Foundations of Context-Oriented Programming or Typing Dynamic Layer Composition

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joint work with

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Context-Oriented Programming (COP) Language [Costanza, Hirshfeld DLS05] [Hirschfeld, Costanza, Nierstrasz JOT08]

Goal:

Support for *behavioral variations* depending on the *dynamic* context of execution

Example: Mobile email app

When network is fast
inline images are shown

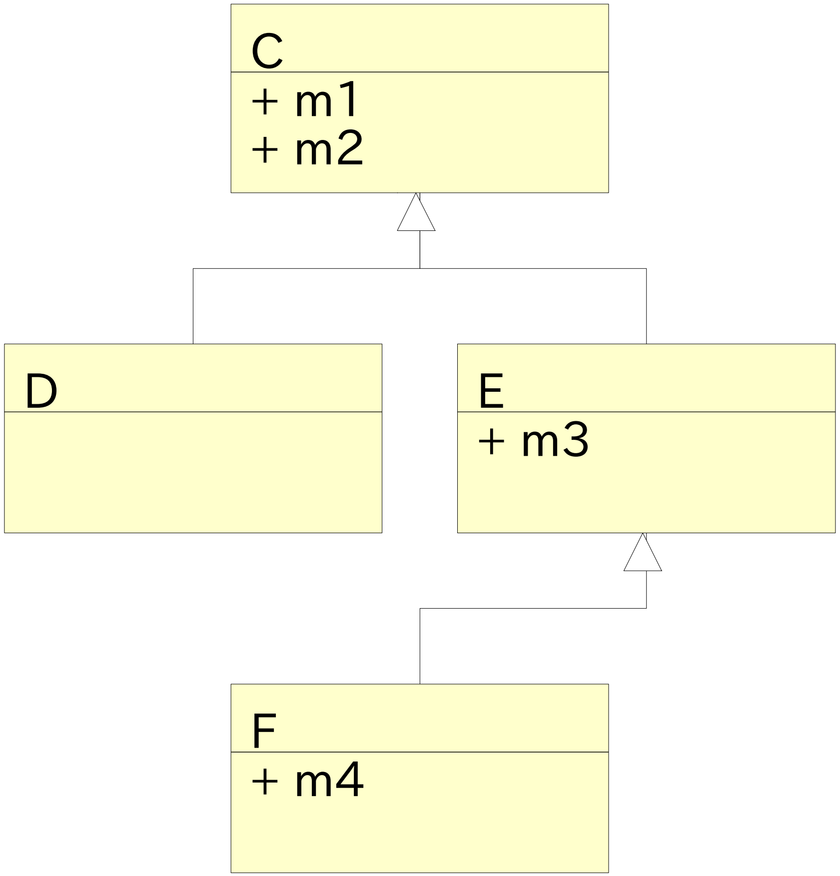
When network is slow
no images are shown

Common COP language features

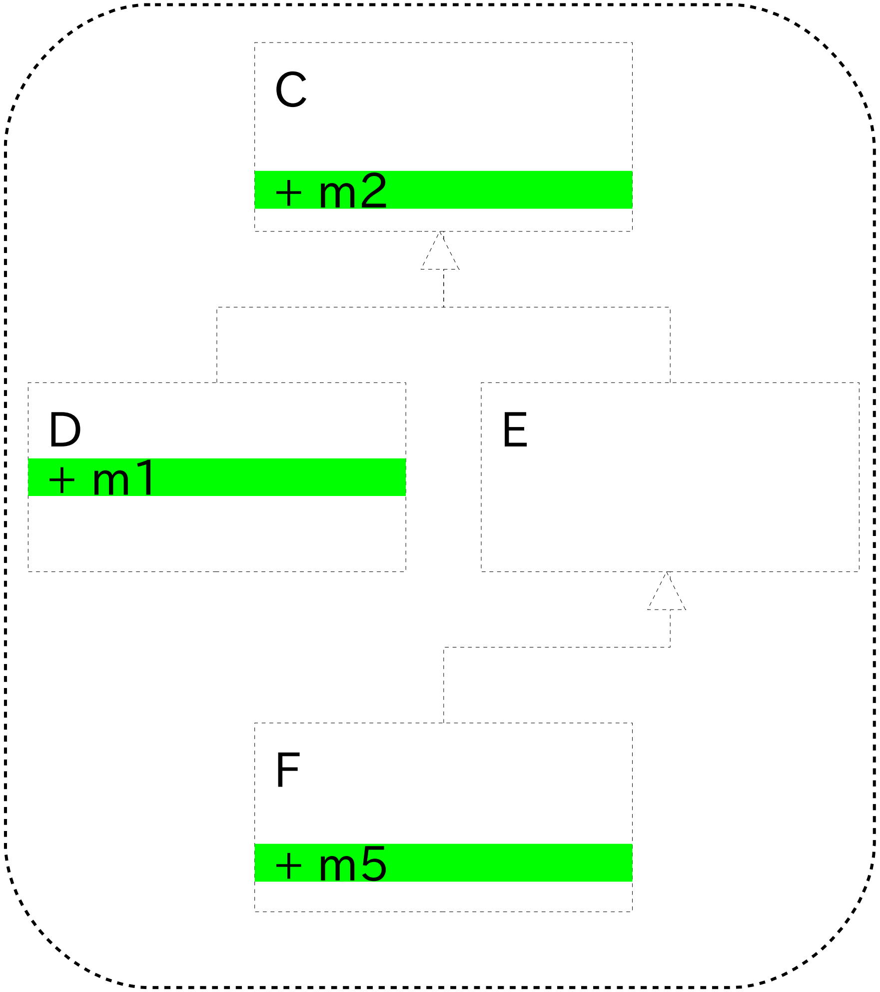
- Layer
  - A unit of behavioral variations, consisting of *partial* method definitions for multiple classes
  - (Loose) correspondence to contexts
  - A unit of cross-cutting modularity
- Dynamic layer activation
  - To change the behavior of a set of objects at the same time

Dynamic Layer Activation in COP

Base class hiearchy



Layer of partial methods



Dynamic Layer Activation in COP

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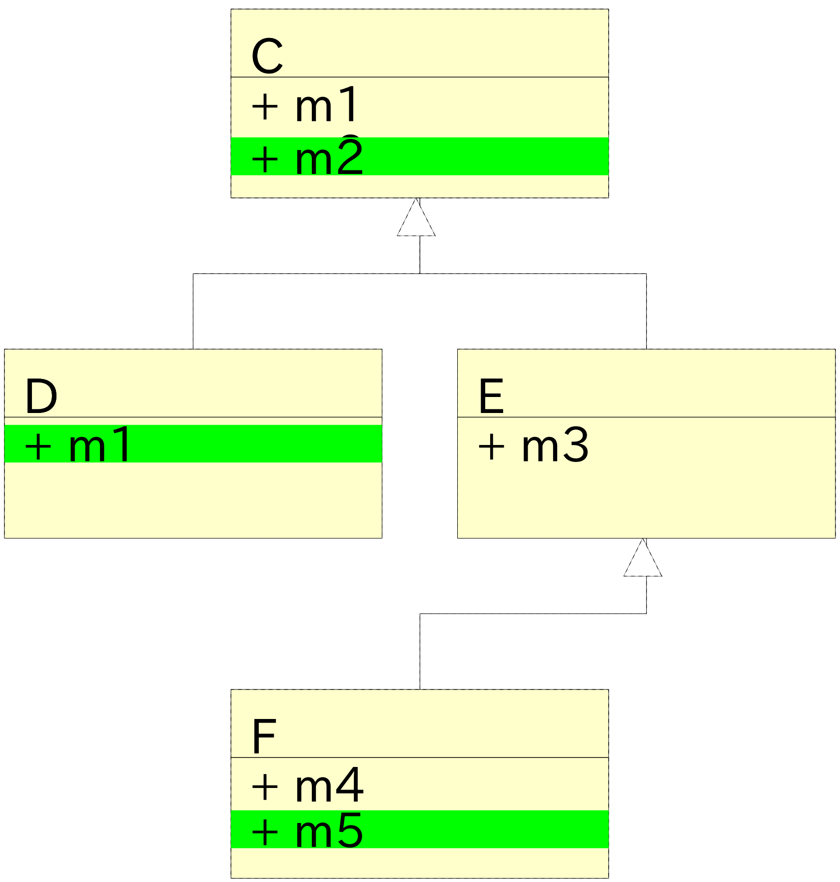

Layer of partial methods

- Layer activation changes behavior of objects *that have been already instantiated*
- Partial methods can call the original behavior by **`proceed()`**

This Talk

- Quick tour on JCop [Appeltauer+], a specific implementation of COP on top of Java
  - With a more concrete example
  - (Comparison with AOP using pointcut/advice)
- Foundations for COPL
  - (Operational) Semantics
  - Type System

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Example: Telecom simulation
(adapted from AOP example)

- Class `Conn` to represent connection between two `Customers`
  - `complete()` when a connection has been established
  - `drop()` when the customers are disconnected
- Behavioral variations to consider
  - Recording the lengths of conversations
  - Billing

Base Program

```
class Conn { // Connection
  Conn(Customer a, Customer b) { … }
  void complete() { … }
  void drop() { … }
    // details are not important ...
}
```

```
Conn simulate() {
  Customer robert = …, hidehiko = …;
  Conn c = new Conn(robert, hidehiko);
                     // Robert calls Hidehiko
  c.complete();      // Hidehiko accepts
  c.drop();          // and hangs up
  return c;
}
```

Layer for Measuring Time

```
layer Timing {
  Timer timer = …;
  void Conn.complete(){ proceed(); timer.start();}
  void Conn.drop(){ timer.stop(); proceed(); }
  int Conn.getTime() { return timer.getTime(); }
}
```

- The two methods in `Conn` are modified by *partial* method definitions to operate the timer
  - The original behavior is represented by **`proceed()`**
- **`getTime()`** is newly introduced
  - but also called "partial" method

Layer Activation with `with`

```
with (new Timing()) {  // layer activation!
   Conn c = simulate();
   System.out.println(c.getTime());
}
```

- **`with`** block to activate a layer
- Activation is effective even in methods invoked inside the block
- A layer *instance* has to be created
  - Layer instances are also first-class objects

Layer for Billing

```
layer Billing {
  void Conn.drop() { proceed(); charge(); }
  void Conn.charge() { … getTime(); … }
}
```

```
with (new Timing()) {
  with (new Billing()) {
    Connection c = simulate();
} }
```

- Recently activated layer has priority
  - **drop()** will stop the timer, hang the call, and charge

Not in this example, but...

- One layer can contain partial methods belonging to different classes
  - c.f. Mixin layers [Smaragdakis&Batory 98]
- **`super()`** is also supported
- Layer inheritance/subtyping

Layer Inheritance/Subtyping

- Implementation of different billing policies, switched by run-time conditions

```
abstract layer AbsBilling {
  void Conn.drop();
  void Conn.charge();
}
layer Billing1 extends AbsBilling { … }
layer Billing2 extends AbsBilling { … }
```

```
AbsBilling b =
  some_cond ? new Billing1():new Billing2();

with(b) { … }
```

Very rough Comparison with PA-style AOP

	COP	AOP
Unit of behavior	partial meth.	advice
Oblivious?	No	Yes
Join points	Meth. exec.	Many kinds
Pointcut	cflow + execution	Many kinds

Some Foundational Questions

- What is the semantics of method invocations?
  - What happens when the same layer is activated more than once?
  - How do `proceed`, `super`, and `with` interact with each other?
- How can types prevent `NoSuchMethodError`?
  - Object interface can change dynamically!
  - Only overriding partial methods can `proceed`

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  - With a more concrete example
- Foundations for COPL
  - (Operational) Semantics
  - Type System

A core calculus of COP: ContextFJ

[Hirschfeld, I., Masuhara FOAL11]

ContextFJ = Featherweight Java [I.,Pierce,Wadler'99]

+ partial methods

+ proceed(), super()

+ with expressions

- layers are global and second-class

- no layer inheritance

ContextFJ<:

[I., Inoue APLAS'15]

ContextFJ<: = Featherweight Java

+ partial methods
+ proceed(), super()
+ with expressions

+ first-class layers (w/o fields)

+ layer inheritance

+ layer subtyping

Syntax (1/2)

"~" for sequences

$T ::= C \mid L$	*types*
$CL ::=$ class $C < D$ { $\sim T \sim f$; $\sim M$ }	classes
$LA ::=$ layer $L < L$ { $\sim PM$; }	layers
$M ::= T\ m(\sim T \sim x)${ return e; }	methods
$PM ::= T\ C.m(\sim T \sim x)${ return e; }	partial meth.
$e ::= x \mid e.f \mid e.m(\sim e) \mid$ new $T(\sim e)$	expressions
$\mid$ with e e	layer activation
$\mid$ proceed($\sim e$)	proceed call
$\mid$ super.$m(\sim e)$	super call

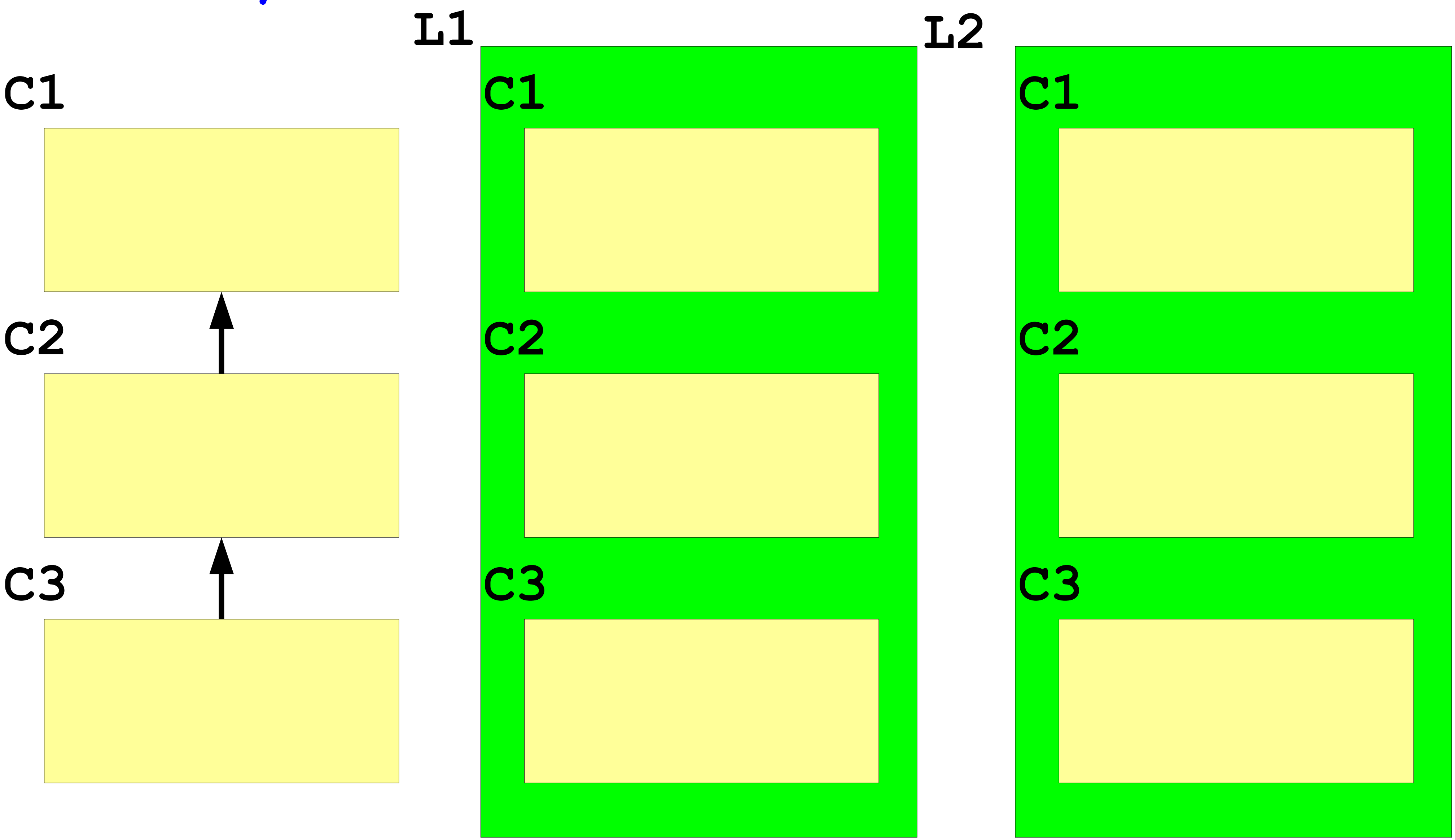
Syntax (2/2)

ContextFJ program: (CT, LT, e)

- Class table: $CT(C) = CL$
- Layer table: $LT(L) = LA$
- Main expression: e

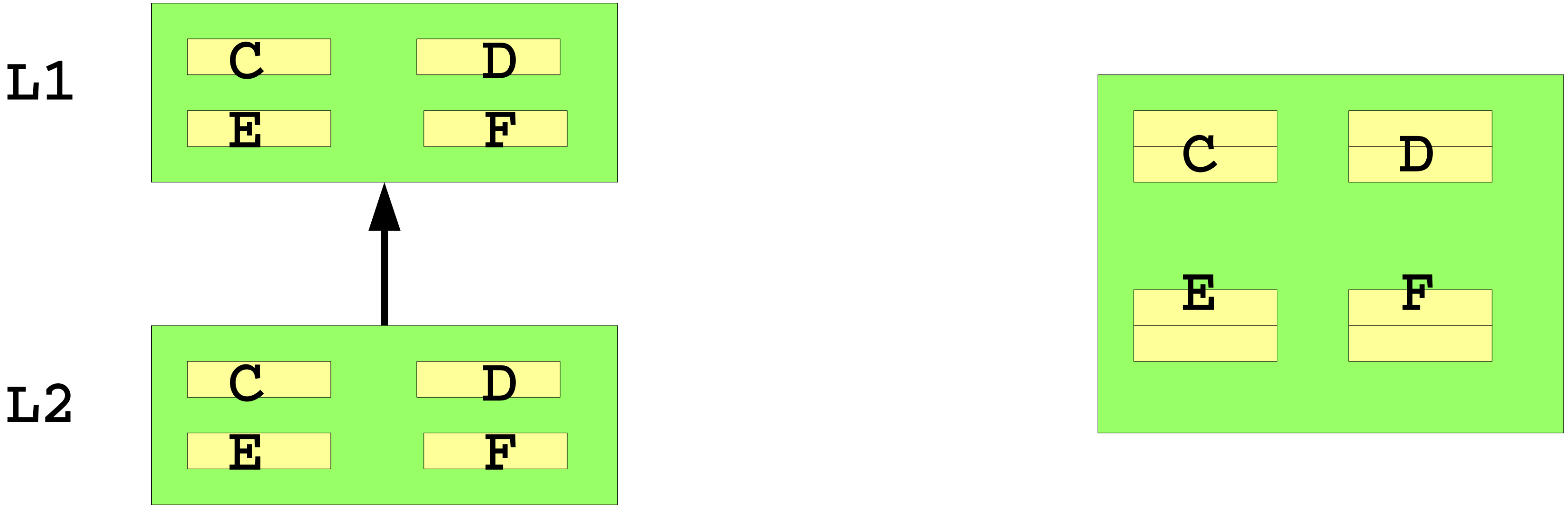
Semantics of Method Dispatch w/o Layer Inheritance

```
with (new L1()) {
  with (new L2()) {
    c3.m(…);
} }
```



Semantics with Layer Inheritance

- "3D" dispatching
- Each layer can be thought of as the result of (possibly overriding) composition of superlayers



Lookup function: *mbody*

$mbody(m, C, \sim L_1, \sim L_2) = \sim x.e$ in D, $\sim L_3$

- "Body of method *m* in *C* is *e* with params $\sim x$"
- $\sim L_2$ is the list of activated layers
- C, $\sim L_1$ denote the currently focused position
  - Acting like a cursor
- D, $\sim L_3$ denote where $\sim x.e$ is found

Reduction: $\sim L \vdash e \rightarrow e'$

- "*e* reduces to *e'* under activated layers $\sim L$"
  - Instances from the same layer are not really distinguished (because there are no states)
- *e.g,*
  - `Timing` $\vdash$ `new Conn(...).drop()` $\rightarrow$ `new Conn(...).timer.stop(); proceed()`
  - `Timing; Billing` $\vdash$ `new Conn(...).drop()` $\rightarrow$ `proceed(); charge()`
    - … actually, **`proceed`** is replaced at this point (see next slides)

Reduction rule for layer activation

$$\frac{remove(L, \sim L) = \sim L' \quad \sim L'; L \vdash e \rightarrow e'}{\sim L \vdash \text{with } L\ e \rightarrow \text{with } L\ e'}$$

- The body e is reduced under the context where L is added
  - Activated layer L *always* comes at the top
    - Even when it's already been activated

```
Timing ⊢
  with Billing (new Conn(...).drop())
 → with Billing (proceed(); charge())
```

Run-time expression to deal with proceed and super

e ::= … | new *C*<*D*,~*L1*,~*L2*>(~*v*)

- Essentially new *C*(~*v*).*m*(~*e*)
- Annotation <*D*,~*L1*,~*L2*> remembers
  - where method lookup starts next time (*D*, ~*L1*)
  - what layers have been activated (~*L2*)

```
Timing; Billing ⊢ new Conn(...).drop() →
 new Conn<Conn,Timing,(Timing;Billing)>
   (...).drop();
 charge()
```

Reduction Rules for Method Invocation

$$\frac{\sim L \vdash \text{new } C(\sim v)\langle C,\sim L,\sim L\rangle.m(\sim w) \to e'}{\sim L \vdash \text{new } C(\sim v).m(\sim w) \to e'}$$

$$\frac{\begin{array}{l} mbody(m, D, \sim L_1, \sim L_2) = \sim x.e \text{ in } E, (\sim L_3; L) \\ \text{class } E < F \end{array}}{\begin{array}{l} \sim L_4 \vdash \text{new } C(\sim v)\langle D,\sim L_1,\sim L_2\rangle.m(\sim w) \to \\ \quad [\text{new } C(\sim v) / \text{this}, \\ \quad \sim w \qquad / \sim x, \\ \quad \text{new } C\langle E, \sim L_3, \sim L_2\rangle(\sim v).m \;\; / \text{ proceed}, \\ \quad \text{new } C\langle F, \sim L_2, \sim L_2\rangle(\sim v) \;\; / \text{ super} \;\;]\; e \end{array}}$$

Reduction Rules for Method Invocation

$$\frac{\sim L \vdash \text{new } C(\sim v)\langle C, \sim L, \sim L\rangle.m(\sim w) \rightarrow e'}{\sim L \vdash \text{new } C(\sim v).m(\sim w) \rightarrow e'}$$

Invocation on an "unannotated" object
is affected by currently activated layers ~L

[new $C(\sim v)$ / this,
$\sim w$ / $\sim x$,
new $C\langle E, \sim L_3, \sim L_2\rangle(\sim v).m$ / proceed,
new $C\langle F, \sim L_2, \sim L_2\rangle(\sim v)$ / super] e

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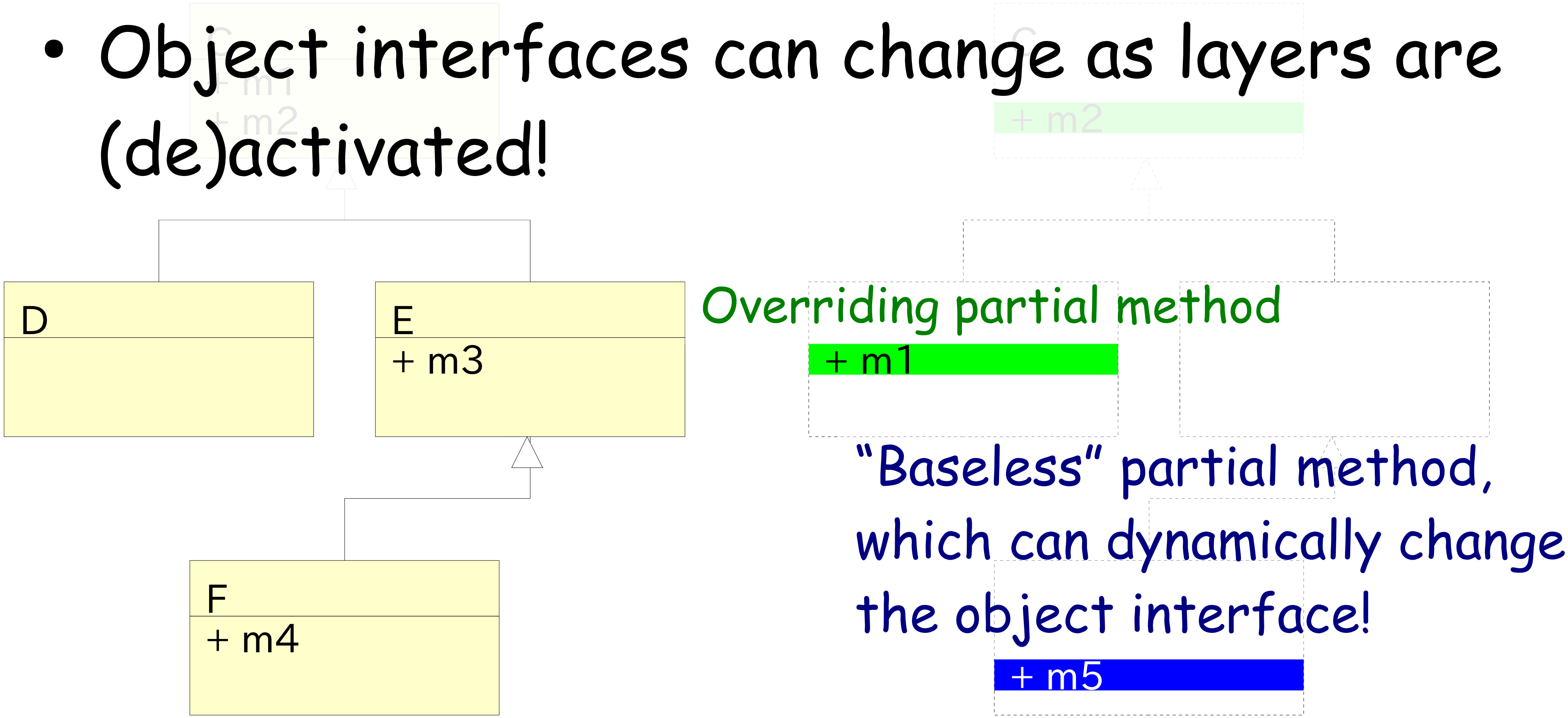
- Quick tour on COP language features
  - With a more concrete example
- Foundations for COPL
  - (Operational) Semantics
  - Type System
    - To prevent "NoSuchMethodError" including dangling `proceed` calls

"Sounds like an old problem. What is a challenge?"

- Object interfaces can change as layers are (de)activated!



Key Idea (1/2)

Approximating activated layers at each program point

- With the help of explicit "**`requires`**" declarations to specify inter-layer dependency
  - Static analysis could dispense with such explicit declarations, though

Key Idea (2/2)

Two kinds of substitutability for layers

- When one layer L1 `requires` layer L2, does a sublayer of L2 can satisfy L1's requirement?
- When is it safe to pass an instance of a layer to where a supertype is expected?

should be distinguished

Telecom example, revisited

```
class Conn {
  Conn(Custome
  void complet
  void drop()
}
```

```
layer Timing {
  Timer Conn.tim
  void Conn.comp
  void Conn.drop
  int Conn.getTi
}
```

```
layer Billing                                  {


  void Conn.drop(){ proceed(); cl

  void Conn.charge(){ … getTime()
}
```

- For **charge()** in **Billing** to work, baseless partial method **getTime()** defined in **Timing** should be active beforehand

Telecom example, revisited

```
class Conn {
  Conn(Custome
  void complet
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}
```

```
layer Timing {
  Timer Conn.tim
  void Conn.comp
  void Conn.drop
  int Conn.getTi
}
```

```
layer Billing requires Timing  {


  void Conn.drop(){ proceed(); ch

  void Conn.charge(){ … getTime(
}
```

- For `charge()` in `Billing` to work, baseless method `getTime()` defined in `Timing` should be active beforehand
- In other words, `Billing requires Timing`

Meaning of `requires`

When layer L **`requires`** $L_1, \ldots, L_n$

- All of $L_1, \ldots, L_n$ must have been already activated (in any order) before activating L
- Partial method in L can invoke methods defined in any of $L_1, \ldots, L_n$ (or base class)
- Partial method m in L can **`proceed`** when m is defined in any of $L_1, \ldots, L_n$ (or base class)

Coeffect system?

Type Judgment $\Lambda; \Gamma \vdash e : T$

"Under set Λ of activated layers and type env. Γ, exp e is given type C"

- {}; c: **`Conn`** $\vdash$ **`c.getTime()`** : **`int`**
- {**`Timing`**}; c: **`Conn`** $\vdash$ **`c.getTime()`** : **`int`**
- {}; c: **`Conn`** $\vdash$ **`with (new Timing())c.getTime()`** : **`int`**
- {}; c: **`Conn`** $\vdash$ **`with (new Billing())c.drop()`** : **`void`**
- {**`Timing`**}; c: **`Conn`**

  $\vdash$ **`with (new Billing()) c.drop()`** : **`void`**

Main Typing Rules

- Typing rule for method invocation

$$\frac{\Lambda; \Gamma \vdash e_0 : C_0 \qquad mtype(m, C_0, \Lambda) = \sim T \rightarrow T_0 \qquad \Lambda; \Gamma \vdash \sim e : \sim S \qquad \sim S <: \sim T}{\Lambda; \Gamma \vdash e_0 . m (\sim e) : T_0}$$

- Typing rule for layer activation

$$\frac{\Lambda; \Gamma \vdash e1 : L \qquad \Lambda \cup \{L\}; \Gamma \vdash e2 : T}{\Lambda; \Gamma \vdash \texttt{with}\ e1\ e2 : T}$$

Inheritance and `requires`

- Sublayer can't require fewer layers than its parent
  - Otherwise, requirement by inherited partial methods may be invalidated
- It seems natural to allow a sublayer to require more layers ...

...Or, maybe not!

```
AbsBilling b =
  some_condition ? new Billing1():new Billing2();

with(b) { … }
```

- The type system seems to always allow `with(b)` (if `AbsBilling` requires no layer)
- But, what if `Billing2` requires more layers than `AbsBilling`?
  - At run time, dependecy is broken!!

Our Solution: Two subtyping rels for layer types

- Weak subtyping: reflexive transitive closure of `extends`
- Normal subtyping: reflexive transitive closure of `extends` *with invariant* `requires`

Main Typing Rules, revisited

- Typing rule for method invocation

$$\frac{\Lambda; \Gamma \vdash e_0 : C_0 \qquad mtype(m, C_0, \Lambda) = \sim T \to T_0 \qquad \Lambda; \Gamma \vdash \sim e : \sim S \qquad \sim S <: \sim T}{\Lambda; \Gamma \vdash e_0\texttt{.}m\,\texttt{(}\sim e\texttt{)} : T_0}$$

- Typing rule for layer activation

$$\frac{L\ \texttt{req}\ \Lambda' \qquad \Lambda <:_w \Lambda' \qquad \Lambda; \Gamma \vdash e1 : L \qquad \Lambda \cup \{L\}; \Gamma \vdash e2 : T}{\Lambda; \Gamma \vdash \texttt{with}\ e1\ e2 : T}$$

Other notable features

- Checking correct method overriding requires the whole program
  - Accidental conflict between partial layers

Type Soundness

- Thm. (Type Soundness):
  - If $\vdash e : T$ and $\vdash e \rightarrow^* e'$ (normal), then e' = new $S(\sim v)$ and $S <: T$
- Proof by showing Preservation and Progress
  - Induction is trickier than you might expect

Related Work

- Type System for COP [Clarke & Sergey@COP'09]
  - ContextFJ
    - proposed independently of us
    - no inheritance, subtly different semantics
  - Set of method signatures as method-wise dependency information
    - Finer-grained specification
  - No proof of soundness
    - In fact, the type system turns out to be flawed (personal communication), due to **`without`**

Related Work, contd.

- Type Systems for Mixins [Bono et al., Flatt et al., Kamina&Tamai, etc.]
  - Interfaces of classes to be composed
    - Structural type information
  - Composition is fixed once an object is instantiated
  - A similar idea works (to some extent ;-) also for more dynamic composition as in COP
- Types for FOP, DOP

Related Work, contd.^2

- Typestate checking [Strom&Yemini'86, etc.]
  - Checking state transition for computational resources (such as files and sockets)
  - Layer configuration can be considered a state
  - Resources are first-class whereas layers are global

Conclusion

- Dynamic layer composition for describing context-dependent behavioral change concisely and modularly
- Core calculus ContextFJ<: for formal semantics and type system
  - Estimation of (globally) activated layers
  - Explicit `requires` clauses to help typechecking
  - Two kinds of subtyping
  - (Layer swapping)
- (Implementation will be available)

Future work

- Interfaces for layers
  - Specifying layer names makes your program too implementation-specific
- Formal accounts of advanced COP features
  - Other activation mechanisms, e.g., in EventCJ [Kamina, Aotani, Masuhara AOSD'11]
- More formal connection to coeffects?
- Verification?