Script **generated by TTT**

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TECHNISCHE UNIVERSITÄT MÜNCHEN
FAKULTÄT FÜR INFORMATIK

Programming Languages

Multiple Inheritance

Dr. Michael Petter
Winter term 2014

Outline

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“Wouldn’t it be nice to inherit from several parents?”

Interface vs. Implementation inheritance

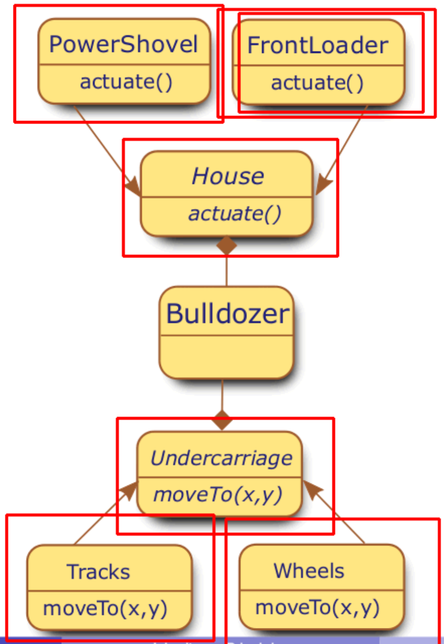
The classic motivation for inheritance is implementation inheritance

- *Code reusage*
- Child specializes parents, replacing particular methods with custom ones
- Parent acts as library of common behaviours
- Implemented in languages like C++ or Lisp

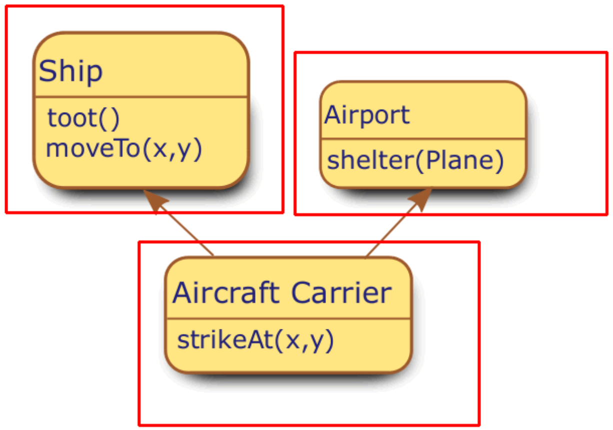
Code sharing in interface inheritance inverts this relation

- *Behaviour contract*
- Child provides methods, with signatures predetermined by the parent
- Parent acts as generic code frame with room for customization
- Implemented in languages like Java or C#

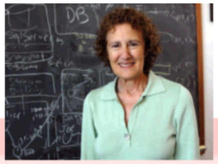
Interface Inheritance



Implementation inheritance



Excursion: LSP and Square-Rect-Problem



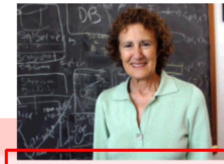
The Liskov Substitution Principle

Functions that use pointers or references to base classes must be able to use objects of derived classes without knowing it.

```
class Rectangle {
  void setWidth (int w){ this.w=w; }
  void setHeight(int h){ this.h=h; }
  void getWidth ()      { return w; }
  void getHeight()      { return h; }
}
class Square extends Rectangle {
  void setWidth (int w){ this.w=w;h=w; }
  void setHeight(int h){ this.h=h;w=h; }
}
```

```
Rectangle r =
        new Square(2);
r.setWidth(3);
r.setHeight(4);
assert r.getHeight()*
        r.getWidth()==12;
```


Excursion: LSP and Square-Rect-Problem



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```
class Rectangle {
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class Square extends Rectangle {
  void setWidth (int w){ this.w=w;h=w; }
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}
```

```
Rectangle r =
        new Square(2);
r.setWidth(3);
r.setHeight(4);
assert r.getHeight()*
        r.getWidth()==12;
```


⚠ Behavioural assumptions

“So how do we lay out objects in heap anyway?”

Excursion: Brief introduction to LLVM IR

Low Level Virtual Machine as reference semantics:

```
;(recursive) struct definitions
%struct.A = type { i32, %struct.B, i32(i32)* }
%struct.B = type { i64, [10 x [20 x i32]], i8 }

;allocation of objects
%a = alloca %struct.A
;adress computation for selection in structure (pointers):
%1 = getelementptr %struct.A* %a, i64 0, i64 2
;load from memory
%2 = load i32(i32)* %1
;indirect call
%retval = call i32 (i32)* %2(i32 42)
```

Retrieve the memory layout of a compilation unit with:

```
clang -cc1 -x c++ -v -fdump-record-layouts -emit-llvm source.cpp
```

Retrieve the IR Code of a compilation unit with:

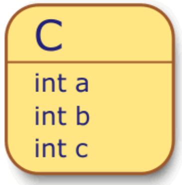
```
clang -O1 -S -emit-llvm source.cpp -o IR.llvm
```

Object layout

```
class A {
  int a; int f(int);
};
class B : public A {
  int b; int g(int);
};
class C : public B {
  int c; int h(int);
};

...

C c;
c.g(42);
```

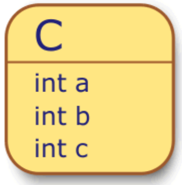



```
%class.C = type { %class.B, i32 }
%class.B = type { %class.A, i32 }
%class.A = type { i32 }
```

```
%c = alloca %class.C
%1 = bitcast %class.C* %c to %class.B*
%2 = call i32 @_g(%class.B* %1, i32 42) ; g is statically known
```


Translation of a method body

```
class A {
  int a; int f(int);
};
class B : public A {
  int b; int g(int);
};
class C : public B {
  int c; int h(int);
};
int B::g(int p) {
  return p+b;
};
```




```
%class.C = type { %class.B, i32 }
%class.B = type { %class.A, i32 }
%class.A = type { i32 }
```

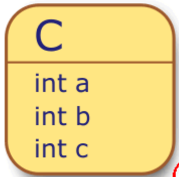
```
define i32 @_g(%class.B* %this, i32 %p) {
  %1 = getelementptr %class.B* %this, i64 0, i32 1
  %2 = load i32* %1
  %3 = add i32 %2, %p
  ret i32 %3
}
```


Object layout

```
class A {
  int a; int f(int);
};
class B : public A {
  int b; int g(int);
};
class C : public B {
  int c; int h(int);
};

...

C c;
c.g(42);
```




```
%class.C = type { %class.B, i32 }
%class.B = type { %class.A, i32 }
%class.A = type { i32 }
```

```
%c = alloca %class.C
%1 = bitcast %class.C* %c to %class.B*
%2 = call i32 @_g(%class.B* %1, i32 42) ; g is statically known
```

Multiple Inheritance | Standard Object Heap Layout | Object layout & inheritance 10 / 44

Translation of a method body

```
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  int a; int f(int);
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class B : public A {
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};
class C : public B {
  int c; int h(int);
};
int B::g(int p) {
  return p+b;
};
```
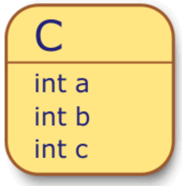



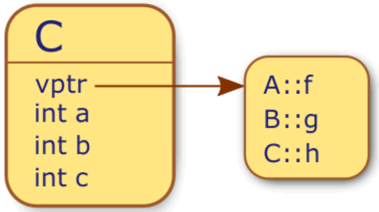

```
%class.C = type { %class.B, i32 }
%class.B = type { %class.A, i32 }
%class.A = type { i32 }
```

```
define i32 @_g(%class.B* %this, i32 %p) {
  %1 = getelementptr %class.B* %this, i64 0, i32 1
  %2 = load i32* %1
  %3 = add i32 %2, %p
  ret i32 %3
}
```

Multiple Inheritance | Standard Object Heap Layout | Object layout & inheritance 11 / 44

Object layout – virtual methods

```
class A {
  int a; virtual int f(int);
         virtual int g(int);
         virtual int h(int);
};
class B : public A {
  int b; int g(int);
};
class C : public B {
  int c; int h(int);
};
...
C c;
c.g(42);
```

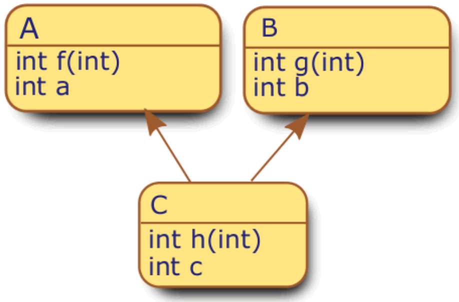



```
%class.C = type { %class.B, i32, [4 x i8] }
%class.B = type { [12 x i8], i32 }
%class.A = type { i32 (...)**, i32 }
```

```
%c.vptr = bitcast %class.C* %c to i32 (%class.B*, i32)*** ; vtbl
%1 = load (%class.B*, i32)*** %c.vptr    ; dereference vptr
%2 = getelementptr %1, i64 1             ; select g()-entry
%3 = load (%class.B*, i32)** %2          ; dereference g()-entry
%4 = call i32 %3(%class.B* %c, i32 42)
```

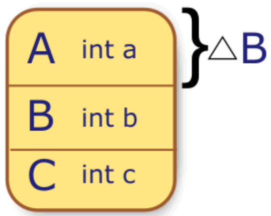

"So how do we include several parent objects?"

Multiple inheritance class diagram



Multiple Base Classes

```
class A {
  int a; int f(int);
};
class B {
  int b; int g(int);
};
class C : public A , public B {
  int c; int h(int);
};
...
C c;
c.g(42);
```

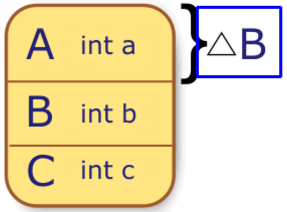



```
%class.C = type { %class.A, %class.B, i32 }
%class.A = type { i32 }
%class.B = type { i32 }
```

```
%c = alloca %class.C
%1 = bitcast %class.C* %c to i8*
%2 = getelementptr i8* %1, i64 4           ; select B-offset in C
%3 = call i32 @_g(%class.B* %2, i32 42) ; g is statically known
```

Multiple Base Classes

```
class A {
  int a; int f(int);
};
class B {
  int b; int g(int);
};
class C : public A , public B {
  int c; int h(int);
};
...
C c;
c.g(42);
```



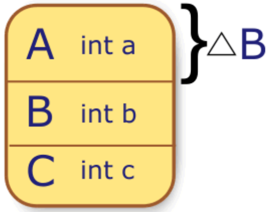

```
%class.C = type { %class.A, %class.B, i32 }
%class.A = type { i32 }
%class.B = type { i32 }
```

```
%c = alloca %class.C
%1 = bitcast %class.C* %c to i8*
%2 = getelementptr i8* %1, i64 4         ; select B-offset in C
%3 = call i32 @_g(%class.B* %2, i32 42)  ; g is statically known
```

⚠ `getelementptr` implements ΔB as $4 \cdot i8$!

Static Type Casts

```
class A {
  int a; int f(int);
};
class B {
  int b; int g(int);
};
class C : public A , public B {
  int c; int h(int);
};
...
B* b = new C();
```




```
%class.C = type { %class.A, %class.B, i32 }
%class.A = type { i32 }
%class.B = type { i32 }
```

```
%1 = call i8* @_new(i64 12)
call void @_memset.p0i8.i64(i8* %1, i8 0, i64 12, i32 4, i1 false)
%2 = getelementptr i8* %1, i64 4
%b = bitcast i8* %2 to %class.B*
```


Ambiguities

```
class A { void f(int); };
class B { void f(int); };
class C : public A, public B {};

C* pc;
pc->f(42);
```

⚠ Which method is called?

Solution I: Explicit qualification

```
pc->A::f(42);
pc->B::f(42);
```

Solution II: Automagical resolution
Idea: The Compiler introduces a linear order on the nodes of the inheritance graph

Linearization

Principle 1: Inheritance Relation
Defined by parent-child. Example:
$C(A, B) \implies C \to A \wedge C \to B$

Principle 2: Multiplicity Relation
Defined by the succession of multiple parents. Example:
$C(A, B) \implies A \to B$

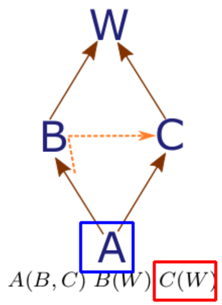
In General:

1. Inheritance is a uniform mechanism, and its searches ($\to$ total order) apply identically for all object fields or methods
2. In the literature, we also find the set of constraints to create a linearization as Method Resolution Order
3. Linearization is a best-effort approach at best

MRO via DFS

Leftmost Preorder Depth-First Search

A B W C



MRO via DFS

Leftmost Preorder Depth-First Search

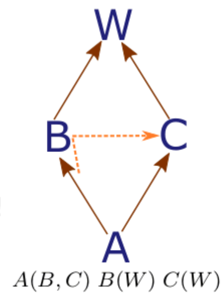
L[A] = A B W C

⚠ Principle 1 *inheritance* is violated

Python: classical python objects ($\leq$ 2.1) use LPDFS!

LPDFS with Duplicate Cancellation

A B ~~W~~ C W



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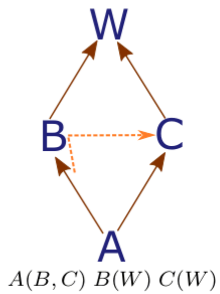
LPDFS with Duplicate Cancellation

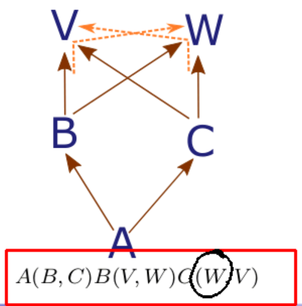
L[A] = A B C W

✓ Principle 1 *inheritance* is fixed

LPDFS with Duplicate Cancellation

A B ~~W V~~ C W V





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LPDFS with Duplicate Cancellation

L[A] = A B C W

✓ Principle 1 *inheritance* is fixed

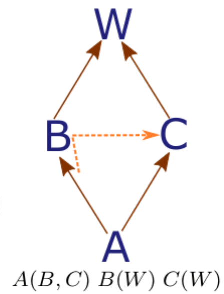
Python: new python objects (2.2) use LPDFS(DC)!

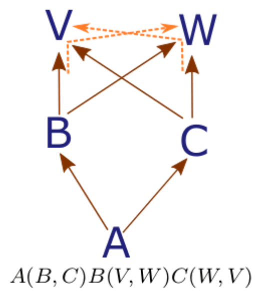
LPDFS with Duplicate Cancellation

L[A] = A B C W V

⚠ Principle 2 *multiplicity* not fullfillable

⚠ However $B \rightarrow C \implies W \rightarrow V$??

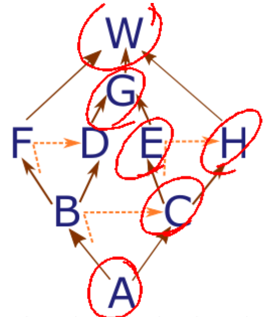




MRO via Refined Postorder DFS

Reverse Postorder Rightmost DFS

E G H W



$A(B,C)$ $B(F,D)$ $C(E,H)$
$D(G)$ $E(G)$ $F(W)$ $G(W)$ $H(W)$

MRO via Refined Postorder DFS

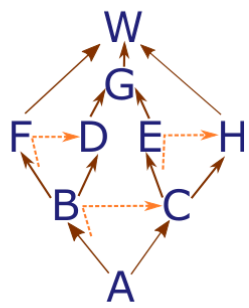
Reverse Postorder Rightmost DFS

L[A] = A B F D C E G H W

✓ Linear extension of inheritance relation

⇝ Topological sorting

RPRDFS



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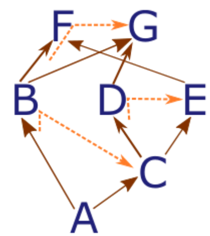

$A(B,C)$ $B(F,G)$ $C(D,E)$
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Reverse Postorder Rightmost DFS

L[A] = A B F D C E G H W

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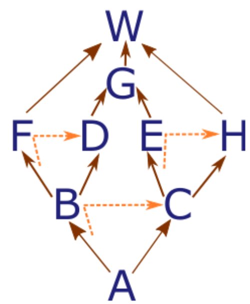
L[A] = A B C D G E F

⚠ But principle 2 *multiplicity* is violated!



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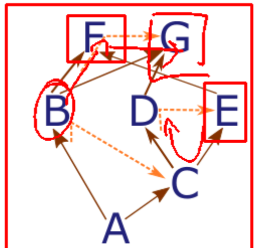

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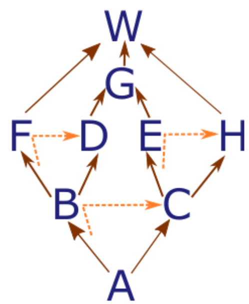

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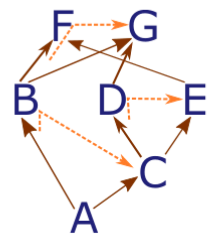

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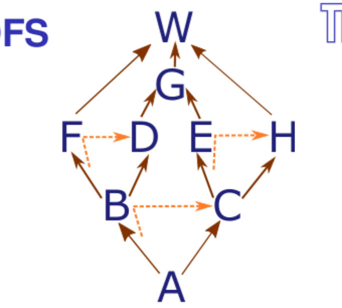
Refined RPRDFS



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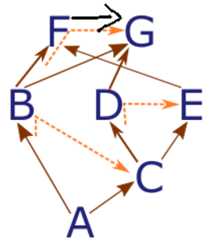

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MRO via Refined Postorder DFS

Reverse Postorder Rightmost DFS

L[A] = A B F D C E G H W

✓ Linear extension of inheritance relation

⇝ Topological sorting

RPRDFS

L[A] = A B C D G E F

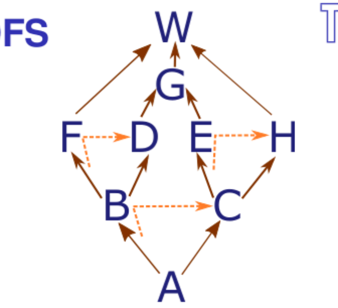
⚠ But principle 2 *multiplicity* is violated!

CLOS: uses Refined RPDFS [3]

Refined RPRDFS

L[A] = A B C D E F G

✓ Refine graph with conflict edge & rerun RPRDFS!



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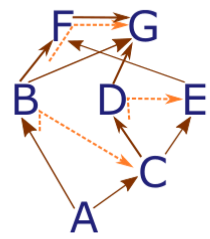
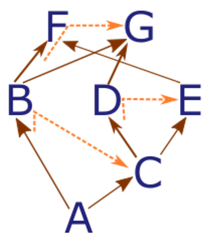


$A(B,C)$ $B(F,G)$ $C(D,E)$
$D(G)$ $E(F)$

MRO via Refined Postorder DFS

Extension Principle: Monotonicity

If $C_1 \to C_2$ in C's linearization, then $C_1 \to C_2$ for every linearization of C's children.



$A(B,C)$ $B(F,G)$ $C(D,E)$
$D(G)$ $E(F)$

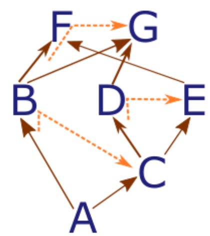
MRO via Refined Postorder DFS

Refined RPRDFS

⚠ *Monotonicity* is not guaranteed!

Extension Principle: Monotonicity

If $C_1 \to C_2$ in C's linearization, then $C_1 \to C_2$ for every linearization of C's children.



$A(B,C)$ $B(F,G)$ $C(D,E)$
$D(G)$ $E(F)$

MRO via Refined Postorder DFS

Refined RPRDFS

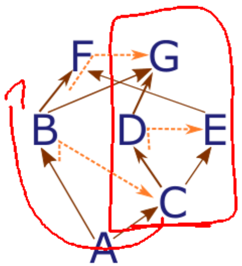
⚠ *Monotonicity* is not guaranteed!

Extension Principle: Monotonicity

If $C_1 \rightarrow C_2$ in C's linearization, then $C_1 \rightarrow C_2$ for every linearization of C's children.

$$L[A] = A\ B\ C\ D\ E\ F\ G \quad \Longrightarrow \quad \boxed{F \rightarrow G}$$

$$\boxed{L[C] = \boxed{D\ G\ E\ F}} \quad \Longrightarrow \quad G \rightarrow F$$



$A(B,C)\ B(F,G)\ C(D,E)$
$D(G)\ E(F)$

MRO via C3 Linearization

A linearization L is an attribute $L[C]$ of a class C. Classes $B_1 \dots B_n$ are superclasses to child class C, defined in the *local precedence order* $C(B_1 \dots B_n)$. Then

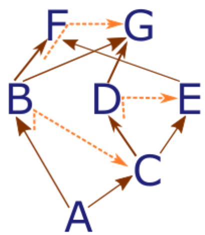
$$L[C(B_1 \dots B_n)] = C \cdot \bigsqcup(L[B_1] \dots L[B_n], B_1 \dots B_n)$$
$$L[Object] = Object$$

with

$$\bigsqcup(L_i) = \begin{cases} c \cdot (tail(L_k) \sqcup \bigsqcup_{j \neq k}(L_j \setminus c)) & \text{if } \exists_{\text{min } k}\ c = head(L_k) \notin tail(L_j) \\ ⚠ \text{ fail} & \text{else} \end{cases}$$

MRO via C3 Linearization

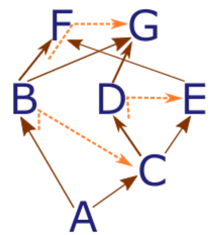
$L[G]$ G
$L[F]$ F
$L[E(F)]$
$L[D(G)]$
$L[B(F,G)]$
$L[C(D,E)]$
$L[A(B,C)]$



$A(B,C)\ B(F,G)\ C(D,E)$
$D(G)\ E(F)$

MRO via C3 Linearization

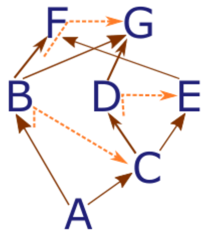
$L[G]$ G
$L[F]$ F
$L[E(F)]$ $E\ F$
$L[D(G)]$ $D\ G$
$L[B(F,G)]$
$L[C(D,E)]$
$L[A(B,C)]$



$A(B,C)\ B(F,G)\ C(D,E)$
$D(G)\ E(F)$

MRO via C3 Linearization

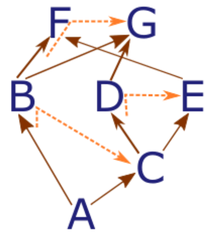
$L[G]$	G
$L[F]$	F
$L[E(F)]$	$E\ F$
$L[D(G)]$	$D\ G$
$L[B(F,G)]$	$B \cdot (L[F] \sqcup L[G] \sqcup \{F,G\})$
$L[C(D,E)]$	
$L[A(B,C)]$	



$A(B,C)\ B(F,G)\ C(D,E)\ D(G)\ E(F)$

MRO via C3 Linearization

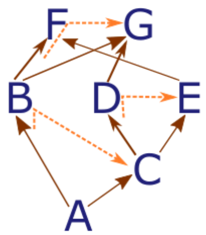
$L[G]$	G
$L[F]$	F
$L[E(F)]$	$E\ F$
$L[D(G)]$	$D\ G$
$L[B(F,G)]$	$B \cdot (\{F\} \sqcup \{G\} \sqcup \{F,G\})$
$L[C(D,E)]$	
$L[A(B,C)]$	



$A(B,C)\ B(F,G)\ C(D,E)\ D(G)\ E(F)$

MRO via C3 Linearization

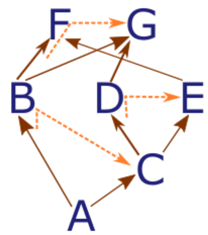
$L[G]$	G
$L[F]$	F
$L[E(F)]$	$E\ F$
$L[D(G)]$	$D\ G$
$L[B(F,G)]$	$B\ F\ G$
$L[C(D,E)]$	$C \cdot (\{D,G\} \sqcup \{E,F\} \sqcup \{D,E\})$
$L[A(B,C)]$	



$A(B,C)\ B(F,G)\ C(D,E)\ D(G)\ E(F)$

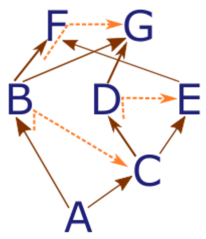
MRO via C3 Linearization

$L[G]$	G
$L[F]$	F
$L[E(F)]$	$E\ F$
$L[D(G)]$	$D\ G$
$L[B(F,G)]$	$B\ F\ G$
$L[C(D,E)]$	$C \cdot D \cdot (\{G\} \sqcup \{E,F\} \sqcup \{E\})$
$L[A(B,C)]$	



$A(B,C)\ B(F,G)\ C(D,E)\ D(G)\ E(F)$

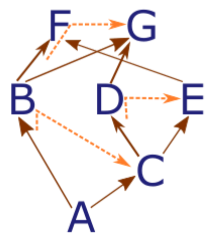
MRO via C3 Linearization



$A(B,C)\ B(F,G)\ C(D,E)$
$D(G)\ E(F)$

$L[G]$	G
$L[F]$	F
$L[E(F)]$	$E\ F$
$L[D(G)]$	$D\ G$
$L[B(F,G)]$	$B\ F\ G$
$L[C(D,E)]$	$C\ D\ G\ E\ F$
$L[A(B,C)]$	$A \cdot (\{B,F,G\} \sqcup \{C,D,G,E,F\} \sqcup \{B,C\})$

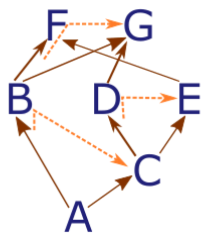
MRO via C3 Linearization



$A(B,C)\ B(F,G)\ C(D,E)$
$D(G)\ E(F)$

$L[G]$	G
$L[F]$	F
$L[E(F)]$	$E\ F$
$L[D(G)]$	$D\ G$
$L[B(F,G)]$	$B\ F\ G$
$L[C(D,E)]$	$C\ D\ G\ E\ F$
$L[A(B,C)]$	$A \cdot B \cdot C \cdot D \cdot (\{F,G\} \sqcup \{G,E,F\})$

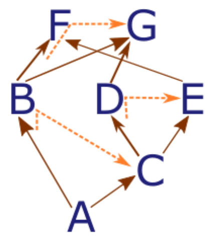
MRO via C3 Linearization



$A(B,C)\ B(F,G)\ C(D,E)$
$D(G)\ E(F)$

$L[G]$	G
$L[F]$	F
$L[E(F)]$	$E\ F$
$L[D(G)]$	$D\ G$
$L[B(F,G)]$	$B\ F\ G$
$L[C(D,E)]$	$C\ D\ G\ E\ F$
$L[A(B,C)]$	⚠ fail

MRO via C3 Linearization



$A(B,C)\ B(F,G)\ C(D,E)$
$D(G)\ E(F)$

$L[G]$	G
$L[F]$	F
$L[E(F)]$	$E\ F$
$L[D(G)]$	$D\ G$
$L[B(F,G)]$	$B\ F\ G$
$L[C(D,E)]$	$C\ D\ G\ E\ F$
$L[A(B,C)]$	⚠ fail

C3 detects and reports a violation of *monotonicity* with the addition of A(B,C) to the class set.
C3 linearization [1]: is used in OpenDylan, Python, and Perl 6

Linearization vs. explicit qualification

Linearization

- No switch/duplexer code necessary
- No explicit naming of qualifiers
- Unique `super` reference
- Reduces number of multi-dispatching conflicts

Qualification

- More flexible, fine-grained
- Linearization choices may be awkward or unexpected

Languages with automatic linearization exist

- *CLOS* Common Lisp Object System
- *Dylan, Python* and *Perl 6* with C3
- Prerequisite for → Mixins

"And what about dynamic dispatching in Multiple Inheritance?"