Software Design Foundations

Nick Sumner
wsumner@sfu.ca
Why care about software design?

- Software Design
Why care about software design?

- **Software Design**
  - The components into which a problem is broken down

- Input
- Audio
- Client Logic
- Network
- Server Logic
- Persistence
- Graphics
Why care about software design?

- **Software Design**
  - The components into which a problem is broken down
  - The ways those components interact
Why care about software design?

- **Software Design**
  - The components into which a problem is broken down
  - The ways those components interact
  - The interfaces and abstractions they expose or hide
Why care about software design?

- Software Design
  - The components into which a problem is broken down
  - The ways those components interact
  - The interfaces and abstractions they expose or hide

- Design affects the value of software
  - Understandability
  - Performance
  - Reliability
  - Ease of change
Why care about software design?

- **Software Design**
  - The components into which a problem is broken down
  - The ways those components interact
  - The interfaces and abstractions they expose or hide

- **Design affects the value of software**
  - Understandability
  - Performance
  - Reliability
  - *Ease of change*

Most programming is “brown field” programming.
Why care about software design?

- **Software Design**
  - The components into which a problem is broken down
  - The ways those components interact
  - The interfaces and abstractions they expose or hide

- **Design affects the value of software**
  - Understandability
  - Performance
  - Reliability
  - Ease of change

  - Poor value on these metrics is a significant risk
  - Good design can mitigate these risks
Why care about software design?

- **Software Design**
  - The components into which a problem is broken down
  - The ways those components interact
  - The interfaces and abstractions they expose or hide

- **Design affects the value of software**
  - Understandability
  - Performance
  - Reliability
  - Ease of change

  My goal is to have you able read and understand design decisions at FAANG....

- Poor value on these metrics is a significant risk
- Good design can mitigate these risks
What is bad design?

- Several red flags [Ousterhout 2018, ...]
What is bad design?

- **Several red flags** [Ousterhout 2018, ...]
  - Seemingly simple changes require modifying many locations
What is bad design?

- **Several red flags** [Ousterhout 2018, ...]
  - Seemingly simple changes require modifying many locations
  - A developer needs to know a great deal to complete a task
What is bad design?

- **Several red flags** [Ousterhout 2018, ...]
  - Seemingly simple changes require modifying many locations
  - A developer needs to know a great deal to complete a task
  - What code must be modified is unclear
What is bad design?

- **Several red flags** [Ousterhout 2018, ...]
  - Seemingly simple changes require modifying many locations
  - A developer needs to know a great deal to complete a task
  - What code must be modified is unclear
  - The impact of a change is unclear
What is bad design?

- **Several red flags** [Ousterhout 2018, ...]
  - Seemingly simple changes require modifying many locations
  - A developer needs to know a great deal to complete a task
  - What code must be modified is unclear
  - The impact of a change is unclear

- **Possible causes** [Ousterhout 2018]
  - **Dependencies** – Code cannot be understood in isolation
  - **Obscurity** – Important information is not obvious
What is bad design?

- Several red flags [Ousterhout 2018, ...]
  - Seemingly simple changes require modifying many locations
  - A developer needs to know a great deal to complete a task
  - What code must be modified is unclear
  - The impact of a change is unclear

- Possible causes [Ousterhout 2018]
  - Dependencies – Code cannot be understood in isolation
  - Obscurity – Important information is not obvious

- Design complexity arises from many portions of code interacting
  - Think of a basket or a braid. [Hickey 2011]
    Changing one strand is hard....
What is common in good designs?

- Loose Coupling (connectivity)
What is common in good designs?

- Loose Coupling (connectivity)
What is common in good designs?

- Loose Coupling (connectivity)

worse  -  Content  

better
What is common in good designs?

- Loose Coupling (connectivity)

"worse"  →  "Content"

```
... goto yourcode...
```

```
... yourcode:
...```

"better"
What is common in good designs?

- Loose Coupling (connectivity)
  - Content
  - Common global data
What is common in good designs?

- Loose Coupling (connectivity)
  - Content
  - Common global data

```
int global = ...
...
= global
```

```
global = ...
...
= global
```
What is common in good designs?

- Loose Coupling (connectivity)
  - Content
  - Common global data

```
int global = ...
... = global
```

```
global = ...
global = ...
... = global
```
What is common in good designs?

- Loose Coupling (connectivity)
  - Content
  - Common global data

Note: “Solutions” like singletons have these constraints and worse.
What is common in good designs?

- Loose Coupling (connectivity)
  - Content
  - Common global data
  - Subclassing
What is common in good designs?

- **Loose Coupling (connectivity)**
  - worse
  - better

  - Content
  - Common global data
  - Subclassing

```cpp
class Parent {
public:
    virtual void foo() { bar(); }
    virtual void bar() {}
};
```

[Bloch, “Effective Java”]
What is common in good designs?

- **Loose Coupling (connectivity)**
  - worse
  - Content
  - Common global data
  - better

```cpp
class Parent {
public:
    virtual void foo() { bar(); }
    virtual void bar() {}
};

class Child : public Parent {
public:
    virtual void bar() { foo(); }
};
```

[Bloch, “Effective Java”]
What is common in good designs?

- Loose Coupling (connectivity)
  - Content
  - Common global data
  - Subclassing

```
class Parent {
public:
  virtual void foo() { bar(); }
  virtual void bar() {};
};
```

```
Non Virtual Interfaces (NVI) help clarify & are common in C++.
```

```
class Parent {
public:
  void foo() { barImpl(); }
  void bar() { barImpl(); }
private:
  virtual void barImpl() = 0;
};
```

[Bloch, “Effective Java”]
What is common in good designs?

- **Loose Coupling (connectivity)**
  - Content
  - Common global data
  - Subclassing
  - Temporal
What is common in good designs?

- Loose Coupling (connectivity)
  - Content
  - Common global data
  - Subclassing
  - Temporal

```
Cat cat = new Cat;
...
delete cat;
```
What is common in good designs?

- **Loose Coupling (connectivity)**
  - Content
  - Common global data
  - Subclassing
  - Temporal

```java
Cat cat = new Cat;
...
delete cat;
```

```java
Process p;
p.doStep1();
p.doStep2();
p.doStep3();
```
What is common in good designs?

- **Loose Coupling (connectivity)**
  - Content
  - Common global data
  - Subclassing
  - Temporal

```
Cat cat = new Cat;
...
delete cat;
```

```
Process p;
p.doStep1();
p.doStep2();
p.doStep3();
```

```
Process p;
p.foo();
p.bar();
p.baz();
```

This is more insidious!
What is common in good designs?

- **Loose Coupling (connectivity)**
  - Content
  - Common global data
  - Subclassing
  - Temporal
  - Passing data to/from each other

```
x = foo(1, 2)
def foo(a, b):
  ...
```
What is common in good designs?

- **Loose Coupling (connectivity)**
  - Content
  - Common global data
  - Subclassing
  - Temporal
  - Passing data to/from each other
  - Independence
What is common in good designs?

- Loose Coupling
- High fan in / low fan out
What is common in good designs?

- Loose Coupling
- High fan in / low fan out
- Layers / Stratification
What is common in good designs?

- Loose Coupling
- High fan in / low fan out
- Layers / Stratification
What is common in good designs?

- Loose Coupling
- High fan in / low fan out
- Layers / Stratification

Layers are just a form of decoupling.
What is common in good designs?

- Loose Coupling
- High fan in / low fan out
- Layers / Stratification
- Cohesion
What is common in good designs?

- Loose Coupling
- High fan in / low fan out
- Layers / Stratification
- Cohesion

These attributes promote ease of change
What are our tools in creating designs?

- The same tools arise across languages
  - Polymorphism
  - Composition
What are our tools in creating designs?

- The same tools arise across languages
  - Polymorphism
  - Composition

- Understanding and leveraging these can enable safe, efficient, modifiable, and clear designs
What are our tools in creating designs?

- The same tools arise across languages
  - Polymorphism
  - Composition
  - Understanding and leveraging these can enable safe, efficient, modifiable, and clear designs
  - So we need to understand them....
What is polymorphism?
Polymorphism

- What is polymorphism?
  - A component is polymorphic if it may operate on multiple types
Polymorphism

- What is polymorphism?
  - A component is polymorphic if it may operate on multiple types

- What kinds of polymorphism are there?
  - At least 4(ish) broad classes that people should be familiar with
  - Even more (and further subdivision) in richer languages
Polymorphism

- **What is polymorphism?**
  - A component is polymorphic if it may operate on multiple types

- **What kinds of polymorphism are there?**
  - At least 4(ish) broad classes that people should be familiar with
  - Even more (and further subdivision) in richer languages

1) **Runtime polymorphism**  (e.g. via inheritance in OOP)
Polymorphism

• What is polymorphism?
  – A component is polymorphic if it may operate on multiple types

• What kinds of polymorphism are there?
  – At least 4(ish) broad classes that people should be familiar with
  – Even more (and further subdivision) in richer languages

  1) Runtime polymorphism (e.g. via inheritance in OOP)
  2) Parametric polymorphism (e.g. via generics / templates)
Polymorphism

- What is polymorphism?
  - A component is polymorphic if it may operate on multiple types

- What kinds of polymorphism are there?
  - At least 4(ish) broad classes that people should be familiar with
  - Even more (and further subdivision) in richer languages

1) Runtime polymorphism (e.g. via inheritance in OOP)
2) Parametric polymorphism (e.g. via generics / templates)
3) Ad-hoc polymorphism (e.g. via overloading / type classes / traits)
Polymorphism

• What is polymorphism?
  – A component is polymorphic if it may operate on multiple types

• What kinds of polymorphism are there?
  – At least 4(ish) broad classes that people should be familiar with
  – Even more (and further subdivision) in richer languages

1) Runtime polymorphism (e.g. via inheritance in OOP)
2) Parametric polymorphism (e.g. via generics / templates)
3) Ad-hoc polymorphism (e.g. via overloading / type classes / traits)
4) Coercion* (e.g. via implicit conversion)
5) ...

*Coercion is not a common term in the context of polymorphism, but it can refer to implicit type conversions.
Polymorphism

- What is polymorphism?
  - A component is polymorphic if it may operate on multiple types

- What kinds of polymorphism are there?
  - At least 4 (ish) broad classes that people should be familiar with
  - Even more (and further subdivision) in richer languages

1) Runtime polymorphism (e.g. via inheritance in OOP)
2) Parametric polymorphism (e.g. via generics / templates)
3) Ad-hoc polymorphism (e.g. via overloading / type classes / traits)
4) Coercion* (e.g. via implicit conversion)
5) ...

Different forms of polymorphism have different design trade offs
Polymorphism via Inheritance
(a quick review)
Polymorphism via Inheritance

- Inheritance
  - An approach of constructing a new entity in terms of an existing one
Polymorphism via Inheritance

- **Inheritance**
  - An approach of constructing a new entity in terms of an existing one
  - Can apply to classes, objects, ...
Polymorphism via Inheritance

- **Inheritance**
  - An approach of constructing a new entity in terms of an existing one
  - Can apply to classes, objects, ...
  - Most familiar nowadays through Object Oriented Programming (OOP)
Polymorphism via Inheritance

- **Inheritance**
  - An approach of constructing a new entity in terms of an existing one
  - Can apply to classes, objects, ...
  - Most familiar nowadays through Object Oriented Programming (OOP)

- **Class Inheritance**
  - Creates a new class in terms of an existing class

![Diagram showing inheritance relationship between List and ArrayList]
Polymorphism via Inheritance

- **Inheritance**
  - An approach of constructing a new entity in terms of an existing one
  - Can apply to classes, objects, ...
  - Most familiar nowadays through Object Oriented Programming (OOP)

- **Class Inheritance**
  - Creates a new class in terms of an existing class
  - Shares properties and behaviors with the new class

```
List
  + add()

ArrayList
  + add()
```
Polymorphism via Inheritance

- Inheritance
  - An approach of constructing a new entity in terms of an existing one
  - Can apply to classes, objects, ...
  - Most familiar nowadays through Object Oriented Programming (OOP)

- Class Inheritance
  - Creates a new class in terms of an existing class
  - Shares properties and behaviors with the new class
  - Can establish a subtyping relationship

```
List + add()

is-a

ArrayList + add()
```
Polymorphism via Inheritance

• Inheritance
  – An approach of constructing a new entity in terms of an existing one
  – Can apply to classes, objects, ...
  – Most familiar nowadays through Object Oriented Programming (OOP)

• Class Inheritance
  – Creates a new class in terms of an existing class
  – Shares properties and behaviors with the new class
  – Can establish a subtyping relationship

```java
List list = new ArrayList();
Java
```

```cpp
void foo(List& someList);
...
Arraylist list;
foo(list);
C++
```
What does good inheritance look like?

- Initial guidelines:
What does good inheritance look like?

- Initial guidelines:
  - Prefer composition to inheritance
What does good inheritance look like?

- **Initial guidelines:**
  - Prefer composition to inheritance
  - **Liskov Substitution Principle**
    - If $\varphi$ is true for the base, then $\varphi$ is true the derived
What does good inheritance look like?

- Initial guidelines:
  - Prefer composition to inheritance
  - Liskov Substitution Principle
    - If $\phi$ is true for the base, then $\phi$ is true the derived

Derived is *substitutable* for Base
What does good inheritance look like?

- Initial guidelines:
  - Prefer composition to inheritance
  - Liskov Substitution Principle
    - If $\phi$ is true for the base, then $\phi$ is true the derived
    - Arguments in the subtype may be more general
What does good inheritance look like?

- Initial guidelines:
  - Prefer composition to inheritance
  - Liskov Substitution Principle
    - If $\phi$ is true for the base, then $\phi$ is true the derived
    - Arguments in the subtype may be more general

$B <: D$

Base
A foo($B$ b)

Derived
C foo($D$ d)

Arguments are **contravariant**
What does good inheritance look like?

- Initial guidelines:
  - Prefer composition to inheritance
  - Liskov Substitution Principle
    - If \( \varphi \) is true for the base, then \( \varphi \) is true the derived
    - Arguments in the subtype may be more general
    - Return values in the subtype may be more constrained

Base
A foo(B b)

Derived
C foo(D d)
What does good inheritance look like?

- Initial guidelines:
  - Prefer composition to inheritance
  - Liskov Substitution Principle
    - If \( \varphi \) is true for the base, then \( \varphi \) is true the derived
    - Arguments in the subtype may be more general
    - Return values in the subtype may be more constrained

\[
\begin{align*}
C & <: A \\
\text{Base} & \text{ foo(B b)} \\
\text{Derived} & \text{ foo(D d)}
\end{align*}
\]

Return types are **covariant**
What does good inheritance look like?

- Initial guidelines:
  - Prefer composition to inheritance
  - Liskov Substitution Principle
    - If $\varphi$ is true for the base, then $\varphi$ is true the derived
    - Arguments in the subtype may be more general
    - Return values in the subtype may be more constrained
    - Preconditions are not stronger

\begin{align*}
\text{assert}(x > 0) & \quad \text{assert}(x \neq 0) \\
\text{Base} & \quad \text{Derived} \\
A \text{ foo}(B b) & \quad C \text{ foo}(D d)
\end{align*}
What does good inheritance look like?

- **Initial guidelines:**
  - Prefer composition to inheritance
  - **Liskov Substitution Principle**
    - If $\phi$ is true for the base, then $\phi$ is true the derived
    - Arguments in the subtype may be more general
    - Return values in the subtype may be more constrained
    - Preconditions are not stronger
    - Postconditions are not weaker

```
Base
A foo(B b)

Derived
C foo(D d)
```

\[
\text{assert}(\text{result} \neq 0) \quad \text{assert}(\text{result} > 0)
\]
What does good inheritance look like?

- Initial guidelines:
  - Prefer composition to inheritance
  - Liskov Substitution Principle
    - If $\phi$ is true for the base, then $\phi$ is true the derived
    - Arguments in the subtype may be more general
    - Return values in the subtype may be more constrained
    - Preconditions are not stronger
    - Postconditions are not weaker
    - Invariants must still hold

<table>
<thead>
<tr>
<th>Base</th>
<th>Derived</th>
</tr>
</thead>
<tbody>
<tr>
<td>A foo(B b)</td>
<td>C foo(D d)</td>
</tr>
</tbody>
</table>
So why is inheritance hard?
So why is inheritance hard?

- Do the LSP and has-a relationships unambiguously tell us how to apply inheritance?
So why is inheritance hard?

- Do the LSP and has-a relationships *unambiguously* tell us how to apply inheritance?
- Every *is-a* relationship could instead be *has-a*!
So why is inheritance hard?

- Do the LSP and has-a relationships unambiguously tell us how to apply inheritance?
- Every is-a relationship could instead be has-a!
  - These often capture finer grained relationships
  - Break individual responsibilities into components
So why is inheritance hard?

- Do the LSP and has-a relationships unambiguously tell us how to apply inheritance?
- Every is-a relationship could instead be has-a!
  - These often capture finer grained relationships
  - Break individual responsibilities into components
So why is inheritance hard?

- Do the LSP and has-a relationships *unambiguously* tell us how to apply inheritance?

- Every *is-a* relationship could instead be *has-a*!
  - These often capture finer grained relationships
  - Break individual responsibilities into components

Diagram:

- Researcher
  - is-a
  - Professor
So why is inheritance hard?

- Do the LSP and has-a relationships *unambiguously* tell us how to apply inheritance?
- Every *is-a* relationship could instead be *has-a*!
  - These often capture finer grained relationships
  - Break individual responsibilities into components
So why is inheritance hard?

• Do the LSP and has-a relationships unambiguously tell us how to apply inheritance?

• Every is-a relationship could instead be has-a!
  – These often capture finer grained relationships
  – Break individual responsibilities into components
So why is inheritance hard?

- Do the LSP and has-a relationships unambiguously tell us how to apply inheritance?
- Every is-a relationship could instead be has-a!
  - These often capture finer grained relationships
  - Break individual responsibilities into components
So why is inheritance hard?

- Do the LSP and has-a relationships unambiguously tell us how to apply inheritance?
- Every is-a relationship could instead be has-a!
  - These often capture finer grained relationships
  - Break individual responsibilities into components
So why is inheritance hard?

- Do the LSP and has-a relationships unambiguously tell us how to apply inheritance?
- Every is-a relationship could instead be has-a!
  - These often capture finer grained relationships
  - Break individual responsibilities into components
So why is inheritance hard?

- Do the LSP and has-a relationships unambiguously tell us how to apply inheritance?

- Every is-a relationship could instead be has-a!
  - These often capture finer grained relationships
  - Break individual responsibilities into components

Note, these are now roles, not people.
So why is inheritance hard?

- Do the LSP and has-a relationships *unambiguously* tell us how to apply inheritance?
- Every *is-a* relationship could instead be *has-a*!
  - These often capture finer grained relationships
  - Break individual responsibilities into components

```
Professor
  has-a
    Researcher
    Teacher
    Napper
```

Note, these are now *roles*, not *people*.

- Whenever *is-a* applies, you must still make a decision
Choosing is-a or has-a

- Guide 1: Might the behavior need to change?
  - Inheritance often *precludes* it
Choosing is-a or has-a

Guide 1: Might the behavior need to change?
- Inheritance often precludes it
- Composition often simplifies it
Choosing is-a or has-a

- Guide 1: Might the behavior need to change?
  - Inheritance often precludes it
  - Composition often simplifies it
  - Use composition if the relationship is dynamic
Choosing is-a or has-a

Guide 1: Might the behavior need to change?
- Inheritance often precludes it
- Composition often simplifies it
- Use composition if the relationship is dynamic
Choosing is-a or has-a

- **Guide 1:** Might the behavior need to change?
  - Inheritance often precludes it
  - Composition often simplifies it
  - Use composition if the relationship is dynamic

- **Guide 2:** Might the type be used *polymorphically*?
  - Composition does not intrinsically aid it
Choosing is-a or has-a

- **Guide 1:** Might the behavior need to change?
  - Inheritance often precludes it
  - Composition often simplifies it
  - Use composition if the relationship is dynamic

- **Guide 2:** Might the type be used *polymorphically*?
  - Composition does not intrinsically aid it
  - Inheritance can enable it
Choosing is-a or has-a

- **Guide 1:** Might the behavior need to change?
  - Inheritance often precludes it
  - Composition often simplifies it
  - Use composition if the relationship is dynamic

- **Guide 2:** Might the type be used polymorphically?
  - Composition does not intrinsically aid it
  - Inheritance can enable it
  - **Consider** inheritance when a reference to a general type may point to a more specific one.
Choosing is-a or has-a

Guide 1: Might the behavior need to change?
- Inheritance often precludes it
- Composition often simplifies it
- Use composition if the relationship is dynamic

Guide 2: Might the type be used polymorphically?
- Composition does not intrinsically aid it
- Inheritance can enable it
- Consider inheritance when a reference to a general type may point to a more specific one.

std::vector<People*> folks;

0) Student
1) Student
2) Lecturer
3) Professor
4) Student
Choosing is-a or has-a

- Guide 1: Might the behavior need to change?
  - Inheritance often precludes it
  - Composition often simplifies it
  - Use composition if the relationship is dynamic

- Guide 2: Might the type be used polymorphically?
  - Composition does not intrinsically aid it
  - Inheritance can enable it
  - Consider inheritance when a reference to a general type may point to a more specific one.

We will revisit this in the context of algebraic data types.
So let’s try it out...

- I need
  - Many different types of animals.

This should sound familiar...
So let’s try it out...

- I need
  - Many different types of animals.
  - Each should be able to `move()` and `speak()`.
So let’s try it out...

- I need
  - Many different types of animals.
  - Each should be able to `move()` and `speak()`.
  - An `Animal&` should be able to refer to any of them.
So let’s try it out...

- I need
  - Many different types of animals.
  - Each should be able to `move()` and `speak()`.
  - An `Animal&` should be able to refer to any of them.

What does my design look like based on the rules?
So let’s try it out...

- I need
  - Many different types of animals.
  - Each should be able to `move()` and `speak()`.
  - An `Animal&` should be able to refer to any of them.
So let’s try it out...

- I need
  - Many different types of animals.
  - Each should be able to `move()` and `speak()`.
  - An `Animal&` should be able to refer to any of them.
So let’s try it out...

- I need
  - Many different types of animals.
  - Each should be able to `move()` and `speak()`.
  - An `Animal&` should be able to refer to any of them.

Does Cat serve a purpose?

Is this good?
So let’s try it out...

- I need
  - Many different types of animals.
  - Each should be able to `move()` and `speak()`.
  - An `Animal&` should be able to refer to any of them.

```
Parrot    Cat    Professor    Corgi
    ^          
   Animal

Maine Coon    Bengal
```

Is this good?

Does it achieve reuse?
So let’s try it out...

- I need
  - Many different types of animals.
  - Each should be able to `move()` and `speak()`.
  - An `Animal` should be able to refer to any of them.
So let’s try it out... 

- I need
  - Many different types of animals.
  - Each should be able to `move()` and `speak()`.
  - An `Animal&` should be able to refer to any of them.

Can we do better?
So let’s try it out...

- I need
  - Many different types of animals.
  - Each should be able to `move()` and `speak()`.
  - An `Animal&` should be able to refer to any of them.

Can we do better?

If someone on my team did this multiple times, I would consider firing them.

Hierarchies in *data* need not be hierarchies in the *type system*!
So let’s try it out...

- I need
  - Many different types of animals.
  - Each should be able to `move()` and `speak()`.
  - An `Animal&` should be able to refer to any of them.

Can we do better?  

Recall: identify & isolate change
So let’s try it out...

- I need
  - Many different types of animals.
  - Each should be able to \texttt{move()} and \texttt{speack()}.
  - An \texttt{Animal} should be able to refer to any of them.

Can we do better?  Recall: identify \\& isolate change
So let’s try it out...

- I need
  - Many different types of animals.
  - Each should be able to `move()` and `speak()`.
  - An `Animal` should be able to refer to any of them.

Can we do better? Recall: identify & isolate change

```
Animal
  has-a Movement
```

Movement selects from the ways any Animal can move.
So let’s try it out...

- I need
  - Many different types of animals.
  - Each should be able to **move()** and **speak()**.
  - An **Animal** should be able to refer to any of them.

Can we do better?  Recall: identify & isolate change

```
Animal
  has-a Movement
  has-a Vocalization
```
So let’s try it out...

- **I need**
  - Many different types of animals.
  - Each should be able to `move()` and `speak()`.
  - An `Animal` should be able to refer to any of them.

Can we do better?  Recall: identify & isolate change

```
Animal

 has-a Movement
  Crawl

 has-a Vocalization
```
So let’s try it out...

- I need
  - Many different types of animals.
  - Each should be able to `move()` and `speak()`.
  - An `Animal` should be able to refer to any of them.

Can we do better? Recall: identify & isolate change
So let’s try it out...

- I need
  - Many different types of animals.
  - Each should be able to `move()` and `speak()`.
  - An `Animal`& should be able to refer to any of them.

Can we do better?  Recall: identify & isolate change

```
Animal
    has-a
    Movement
      Crawl
      Fly
      Saunter
    has-a
    Vocalization
```
So let’s try it out...

- I need
  - Many different types of animals.
  - Each should be able to `move()` and `speak()`.
  - An `Animal` should be able to refer to any of them.

Can we do better?  Recall: identify & isolate change

```
Animal
  has-a Movement
    has-a Crawl
    has-a Fly
    has-a Saunter

Animal
  has-a Vocalization
    has-a Tweet
```
So let’s try it out...

- I need
  - Many different types of animals.
  - Each should be able to `move()` and `speak()`.
  - An `Animal*` should be able to refer to any of them.

Can we do better? Recall: identify & isolate change

```
Animal
  has-a Movement
    Crawl
    Fly
    Saunter
  has-a Vocalization
    Tweet
    Meow
```
So let’s try it out...

- I need
  - Many different types of animals.
  - Each should be able to \texttt{move}() and \texttt{speak}().
  - An \texttt{Animal} should be able to refer to any of them.

Can we do better?  Recall: identify & isolate change
So let’s try it out...

- I need
  - Many different types of animals.
  - Each should be able to `move()` and `speak()`.
  - An `Animal` should be able to refer to any of them.

Can we do better?

Recall: identify & isolate change

```
Animal
  has-a Movement
  has-a Vocalization

Movement
  has-a Crawl
  has-a Fly
  has-a Saunter

Vocalization
  has-a Tweet
  has-a Meow
  has-a Ramble
  has-a Bark
```
So let’s try it out...

- I need
  - Many different types of animals.
  - Each should be able to \texttt{move()} and \texttt{spea}\texttt{k}().
  - An \texttt{Animal} should be able to refer to any of them.

Can we do better?

Recall: identify & isolate change

```java
class Animal {
    Movement& m;
    void move() {
        m.move();
    }
};
```
Shallow, fine grained inheritance

- Avoids reimplementaion of common behavior
  - e.g. Common aspects of Animal are just fields of Animal
Shallow, fine grained inheritance

- Avoids reimplementations of common behavior
  - e.g. Common aspects of Animal are just fields of Animal

- Inheritance contracts for fine grained policies
Shallow, fine grained inheritance

- Avoids reimplementations of common behavior
  - e.g. Common aspects of Animal are just fields of Animal
- Inheritance contracts for fine grained policies
- Enables dynamic selection & configuration of which policies are desired
Shallow, fine grained inheritance

- Avoids reimplementation of common behavior
  - e.g. Common aspects of Animal are just fields of Animal
- Inheritance contracts for fine grained policies
- Enables dynamic selection & configuration of which policies are desired
  - e.g. A Cat may start out Stationary, then Run, then be Stationary
Shallow, fine grained inheritance

- Avoids reimplementation of common behavior
  - e.g. Common aspects of Animal are just fields of Animal
- Inheritance contracts for fine grained policies
- Enables dynamic selection & configuration of which policies are desired
  - e.g. A Cat may start out Stationary, then Run, then be Stationary

Previously static requirements will often become dynamic.
Shallow, fine grained inheritance

- Avoids reimplementation of common behavior
  - e.g. Common aspects of Animal are just fields of Animal

- Inheritance contracts for fine grained policies

- Enables dynamic selection & configuration of which policies are desired
  - e.g. A Cat may start out Stationary, then Run, then be Stationary

- Directly identifies & addresses risks of change in class design
Parametric Polymorphism
(a quick review?)
Parametric Polymorphism

- Parametric polymorphism enables defining generic components over a family of types using type parameters.
Parametric Polymorphism

- Parametric polymorphism enables defining generic components over a family of types using type parameters.

Commonly referred to as *generics* or *templates*
Parametric Polymorphism

- Parametric polymorphism enables defining generic components over a family of types using type parameters.

Java
public class ArrayList<E> {...}

C++
template <class E>
class vector;

template <class E>
class ArrayList

Typescript
class ArrayList<E> {...}

Python
T = TypeVar('T')
class SpecialList(Generic[T]):
    def __init__(self, value: T) -> None:
        ...

Commonly referred to as generics or templates
Parametric Polymorphism

- Parametric polymorphism enables defining generic components over a family of types using type parameters

```cpp
std::vector<int> v1 = {1, 2, 3, 4, 5};
```

Java

```java
public class ArrayList<E> {...
```

Typescript

```typescript
class ArrayList<E> {...
```

Python

```
T = TypeVar('T')
class SpecialList(Generic[T]):
    def __init__(self, value: T) -> None:
        ...
```

```cpp
template <class E>
class vector;
```

```cpp
class ArrayList<E> {...
```

```cpp
std::vector<int> v1 = {1, 2, 3, 4, 5};
```
Parametric Polymorphism

- Parametric polymorphism enables defining generic components over a family of types using type parameters

Java
```
public class ArrayList<E> {...}
```

TypeScript
```
class ArrayList<E> {...}
```

Python
```
T = TypeVar('T')
class SpecialList(Generic[T]):
    def __init__(self, value: T) -> None: ...
```

C++
```
template <class E>
class vector;
```

```
std::vector<int> v1 = {1, 2, 3, 4, 5};
```

Parameters can sometimes be inferred.
Parametric Polymorphism

- Parametric polymorphism enables defining generic components over a family of types using type parameters

- Enables careful *abstraction* of design components
  - A class/function/data structure/algorithm can be written & validated once
  - Intentions can be clearer within code
Suppose an algorithm needs to find an element in a collection & increment it.
Suppose an algorithm needs to find an element in a collection & increment it.

```cpp
void bigAlgorithm(...) {
    std::vector<int> c;
    ...
    for (auto i = begin(c), e = end(c); i != e; ++i) {
        if (*i == v) {
            ++*i;
            break;
        }
    }
    ...
}
```
Suppose an algorithm needs to find an element in a collection & increment it.

```cpp
void bigAlgorithm(...) {
    std::vector<int> c;
    ...
    for (auto i = begin(c), e = end(c); i != e; ++i) {
        if (*i == v) {
            ++*i;
            break;
        }
    }
    ...
}
```

This is awful.
Intentions are unclear.
Modifiability is low.
Reusability is low.
Suppose an algorithm needs to find an element in a collection & increment it.

```cpp
template<typename C, typename V>
auto find(const C& c, const V& v) {
    for (auto i = begin(c), e = end(c); i != e; ++i) {
        if (*i == v) {
            return i;
        }
    }
    return end(c);
}
```

```cpp
void bigAlgorithm(...) {
    std::vector<int> c;
    ...
    for (auto i = begin(c), e = end(c); i != e; ++i) {
        if (*i == v) {
            ++*i;
            break;
        }
    }
    ...
}
```
Suppose an algorithm needs to find an element in a collection & increment it.

```cpp
void bigAlgorithm(...) {
    std::vector<int> c;
    ...
    for (auto i = begin(c), e = end(c); i != e; ++i) {
        if (*i == v) {
            ++*i;
            break;
        }
    }
    ...
}
```

```
template<typename C, typename V>
auto find(const C& c, const V& v) {
    for (auto i = begin(c), e = end(c); i != e; ++i) {
        if (*i == v) {
            return i;
        }
    }
    return end(c);
}
```

```cpp
void bigAlgorithm(...) {
    std::vector<int> c;
    ...
    auto element = find(c, v);
    ++*element;
    ...
}
```
Suppose an algorithm needs to find an element in a collection & increment it.

```cpp
void bigAlgorithm(...) {
    std::vector<int> c;
    ...
    for (auto i = begin(c), e = end(c); i != e; ++i) {
        if (*i == v) {
            ++*i;
            break;
        }
    }
}
```

```cpp
template<typename C, typename V>
auto find(const C& c, const V& v) {
    for (auto i = begin(c), e = end(c); i != e; ++i) {
        if (*i == v) {
            return i;
        }
    }
    return end(c);
}
```

```cpp
void otherAlgorithm(...) {
    std::vector<std::string> d = ...;
    auto element = find(d, w);
    ...
}
```
Parametric Polymorphism

- Type variables can also be bounded / restricted
  - Consider `find(C, V)`, it should require that `Element Type(C) = V`  
  - Restricting to subtypes / supertypes is common

Java

```java
class D <T extends A & B & C> { }
class F <? extends E> { }
```
Parametric Polymorphism

- Type variables can also be bounded / restricted
  - Consider `find(C,V)`, it should require that `ElementType(C) = V`
  - Restricting to subtypes / supertypes is common

Java

```java
class D <T extends A & B & C> { }
class F <? extends E> { }
```

C++

```cpp
template <typename T, typename=std::enable_if_t<std::is_class_v<T>>>
void foo(const T& t) {
    std::cout << "T is a class type\n";
}
```

Such constraints can be cleaner in C++20.
Parametric Polymorphism

- Type variables can also be bounded / restricted
  - Consider `find(C, V)`, it should require that `ElementType(C) = V`
  - Restricting to subtypes / supertypes is common

Java
```java
class D <T extends A & B & C> {}
class F <? extends E> {}
```

C++
```cpp
template <typename T, typename=std::enable_if_t<std::is_class_v<T>>>
void foo(const T& t) {
    std::cout << "T is a class type\n";
}

template <typename C>
C::iterator_type find(const C& c, C::element_type v) {
    ...
}
```

Some scenarios are bounded by convention.
Parametric Polymorphism

- *Specialized* instances can sometimes be created
  - Sometimes domain knowledge allows more efficient implementations
Parametric Polymorphism

- *Specialized* instances can sometimes be created

```cpp
template <class PointedTo, class Value>
class PointerValuePair {
    PointedTo* p;
    Value v;
    PointedTo* getP();
    Value getV();
};
```
Parametric Polymorphism

- *Specialized* instances can sometimes be created

```cpp
template <class PointedTo, class Value>
class PointerValuePair {
    PointedTo* p;
    Value v;
    PointedTo* getP();
    Value getV();
};

template <class PointedTo>
class PointerValuePair<PointedTo,int> {
    uintptr_t compact;
    PointedTo* getP() {
        return reinterpret_cast<PointedTo*>(compact & ~0xFFFFFFFF8);
    }
    Value getV() { return compact & 0x00000007; }
};
```
Parametric Polymorphism

- **Specialized** instances can sometimes be created

```cpp
template <class PointedTo, class Value>
class PointerValuePair {
    PointedTo* p;
    Value v;
    PointedTo* getP();
    Value getV();
};

template <class PointedTo>
class PointerValuePair<PointedTo,int> {
    uintptr_t compact;
    PointedTo* getP() {
        return reinterpret_cast<PointedTo*>(compact & ~0xFFFFFFF8);
    }
    Value getV() { return compact & 0x00000007; }
};
```

Note, this example is still too simple to be safe.
Selecting forms of polymorphism

- Sometimes information needs to flow from a derived class to a base class.
Selecting forms of polymorphism

- Sometimes information needs to flow from a derived class to a base class.

```cpp
template<class T>
class Base {
public:
    void print() { getDerived().printImpl(); }
private:
    T& getDerived() { return *static_cast<T*>(this); }
};
```
Selecting forms of polymorphism

Sometimes information needs to flow from a derived class to a base class.

```c++
template<class T>
class Base {
    public:
        void print() { getDerived().printImpl(); }
    private:
        T& getDerived() { return *static_cast<T*>(this); }
};

class Specific : public Base<Specific> {
    public:
        void printImpl() { printf("Yo\n"); }
};
```
Sometimes information needs to flow from a derived class to a base class.

```cpp
template<class T>
class Base {
public:
    void print() { getDerived().printImpl(); }
private:
    T& getDerived() { return *static_cast<T*>(this); }
};

class Specific : public Base<Specific> {
public:
    void printImpl() { printf("Yo\n"); }
};
```
Selecting forms of polymorphism

- Sometimes information needs to flow from a derived class to a base class.

```cpp
template<class T>
class Base {
public:
    void print() { getDerived().printImpl(); }
private:
    T& getDerived() { return *static_cast<T*>(this); }
};

class Specific : public Base<Specific> {
public:
    void printImpl() { printf("Yo\n"); }
};
```
Selecting forms of polymorphism

- Sometimes information needs to flow from a derived class to a base class.

```cpp
template<class T>
class Base {
    public:
        void print() { getDerived().printImpl(); }
    private:
        T& getDerived() { return *static_cast<T*>(this); }
};

class Specific : public Base<Specific> {
    public:
        void printImpl() { printf("Yo\n"); }
};
```

What other approaches could we have used?
What are the trade offs?
Selecting forms of polymorphism

- Sometimes information needs to flow from a derived class to a base class.

```cpp
template<class T>
class Base {
public:
    void print() { getDerived().printImpl(); }
private:
    T& getDerived() { return *static_cast<T*>(this); }
};

class Specific : public Base<Specific> {
public:
    void printImpl() { printf("Yo\n"); }
};
```

What other approaches could we have used?
What are the trade offs?

Flexibility vs Efficiency
Selecting forms of polymorphism

- Sometimes information needs to flow from a derived class to a base class.

Have those of you familiar with Java seen this before?
Selecting forms of polymorphism

- Sometimes information needs to flow from a derived class to a base class.

Have those of you familiar with Java seen this before?

```java
public class LocalTime implements Comparable<LocalTime> {
    // ...
}
```
Selecting forms of polymorphism

- Sometimes information needs to flow from a derived class to a base class.

```java
public class LocalTime implements Comparable<LocalTime> {
    ...
}

public interface Comparable<T> {
    int compareTo(T o);
}
```
Selecting forms of polymorphism

- Sometimes information needs to flow from a derived class to a base class.

```java
public class LocalTime implements Comparable<LocalTime> {
    ...
}
```

```java
public interface Comparable<T> {
    int compareTo(T o);
}
```

This *Curiosly Recurring Template Pattern* (CRTP) can help in building more robust APIs.
Ad-hoc Polymorphism
Ad-hoc Polymorphism

- Ad-hoc polymorphism can occur on a case by case basis
  - Overloading
  - Type conversions / coercion
  - Type traits & type classes for flexible & structured overloading
Coercion

- Defining allowed conversions can lead to safe & intuitive APIs
- Example: Suppose we want APIs that can operate on contiguous collections.
Coercion

- Defining allowed conversions can lead to safe & intuitive APIs
- Example:
  Suppose we want APIs that can operate on contiguous collections.

```cpp
template<class E, auto N>
void foo(const E(&c)[N]);
```
Coercion

- Defining allowed conversions can lead to safe & intuitive APIs
- Example:
  Suppose we want APIs that can operate on contiguous collections.

```cpp
template<class E, auto N>
void foo(const E(&c)[N]);

template<class E, auto N>
void foo(const std::array<E,N>& c);
```
Coercion

- Defining allowed conversions can lead to safe & intuitive APIs
- **Example:**
  Suppose we want APIs that can operate on contiguous collections.

```cpp
template<class E, auto N>
void foo(const E(&c)[N]);

template<class E, auto N>
void foo(const std::array<E,N>& c);

template<class E>
void foo(const std::vector<E>& c);
```
Coercion

- Defining allowed conversions can lead to safe & intuitive APIs
- Example:
  Suppose we want APIs that can operate on contiguous collections.

```cpp
template<class E, auto N>
void foo(const E(&c)[N]);

template<class E, auto N>
void foo(const std::array<E,N>& c);

template<class E>
void foo(const std::vector<E>& c);

void foo(const std::string& c);
```
Coercion

- Defining allowed conversions can lead to safe & intuitive APIs
- Example:
  Suppose we want APIs that can operate on contiguous collections.

```cpp
template<class E, auto N>
void foo(const E(&c)[N]);

template<class E, auto N>
void foo(const std::array<E,N>& c);

template<class E>
void foo(const std::vector<E>& c);

void foo(const std::string& c);
```

```cpp
template<class E, auto N>
void bar(const E(&c)[N]);

template<class E, auto N>
void bar(const std::array<E,N>& c);

template<class E>
void bar(const std::vector<E>& c);

void bar(const std::string& c);
```
Coercion

- Defining allowed conversions can lead to safe & intuitive APIs
- Example:
  Suppose we want APIs that can operate on contiguous collections.

```cpp
template<class E, auto N>
void foo(const E(&c)[N]);

template<class E, auto N>
void foo(const std::array<E,N>& c);

template<class E>
void foo(const std::vector<E>& c);

void foo(const std::string& c);
```

```
template<class E, auto N>
void bar(const E(&c)[N]);

template<class E, auto N>
void bar(const std::array<E,N>& c);

template<class E>
void bar(const std::vector<E>& c);

void bar(const std::string& c);
```

Yuck.
• Perhaps we can construct a new type that is conversion compatible with all desired types...

We can start by thinking what is common.
Coercion

- Perhaps we can construct a new type that is conversion compatible with all desired types...

```cpp
template<class E>
struct Span {
    E* first;
    size_t count;
};
```
Coercion

- Perhaps we can construct a new type that is conversion compatible with all desired types...

```cpp
template<class E>
struct Span {
    template<class E, auto N>
    Span(const std::array<E,N>& c);
    E* first;
    size_t count;
};

In C++, a non explicit 1 arg constructor defines a compatible conversion
```
Coercion

• Perhaps we can construct a new type that is conversion compatible with all desired types...

```cpp
template<class E>
struct Span {
    template<class E, auto N>
    Span(const std::array<E,N>& c);

    template<class E>
    Span(const std::vector<E>& c);

    E* first;
    size_t count;
};
```
Coercion

- Perhaps we can construct a new type that is conversion compatible with all desired types...

```cpp
template<class E>
struct Span {
    template<class E, auto N>
    Span(const std::array<E,N>& c);

    template<class E>
    Span(const std::vector<E>& c);

    E* first;
    size_t count;
};
```

```cpp
template<class E>  
struct Span {
    template<class E, auto N>
    Span(const std::array<E,N>& c);

    template<class E>
    Span(const std::vector<E>& c);

    E* first;
    size_t count;
};

void foo(Span<E> c);
void bar(Span<E> c);
...

std::vector v = {1, 2, 3, 4, 5};
foo(v);

int v[] = {1, 2, 3, 4, 5};
bar(v);

foo(“This works for free”);
```

This enables convenient & efficient generic APIs.
Coercion

• Perhaps we can construct a new type that is conversion compatible with all desired types...

```
template<class E>
struct Span {
  template<class E, auto N>
  Span(const std::array<E,N>& c);
  template<class E>
  Span(const std::vector<E>& c);
  E* first;
  size_t count;
};

void foo(Span<E> c);
void bar(Span<E> c);
...
std::vector v = {1, 2, 3, 4, 5};
foo(v);
int v[5] = {1, 2, 3, 4, 5};
bar(v);
foo("This works for free");
```

This enables convenient & efficient generic APIs.
Coercion

- Perhaps we can construct a new type that is conversion compatible with all desired types...

This enables convenient & efficient generic APIs.
Type Traits

- Careful use of specialization can structure overloading & extend behaviors
Type Traits

- Careful use of specialization can structure overloading & extend behaviors
- Suppose we want to implement graph algorithms to traverse arbitrary data structures.
Type Traits

- Careful use of specialization can structure overloading & extend behaviors

- Suppose we want to implement graph algorithms to traverse arbitrary data structures.
  - What constraints exist?
Type Traits

- Careful use of specialization can structure overloading & extend behaviors

- Suppose we want to implement graph algorithms to traverse arbitrary data structures.
  - What constraints exist?
  - How might we design a nice API?
    - Via inheritance?
    - Via parametric polymorphism?
Type Traits

- Careful use of specialization can structure overloading & extend behaviors

- Suppose we want to implement graph algorithms to traverse arbitrary data structures.
  - What constraints exist?
  - How might we design a nice API?
    - Via inheritance?
    - Via parametric polymorphism?

- **Type traits** and specialization can convey details about a type that enable generic algorithms
  - Specializations carry the extra details for an overload
Type Traits

template<typename GraphKind>
struct GraphTraits {
  using Error = typename GraphKind::ABCD;
};
Type Traits

template<typename GraphKind>
struct GraphTraits {
    using Error = typename GraphKind::ABCD;
};

template<>
struct GraphTraits<SocialGraph> {

};
template<typename GraphKind>
struct GraphTraits {
    using Error = typename GraphKind::ABCD;
};

template<>
struct GraphTraits<SocialGraph> {
    using NodeRef = ...;
    using ChildIterator = ...;
    static NodeRef get_entry(SocialGraph&) {...}
    static ChildIterator child_begin(NodeRef&) {...}
    static ChildIterator child_end(NodeRef&) {...}
};
template<typename GraphKind>
struct GraphTraits {
    using Error = typename GraphKind::ABCD;
};

template<>
struct GraphTraits<SocialGraph> {
    using NodeRef = ...
    using ChildIterator = ...
    static NodeRef get_entry(SocialGraph&) {...}
    static ChildIterator child_begin(NodeRef&) {...}
    static ChildIterator child_end(NodeRef&) {...}
};
Type Traits

template<typename GraphKind>
struct GraphTraits {
    using Error = typename GraphKind::ABCD;
};

template<>
struct GraphTraits<SocialGraph> {
    using NodeRef = ...;
    using ChildIterator = ...;
    static NodeRef get_entry(SocialGraph&) {...}
    static ChildIterator child_begin(NodeRef&) {...}
    static ChildIterator child_end(NodeRef&) {...}
};

template<class Kind, class GT=GraphTraits<Kind>>
void visualizeGraph(Kind& graph);
Type Traits

```cpp
template<typename GraphKind>
struct GraphTraits {
    using Error = typename GraphKind::ABCD;
};

template<>
struct GraphTraits<SocialGraph> {
    using NodeRef = ...
    using ChildIterator = ...
    static NodeRef get_entry(SocialGraph&) {...}
    static ChildIterator child_begin(NodeRef&) {...}
    static ChildIterator child_end(NodeRef&) {...}
};

template<class Kind, class GT=GraphTraits<Kind>>
void visualizeGraph(Kind& graph);
```
**Type Traits**

```cpp
template<typename GraphKind>
struct GraphTraits {
    using Error = typename GraphKind::ABCD;
};

template<>
struct GraphTraits<SocialGraph> {
    using NodeRef = ...;
    using ChildIterator = ...;
    static NodeRef get_entry(SocialGraph&) {...}
    static ChildIterator child_begin(NodeRef&) {...}
    static ChildIterator child_end(NodeRef&) {...}
};

template<class Kind, class GT=GraphTraits<Kind>>
void visualizeGraph(Kind& graph);

SocialGraph g;
...
visualizeGraph(g);
```
Type Traits

Regardless of the actual graph data structure, or even its API, traits allow generic algorithms to work!
Type Traits

- They are even common in the C++ standard library
Type Traits

- They are even common in the C++ standard library `<functional>`

```cpp
namespace std {
  template< class Key >
  struct hash;
}
```
Type Traits

- They are even common in the C++ standard library

```cpp
namespace std {
    template<class Key>
    struct hash;
}
```

```cpp
<unordered_set>

```template<
    class Key,
    class Hash = std::hash<Key>,
    class KeyEqual = std::equal_to<Key>,
    class Allocator = std::allocator<Key>
>
    class unordered_set;
```
Type Traits

- They are even common in the C++ standard library

```cpp
namespace std {  
  template< class Key >  
  struct hash;  
}
```

This doesn't implement hashing for custom types.

What if I want to add a `Cat` to an `unordered_set`?

```cpp
template<  
  class Key,  
  class Hash = std::hash<Key>,  
  class KeyEqual = std::equal_to<Key>,  
  class Allocator = std::allocator<Key>  
> class unordered_set;
```
Type Traits

- They are even common in the C++ standard library

```cpp
#include <functional>
#include <unordered_set>

namespace std {
    template< class Key >
    struct hash;
}

namespace Cats {
    namespace std {
        template<>
        struct hash<Cat> {
            std::size_t
            operator()(Cat const& s) const noexcept {
                return ...;
            }
        };
    }
}
```
Type Traits

- They are even common in the C++ standard library

```cpp
namespace std {
    template< class Key >
    struct hash;
}
```

```cpp
<unordered_set>
template<class Key,
    class Hash = std::hash<Key>,
    class KeyEqual = std::equal_to<Key>,
    class Allocator = std::allocator<Key> > class unordered_set;
```

```cpp
<Cats.h>
namespace std {
    template<>
    struct hash<Cat> {
        std::size_t
        operator()(Cat const& s) const noexcept {
            return ...;
        }
    };
}

std::unordered_set<Cat> bigBagOfCats;
```
Composition
Composition

- **The Principle of Compositionality (roughly)**
  - The meaning of a complex entity is determined by the meanings of its constituents and the rules used to combine them.
Composition

• The Principle of Compositionality (roughly)
  – The meaning of a complex entity is determined by the meanings of its constituents and the rules used to combine them.
  
  Or in software
  – The meaning of a component should be clear from the meanings of its constituents and how they are used.
Composition

- **The Principle of Compositionality (roughly)**
  - The meaning of a complex entity is determined by the meanings of its constituents and the rules used to combine them.
  
  Or in software
  - The meaning of a component should be clear from the meanings of its constituents and how they are used.

- **But how can we achieve this? We’ll look at a few approaches**
  - Region / scope bounded behavior
  - Ownership
  - Algebraic data types
Region based behaviors

- Consider functions as a unit of abstraction
  - Possible incoming data
  - Behavior
  - Possible outgoing data
Region based behaviors

- Consider functions as a unit of abstraction
  - Possible incoming data
  - Behavior
  - Possible outgoing data
Region based behaviors

- Consider functions as a unit of abstraction
  - Possible incoming data
  - Behavior
  - Possible outgoing data
Region based behaviors

- Consider functions as a unit of abstraction
  - Possible incoming data
  - Behavior
  - Possible outgoing data

- Good abstractions tend to be *self contained*, but bad ones will leak obligations on their users

```python
foo()
```
Region based behaviors

• Consider functions as a unit of abstraction
  – Possible incoming data
  – Behavior
  – Possible outgoing data

• Good abstractions tend to be *self contained*, but bad ones will leak obligations on their users

```c
Mutex m;
lock(m);
...
unlock(m);
```
Region based behaviors

- Consider functions as a unit of abstraction
  - Possible incoming data
  - Behavior
  - Possible outgoing data

- Good abstractions tend to be *self contained*, but bad ones will leak obligations on their users

```c
Mutex m;
lock(m);
...
unlock(m);
```

What if we don’t unlock the mutex?
Region based behaviors

- Modern languages enable denoting the region for an abstraction
  - Helps to bound the impact and provide composable interfaces.
  - Design the inconsistency and lack of hygiene out of a system
Region based behaviors

- Modern languages enable denoting the region for an abstraction
  - Helps to bound the impact and provide composable interfaces.
  - Design the inconsistency and lack of hygiene out of a system

- Examples
  - Java: `synchronized` blocks/methods, `try-with-resources`

```java
synchronized (this) {
    ...
}
```

```java
try (BufferedReader br =
     new BufferedReader(new FileReader(path))) {
    return br.readLine();
}
```
Region based behaviors

- Modern languages enable denoting the region for an abstraction
  - Helps to bound the impact and provide composable interfaces.
  - Design the inconsistency and lack of hygiene out of a system

- **Examples**
  - **Java**: `synchronized` blocks/methods, `try-with-resources`
  - **Python**: `with`
    ```python
    with open(path) as infile:
        ...
    ```
Region based behaviors

- Modern languages enable denoting the region for an abstraction
  - Helps to bound the impact and provide composable interfaces.
  - Design the inconsistency and lack of hygiene out of a system

- Examples
  - Java: `synchronized` blocks/methods, `try-with-resources`
  - Python: `with`
  - C#: `using`

```csharp
using (var reader = new StreamReader(path)) {
    ...
}
```
Region based behaviors

- Modern languages enable denoting the region for an abstraction
  - Helps to bound the impact and provide composable interfaces.
  - Design the inconsistency and lack of hygiene out of a system

- Examples
  - Java: **synchronized** blocks/methods, **try-with-resources**
  - Python: **with**
  - C#: **using**
  - C++: RAII (**Resource Acquisition Is Initialization**)
Region based behaviors

- Modern languages enable denoting the region for an abstraction
  - Helps to bound the impact and provide composable interfaces.
  - Design the inconsistency and lack of hygiene out of a system

- Examples
  - Java: `synchronized` blocks/methods, `try-with-resources`
  - Python: `with`
  - C#: `using`
  - C++: RAII

```cpp
void memoryResource() {
    auto w = std::make_unique<Widget>(3, "bofrot");
    foo(*w);
}
```
Region based behaviors

- Modern languages enable denoting the region for an abstraction
  - Helps to bound the impact and provide composable interfaces.
  - Design the inconsistency and lack of hygiene out of a system

- Examples
  - Java: `synchronized` blocks/methods, `try-with-resources`
  - Python: `with`
  - C#: `using`
  - C++: RAII

```cpp
void memoryResource() {
    auto w = std::make_unique<Widget>(3, "bofrot");
}
```

```cpp
void memoryResource() {
    Widget w(3, "bofrot");
    foo(w);
}
```

Or better...
Region based behaviors

- Modern languages enable denoting the region for an abstraction
  - Helps to bound the impact and provide composable interfaces.
  - Design the inconsistency and lack of hygiene out of a system.

Examples
- Java: `synchronized` blocks/methods, `try-with-resources`
- Python: `with`
- C#: `using`
- C++: RAII

```cpp
void memoryResource() {
    void fileResource() {
        std::ofstream out{"output.txt"];
        out << "Boston cream\n";
    }
}
```
Region based behaviors

- Modern languages enable denoting the region for an abstraction
  - Helps to bound the impact and provide composable interfaces.
  - Design the inconsistency and lack of hygiene out of a system

- **Examples**
  - **Java:** synchronized blocks/methods, try-with-resources
  - **Python:** with
  - **C#:** using
  - **C++:** RAII

```cpp
void memoryResource() {
    auto w = std::make_unique<Widget>(3, "bofrot");
    foo(*w);
}

void fileResource() {
    std::ofstream out{"output.txt"};
    out << "Boston cream\n";
}

std::mutex m;
void synchronization() {
    std::lock_guard<std::mutex> guard(g_pages_mutex);
    out << "Thread safe fritter\n";
}
```
Region based behaviors

- Modern languages enable denoting the region for an abstraction
  - Helps to bound the impact and provide composable interfaces.
  - Design the inconsistency and lack of hygiene out of a system

- Examples
  - Java: `synchronized` blocks/methods, `try-with-resources`
  - Python: `with`
  - C#: `using`
  - C++: RAII
  - Rust: lifetimes, borrowing, RAII, ...
Ownership

- Sometimes lexical bounds are not known
  - Ownership designates whose responsibility it is to manage a resource makes explicit & obvious
Ownership

- Sometimes lexical bounds are not known
  - Ownership designates whose responsibility it is to manage a resource
  - Applies when a resource has uncertain lifetimes
Ownership

Sometimes lexical bounds are not known
- Ownership designates whose responsibility it is to manage a resource
- Applies when a resource has uncertain lifetimes
- Combines region abstractions to clean up automatically
Ownership

- Sometimes lexical bounds are not known
  - Ownership designates whose responsibility it is to manage a resource
  - Applies when a resource has uncertain lifetimes
  - Combines region abstractions to clean up automatically

```cpp
std::unique_ptr<Widget> memoryResource() {
    auto w = std::make_unique<Widget>(3, "bofrot");
    ...
    return w;
}
```

Whose responsibility is it to clean w? When does it happen?
Ownership

- Sometimes lexical bounds are not known
  - Ownership designates whose responsibility it is to manage a resource
  - Applies when a resource has uncertain lifetimes
  - Combines region abstractions to clean up automatically

What do these signatures connote?

```cpp
void foo(unique_ptr<Widget> w);
void foo(unique_ptr<Widget>& w);
void foo(Widget& w);
```
Algebraic Data Types

- Carefully combining types can design more inconsistent & erroneous states out of a system
Algebraic Data Types

- Carefully combining types can design more inconsistent & erroneous states out of a system

```c
struct Cat {
    enum Activity {RUNNING, SLEEPING};
    Activity activity;
    uint64_t runningSpeed;
};
```

What *problems* does this design enable?
Algebraic Data Types

- Carefully combining types can design more inconsistent & erroneous states out of a system

```haskell
type Bool = True | False
```
Algebraic Data Types

- Carefully combining types can design more inconsistent & erroneous states out of a system

```plaintext
type Bool = True | False

type Activity = Running(int speed) | Sleeping
```
Algebraic Data Types

- Carefully combining types can design more inconsistent & erroneous states out of a system

```
type Bool = True | False
```

```
type Activity = Running(int speed) | Sleeping
```

Note: it is impossible to ask for the running speed of something sleeping!
Algebraic Data Types

- Carefully combining types can design more inconsistent & erroneous states out of a system

- **Algebraic Data Types** enable the composable construction of types through combining types
Algebraic Data Types

- Carefully combining types can design more inconsistent & erroneous states out of a system

- **Algebraic Data Types** enable the composable construction of types through combining types
  - **Sum types** express disjoint alternatives

```typescript
type Activity = Running(int speed) | Sleeping
```
Algebraic Data Types

- Carefully combining types can design more inconsistent & erroneous states out of a system

- **Algebraic Data Types** enable the composable construction of types through combining types
  - *Sum types* express disjoint alternatives

```python
type Activity = Running(int speed) | Sleeping
```

How would you express this in C? In C++?
Algebraic Data Types

- Carefully combining types can design more inconsistent & erroneous states out of a system

- **Algebraic Data Types** enable the composable construction of types through combining types
  - **Sum types** express disjoint alternatives

```plaintext
type Activity = Running(int speed) | Sleeping
```
Algebraic Data Types

- Carefully combining types can design more inconsistent & erroneous states out of a system

- **Algebraic Data Types** enable the composable construction of types through combining types
  - **Sum types** express disjoint alternatives
  - **Product types** express combinations

```plaintext
struct MapEntry { Key key; Value value; };
```
Algebraic Data Types

- Carefully combining types can design more inconsistent & erroneous states out of a system

- **Algebraic Data Types** enable the composable construction of types through combining types
  - Sum types express disjoint alternatives
  - Product types express combinations

- Note, the preferred way of extracting from an ADT is through pattern matching
Carefully combining types can design more inconsistent & erroneous states out of a system.

Algebraic Data Types enable the composable construction of types through combining types.

- Sum types express disjoint alternatives
- Product types express combinations

Note, the preferred way of extracting from an ADT is through pattern matching.

```rust
enum Message {
    Quit,
    Move { x: i32, y: i32 },
    Write(String)
}
let msg = Message::Quit;
match msg {
    Message::Quit => {
        println!("The Quit variant has no data to destructre.");
    },
    Message::Move { x, y } => {
        println!("Move {} and {}", x, y);
    },
    Message::Write(text) => println!("Text message: {}", text),
}
```

[From the Rust Book]
Algebraic Data Types

Carefully combining types can design more inconsistent & erroneous states out of a system.

Algebraic Data Types enable the composable construction of types through combining types.

- Sum types express disjoint alternatives
- Product types express combinations

Note, the preferred way of extracting from an ADT is through pattern matching.

```rust
enum Message {
    Quit,
    Move { x: i32, y: i32 },
    Write(String)
}

let msg = Message::Quit;
match msg {
    Message::Quit => {
        println!("The Quit variant has no data to destructurize.");
    },
    Message::Move { x, y } => {
        println!("Move {} and {}", x, y);
    },
    Message::Write(text) => println!("Text message: {}", text),
}
```

[From the Rust Book]
Algebraic Data Types

- Carefully combining types can design more inconsistent & erroneous states out of a system.
- Algebraic Data Types enable the composable construction of types through combining types.
  - Sum types express disjoint alternatives
  - Product types express combinations

Note, the preferred way of extracting from an ADT is through pattern matching.

```rust
cenum Message {
    Quit,
    Move { x: i32, y: i32 },
    Write(String)
}
let msg = Message::Quit;
match msg {
    Message::Quit => {
        println!("The Quit variant has no data to destructure.")
    },
    Message::Move { x, y } => {
        println!("Move {} and {}", x, y);
    },
    Message::Write(text) => println!("Text message: {}", text),
}
```

[From the Rust Book]
Designing Design Patterns
What are design patterns?

- **Design patterns** are reusable solutions and metaphors for addressing problems
What are design patterns?

- **Design patterns** are reusable solutions and metaphors for addressing problems.
- They provide
  - **Common Language**
    - discuss complex solutions more easily by name.
What are design patterns?

- *Design patterns* are reusable solutions and metaphors for addressing problems

- They provide
  - *Common Language*
    - discuss complex solutions more easily by name.
  - *Archetypes*
What are design patterns?

- **Design patterns** are reusable solutions and metaphors for addressing problems

- **They provide**
  - *Common Language*
    - discuss complex solutions more easily by name.
  - *Archetypes*
What are design patterns?

- **Design patterns** are reusable solutions and metaphors for addressing problems.

- They provide:
  - *Common Language*
    - discuss complex solutions more easily by name.
  - *Archetypes*
    - Their trade-offs are well understood
    - New solutions can be *modelled after* them effectively
What are design patterns?

- **Design patterns** are reusable solutions and metaphors for addressing problems

- They provide
  - *Common Language*
    - discuss complex solutions more easily by name.
  - *Archetypes*
    - Their trade-offs are well understood
    - New solutions can be *modelled after* them effectively

**Note:**
- As in literature, you *do not copy the archetype* directly.
What are design patterns?

- **Design patterns** are reusable solutions and metaphors for addressing problems.

- **They provide**
  - *Common Language*
    - discuss complex solutions more easily by name.
  - *Archetypes*
    - Their trade-offs are well understood
    - New solutions can be *modelled after* them effectively

**Note:**
- As in literature, you do not copy the archetype directly.
- Adapt it to your specific needs & trade offs.
What are design patterns?

- **Design patterns** are reusable solutions and metaphors for addressing problems

- They provide
  - *Common Language*
    - discuss complex solutions more easily by name.
  - *Archetypes*
    - Their trade-offs are well understood
    - New solutions can be *modelled after* them effectively

**Note:**
- As in literature, you do not copy the archetype directly.
- Adapt it to your specific needs & trade offs.
- **Why** a pattern exists is more important than just knowing that pattern
What are design patterns?

- **Design patterns** are reusable solutions and metaphors for addressing problems.

- They provide
  - *Common Language*
    - discuss complex solutions more easily by name.
  - *Archetypes*
    - Their trade-offs are well understood
    - New solutions can be *modelled after* them effectively.

**Note:**
- As in literature, you do not copy the archetype directly.
- Adapt it to your specific needs & trade-offs.
- **Why** a pattern exists is more important than just knowing that pattern!
What are design patterns?

- *Design patterns* are reusable solutions and metaphors for addressing problems.

- They provide
  - Common Language
    - discuss complex solutions more easily by name.
  - Archetypes
    - Their trade-offs are well understood
    - New solutions can be modelled after them effectively.

Note:
- As in literature, you do not copy the archetype directly.
- Adapt it to your specific needs & trade offs.
- **Why** a pattern exists is more important than just knowing that pattern.

Blind use of patterns is another reason why people dislike OOP.
Problem: Separate Caller & Callee

- What if we want to fully decouple actions to be taken from their call sites?
Problem: Separate Caller & Callee

- What if we want to fully decouple actions to be taken from their call sites?

```cpp
auto result = foo(x, y, z);
...
```

What are the forms of coupling that arise?
Problem: Separate Caller & Callee

- What if we want to fully decouple actions to be taken from their call sites?

```cpp
auto result = foo(x, y, z);
```

What are the forms of coupling that arise?
Problem: Separate Caller & Callee

- What if we want to fully decouple actions to be taken from their call sites?
  - Sometimes you must execute an action without any knowledge of what that action is.

```cpp
auto result = foo(x, y, z);
```

...
Problem: Separate Caller & Callee

• What if we want to fully decouple actions to be taken from their call sites?
  – Sometimes you must execute an action without any knowledge of what that action is.

Create some work.

Do the created work.
Problem: Separate Caller & Callee

- What if we want to fully decouple actions to be taken from their call sites?
  - Sometimes you must execute an action without any knowledge of what that action is.

Create some work.

Do the created work.

- What interface captures this?
Problem: Separate Caller & Callee

- What if we want to fully decouple actions to be taken from their call sites?
  - Sometimes you must execute an action without any knowledge of what that action is.

```cpp
auto result = foo(x, y, z);
```
Problem: Separate Caller & Callee

- What if we want to fully decouple actions to be taken from their call sites?
  - Sometimes you must execute an action without any knowledge of what that action is.

```c++
auto result = worker.doWork();
```
Problem: Separate Caller & Callee

- What if we want to fully decouple actions to be taken from their call sites?
  - Sometimes you must execute an action without any knowledge of what that action is.

```cpp
auto result = worker.doWork();
```

```cpp
class Work {
  // Information about work
  // ...
  Result doWork() { ... }  
};
```
Problem: Separate Caller & Callee

- What if we want to fully decouple actions to be taken from their call sites?
  - Sometimes you must execute an action without any knowledge of what that action is.

```cpp
auto result = worker.doWork();

class Work {
   // Information about work
   // ...
   Result doWork() { ... }
};

class OtherKindOfWork {
   Result doWork() { ... }
};
```
Problem: Separate Caller & Callee

- What if we want to fully decouple actions to be taken from their call sites?
  - Sometimes you must execute an action without any knowledge of what that action is.

```cpp
class WorkKind1 : public Work {
    Result doWork() override {...}
};

auto result = worker.doWork();

class Work {
    virtual Result doWork() = 0;
};

class WorkKind2 : public Work {
    Result doWork() override {...}
};
```
e.g. Behavioral Pattern: Command

class Command {
public:
    virtual void execute() = 0;
};
e.g. Behavioral Pattern: Command

- This is the *command pattern*

```cpp
class Command {
public:
    virtual void execute() = 0;
};
```
e.g. Behavioral Pattern: Command

- This is the *command pattern*
- It is nothing more than an object oriented callback

```cpp
class Command {
public:
    virtual void execute() = 0;
};
```
e.g. Behavioral Pattern: Command

- This is the *command pattern*
- It is nothing more than an object oriented callback

```cpp
class Command {
public:
    virtual void execute() = 0;
};
```

Why not just use a lambda?
The Command Pattern

- **Benefits**
  - Decouples a request / behavior from the invoker
The Command Pattern

**Benefits**
- Decouples a request / behavior from the invoker
- Invoker decides *when* to invoke without caring *what*
The Command Pattern

- **Benefits**
  - Decouples a request / behavior from the invoker
  - Invoker decides when to invoke without caring what
  - Parametrizable via constructor
The Command Pattern

- **Benefits**
  - Decouples a request / behavior from the invoker
  - Invoker decides when to invoke without caring what
  - Parametrizable via constructor

```cpp
auto result = foo(x, y, z);
...`
The Command Pattern

- Benefits
  - Decouples a request / behavior from the invoker
  - Invoker decides when to invoke without caring what
  - Parameterizable via constructor

```cpp
auto result = foo(x, y, z);
...

auto command = FooCommand(x, y, z);
...

command.execute();
```
The Command Pattern

- **Benefits**
  - Decouples a request / behavior from the invoker
  - Invoker decides when to invoke without caring what
  - Parameterizable via constructor
  - Sequences of commands can be easily batched
Problem: Add new behaviors to a set of types

- Different classes can perform the same action differently
Problem: Add new behaviors to a set of types

- Different classes can perform the same action differently
Problem: Add new behaviors to a set of types

- Different classes can perform the same action differently

```java
Manager manager;
manager.updatePay();

Underling underling;
underling.updatePay();
```
**Problem:** Add new behaviors to a set of types

- Different classes can perform the same action differently
- Sometimes you want to add a *new kind of action* to a set of related classes
**Problem:** Add new behaviors to a set of types

- Different classes can perform the same action differently
- Sometimes you want to add a *new kind of action* to a set of related classes

```java
Manager manager;
manager.serialize();

Underling underling;
underling.serialize();
```
Problem: Add new behaviors to a set of types

- Different classes can perform the same action differently
- Sometimes you want to add a new kind of action to a set of related classes
- There may be many different types of actions to add
Problem: Add new behaviors to a set of types

- Different classes can perform the same action differently
- Sometimes you want to add a new kind of action to a set of related classes
- There may be many different types of actions to add

Operations for Employees

updatePay
**Problem:** Add new behaviors to a set of types

- Different classes can perform the same action differently
- Sometimes you want to add a *new kind of action* to a set of related classes
- There may be many different types of actions to add

**Operations for Employees**

- `updatePay`
- `serialize`
Problem: Add new behaviors to a set of types

- Different classes can perform the same action differently
- Sometimes you want to add a *new kind of action* to a set of related classes
- There may be many different types of actions to add

Operations for Employees

- `updatePay`
- `serialize`
- `printPerformanceReview`
Problem: Add new behaviors to a set of types

- Different classes can perform the same action differently
- Sometimes you want to add a new kind of action to a set of related classes
- There may be many different types of actions to add

Operations for Employees

```
updatePay
serialize
printPerformanceReview
...```

Problem: Add new behaviors to a set of types

- Different classes can perform the same action differently
- Sometimes you want to add a new kind of action to a set of related classes
- There may be many different types of actions to add
- Sometimes, you can't even know all of the actions in advance!
Problem: Add new behaviors to a set of types

- Different classes can perform the same action differently
- Sometimes you want to add a *new kind of action* to a set of related classes
- There may be many different types of actions to add
- Sometimes, you can't even know all of the actions in advance!

Why are these problems?
Problem: Add new behaviors to a set of types

- Let us take a look at our Employee base class...

class Employee {
public:
    ...
    virtual void updatePay() = 0;
    virtual void performJob() = 0;
    virtual void serialize() = 0;
    virtual void displayAvatar() = 0;
    virtual void printPerformanceReview() = 0;
    virtual void findFavoriteOfficeMate() = 0;
    virtual void procrastinate() = 0;
};
Problem: Add new behaviors to a set of types

- Let us take a look at our Employee base class...

```cpp
class Employee {
public:
    ... 
    virtual void updatePay() = 0;
    virtual void performJob() = 0;
    virtual void serialize() = 0;
    virtual void displayAvatar() = 0;
    virtual void printPerformanceReview() = 0;
    virtual void findFavoriteOfficeMate() = 0;
    virtual void procrastinate() = 0;
};
```

Why does this feel so wrong?
Problem: Add new behaviors to a set of types

- Let us take a look at our `Employee` base class...

```cpp
class Employee {
public:
    ...
    virtual void updatePay() = 0;
    virtual void performJob() = 0;
    virtual void serialize() = 0;
    virtual void displayAvatar() = 0;
    virtual void printPerformanceReview() = 0;
    virtual void findFavoriteOfficeMate() = 0;
    virtual void procrastinate() = 0;
};
```

Why does this feel so wrong?
Solutions

- We need to find a better way
  - What are the tools at our disposal?
Solutions

- We need to find a better way
  - What are the tools at our disposal?
    - Classes
    - Polymorphism
Solutions

• We need to find a better way

  – What are the tools at our disposal?
    • Classes
    • Polymorphism

  – How can we use them to attack the problem?
Solutions

- We need to find a better way
  - What are the tools at our disposal?
    - Classes
    - Polymorphism
  - How can we use them to attack the problem?
    - Group related behaviors into classes
    - Invoke them when desired
Grouping Related Behavior

- How should we group related behaviors?

What does SRP dictate?
Grouping Related Behavior

- How should we group related behaviors?
  - Each offending method becomes a new class
Grouping Related Behavior

- How should we group related behaviors?
  - Each offending method becomes a new class

```cpp
class EmployeeSerializer {
    public:
        void serialize(Manager &manager);
        void serialize(Underling &underling);
};

class PerformanceReviewPrinter {
    public:
        void printReview(Manager &manager);
        void printReview(Underling &underling);
};
```
How Do We Invoke It?
How Do We Invoke It?

EmployeeSerializer serializer;
std::vector<Employee*> employees;

for (auto *employee : employees) {
    serializer.serialize(*employee);
}
How Do We Invoke It?

EmployeeSerializer serializer;
std::vector<Employee*> employees;

for (auto *employee : employees) {
    serializer.serialize(*employee);
}
EmployeeSerializer serializer;
std::vector<Employee*> employees;

for (auto *employee : employees) {
    serializer.serialize(*employee);
}
EmployeeSerializer serializer;
std::vector<Employee*> employees;

for (auto *employee : employees)
    serializer.serialize(*employee);

How Do We Invoke It?

No!

What is the core problem?
How Do We Invoke It?

- Problem:
  - We want to call a method based on *multiple dynamic types*

    ```java
    serializer.serialize(*employee);
    ```
How Do We Invoke It?

- **Problem:**
  - We want to call a method based on multiple dynamic types

```java
serializer.serialize(*employee);
```

`EmployeeSerializer`
How Do We Invoke It?

- Problem:
  - We want to call a method based on multiple dynamic types

```java
serializer.serialize(employee);
```

EmployeeSerializer Manager/Underling
How Do We Invoke It?

- **Problem:**
  - We want to call a method based on multiple dynamic types
  - *Multiple Dispatch* (or double dispatch in this case)

```java
employee.serialize("employee");
```
How Do We Invoke It?

- **Problem:**
  - We want to call a method based on multiple dynamic types
  - *Multiple Dispatch* (or double dispatch in this case)

```java
serializer.serialize(employee);
```

But we only know that `employee` is an `Employee*`
How Do We Invoke It?

- **Problem:**
  - We want to call a method based on multiple dynamic types
  - *Multiple Dispatch* (or double dispatch in this case)

```java
serializer.serialize(*employee);
```

But we only know that `employee` is an `Employee*`

```java
for (auto* employee : employees) {
    serializer.serialize(*employee);
}
```
How Do We Invoke It?

- **Problem:**
  - We want to call a method based on multiple dynamic types
  - *Multiple Dispatch* (or double dispatch in this case)

```java
serializer.serialize(employee);
```

EmployeeSerializer        Manager/Underling

But we only know that `employee` is an `Employee`

How can we resolve the issue?
How Do We Invoke It?

- **Problem:**
  - We want to call a method based on multiple dynamic types
  - *Multiple Dispatch* (or double dispatch in this case)

  ```java
  serializer.serialize(*employee);
  ```

- **Solution:**
  - The Visitor Pattern
Abstract away the added behaviors:

class EmployeeSerializer : public Visitor {
public:
    void visit(Manager &manager) override;
    void visit(Underling &underling) override;
};
Change the original classes:

```cpp
class Employee {
public:
    virtual void accept(Visitor &v) = 0;
};
class Manager : public Employee {
    ...
    void accept(Visitor &v) override {
        v.visit(*this);
    }
};
```
The Visitor Pattern

Change the original classes:

```cpp
class Employee {
public:
    virtual void accept(Visitor &v) = 0;
};
class Manager : public Employee {
    ...
    void accept(Visitor &v) override {
        v.visit(*this);
    }
};
The dynamic type of Employee is known!
Calls visit(Manager &manager) here.
```
The Visitor Pattern

Use the new behaviors through their classes:

```cpp
EmployeeSerializer serializer;
PerformanceReviewPrinter reviewer;
std::deque<Employee*> employees;

for (auto *employee : employees) {
    employee->accept(serializer);
    employee->accept(reviewer);
}
```
The Visitor Pattern

Use the new behaviors through their classes:

```cpp
EmployeeSerializer serializer;
PerformanceReviewPrinter reviewer;
std::deque<Employee*> employees;

for (auto *employee : employees) {
    employee->accept(serializer);
    employee->accept(reviewer);
}
```

What if we want a return value?
The Visitor Pattern

- A behavioral pattern
The Visitor Pattern

- A behavioral pattern
- Useful for adding new behaviors to a collection of related classes
The Visitor Pattern

- A behavioral pattern
- Useful for adding new behaviors to a collection of related classes
  - *It also keeps those behaviors isolated!*
The Visitor Pattern

- A behavioral pattern
- Useful for adding new behaviors to a collection of related classes
  - *It also keeps those behaviors isolated!*
  - Useful for designing APIs open to extension
The Visitor Pattern

- A behavioral pattern
- Useful for adding new behaviors to a collection of related classes
- **But what are the downsides?**
  - Can we overcome them?
Designing Design Patterns

- Instead of memorizing them, you should be able to create them
Summary

- Careful software design focuses responsibilities & makes changes easier
Summary

- Careful software design focuses responsibilities & makes changes easier
- Polymorphism & composition help provide clear abstractions