - Remember System/360
- Identify stable and unstable parts of the problem
  - E.g., if database will change, abstract behind database interface
- If change predicted correctly: Only one module to change

Design for Robustness

- Modular Protection: Errors and bugs unavoidable, but exceptions should not leak across modules
- Good modules handle exceptional conditions locally
  - Local input validation and local exception handling where possible
  - **Explicit interfaces** with clear pre/post conditions
  - Explicitly documented and checked exceptions where exceptional conditions may propagate between modules
  - **Information hiding**/encapsulation of critical code (likely bugs, likely exceptions)
- Example
  - Printer crash should not corrupt entire system
  - Exception/infinite loop in rabbit AI should not freeze GUI
  - Exception in shortest-path algorithm should not corrupt graph

Summary

- 5 design goals
  - Design for division of labor
  - Design for understandability
  - Design for change
  - Design for reuse
  - Design for robustness
- 5 design strategies (so far)
  - Explicit interfaces (clear boundaries)
  - Information hiding (hide likely changes)
  - Low coupling (reduce dependencies)
  - High cohesion (one purpose per class)
  - Low repr. gap (align requirements and impl.)