Synthesizing Replacement Classes

Malavika Samak, Deokhwan Kim and Martin Rinard

CSAIL, MIT

Library Usage in Applications

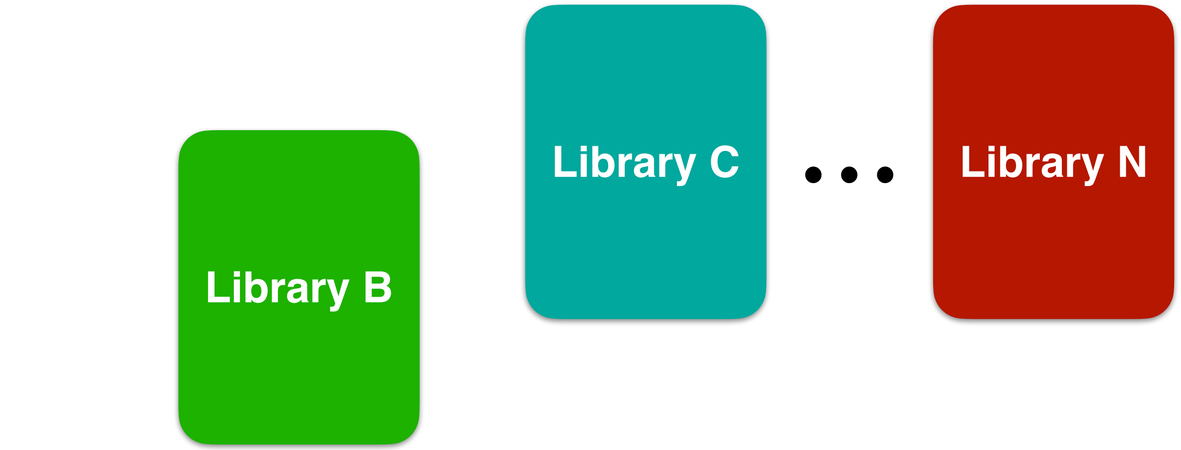
Developer

Library Usage in Applications

Application

Developer

Library Usage in Applications



Application

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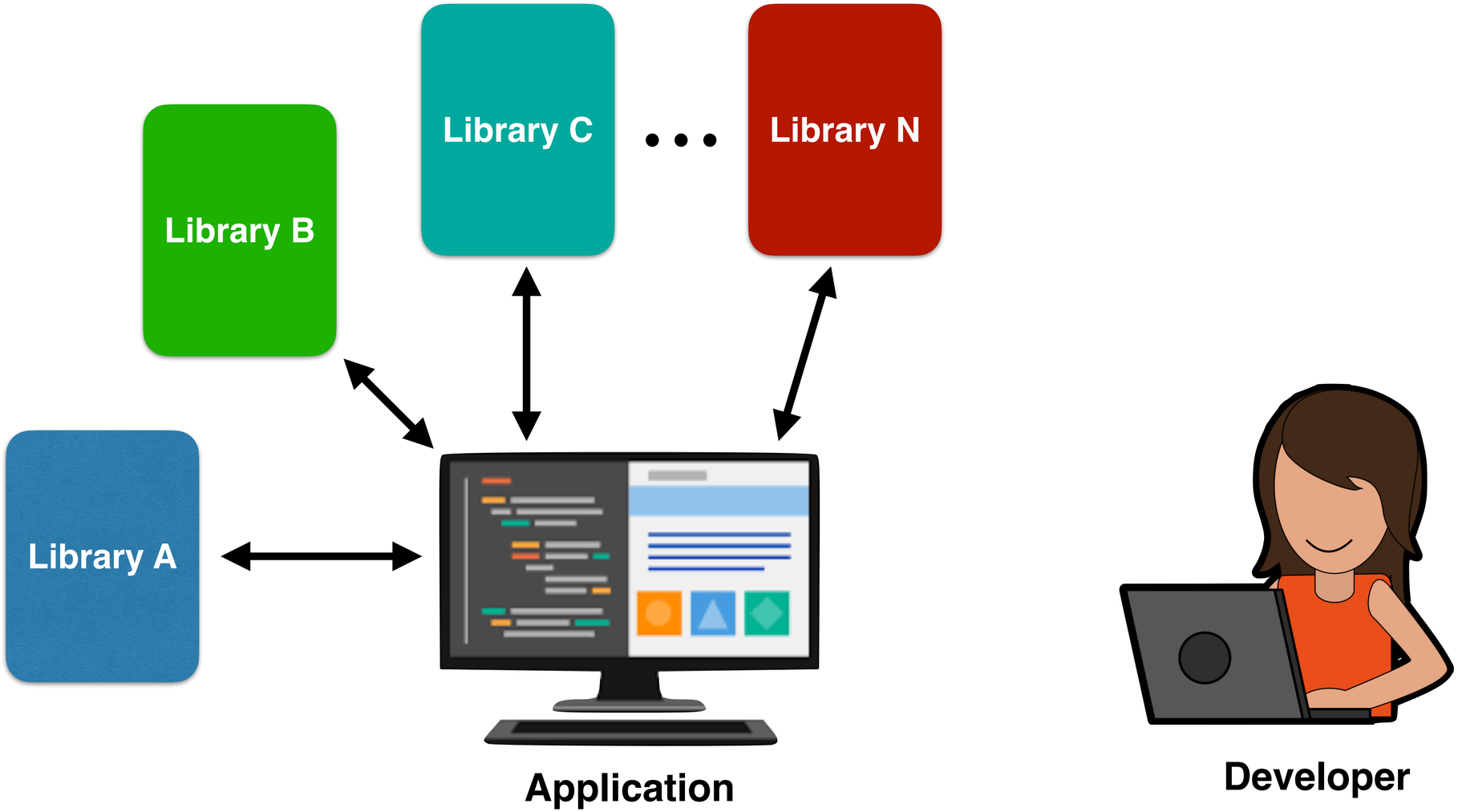
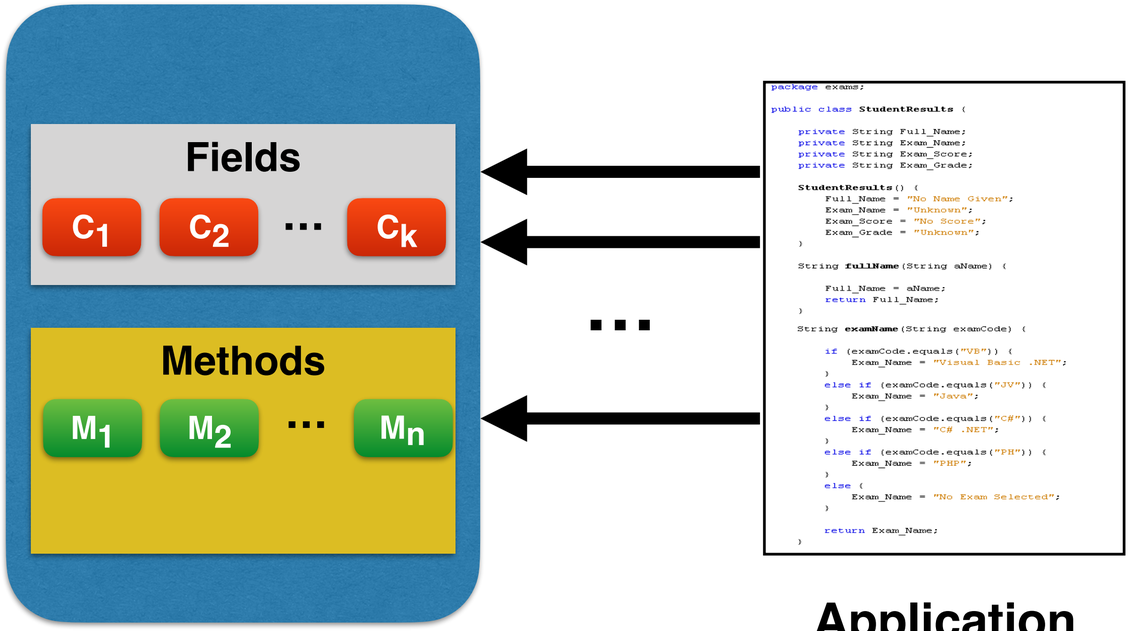
Library Usage in Applications



Class Updates for Applications



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package exams;

public class StudentResults {

    private String Full_Name;
    private String Exam_Name;
    private String Exam_Score;
    private String Exam_Grade;

    StudentResults() {
        Full_Name = "No Name Given";
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    }

    String fullName(String aName) {

        Full_Name = aName;
        return Full_Name;
    }

    String examName(String examCode) {

        if (examCode.equals("VB")) {
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        }
        else if (examCode.equals("JV")) {
            Exam_Name = "Java";
        }
        else if (examCode.equals("C#")) {
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        }
        else if (examCode.equals("PH")) {
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        }
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Application

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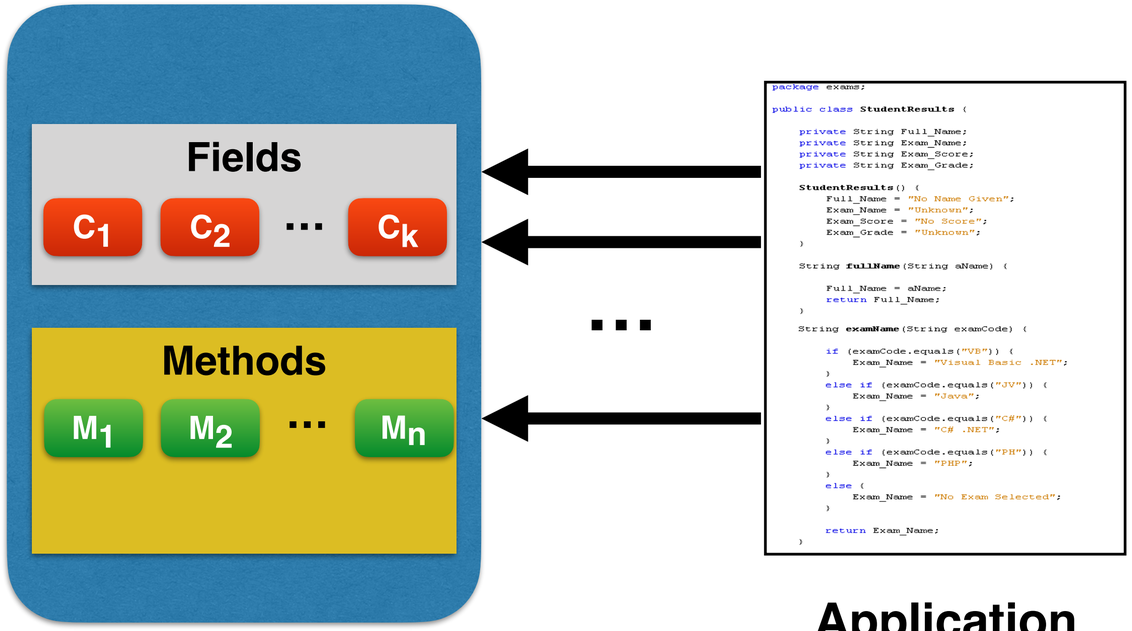
Class Updates for Applications



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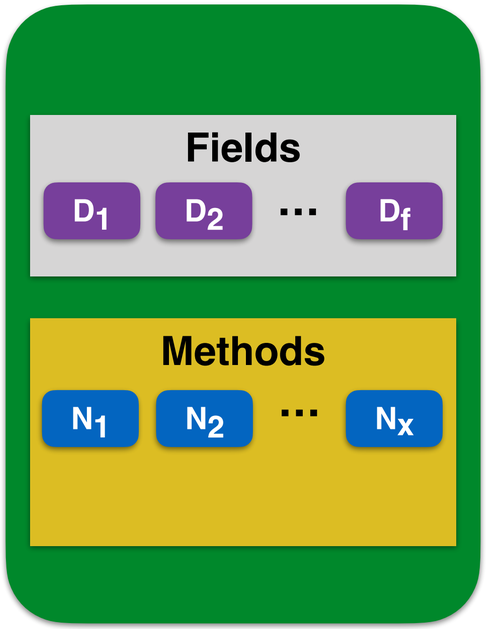
...

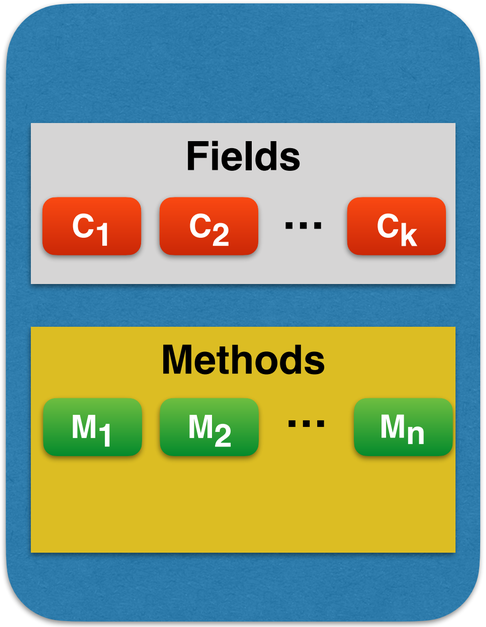
Application



Class R

Developer

Class Updates for Applications



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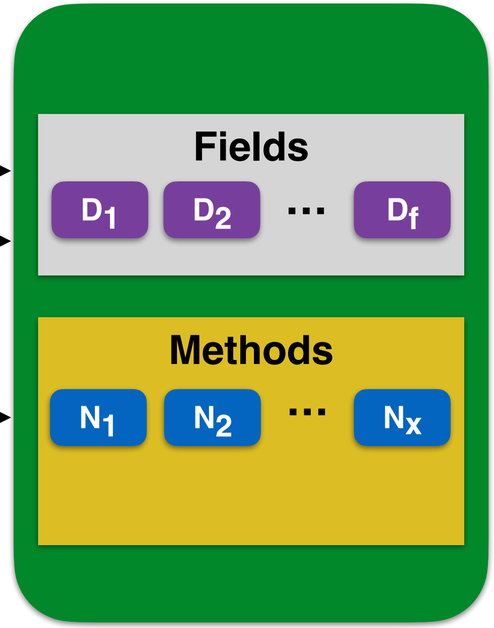

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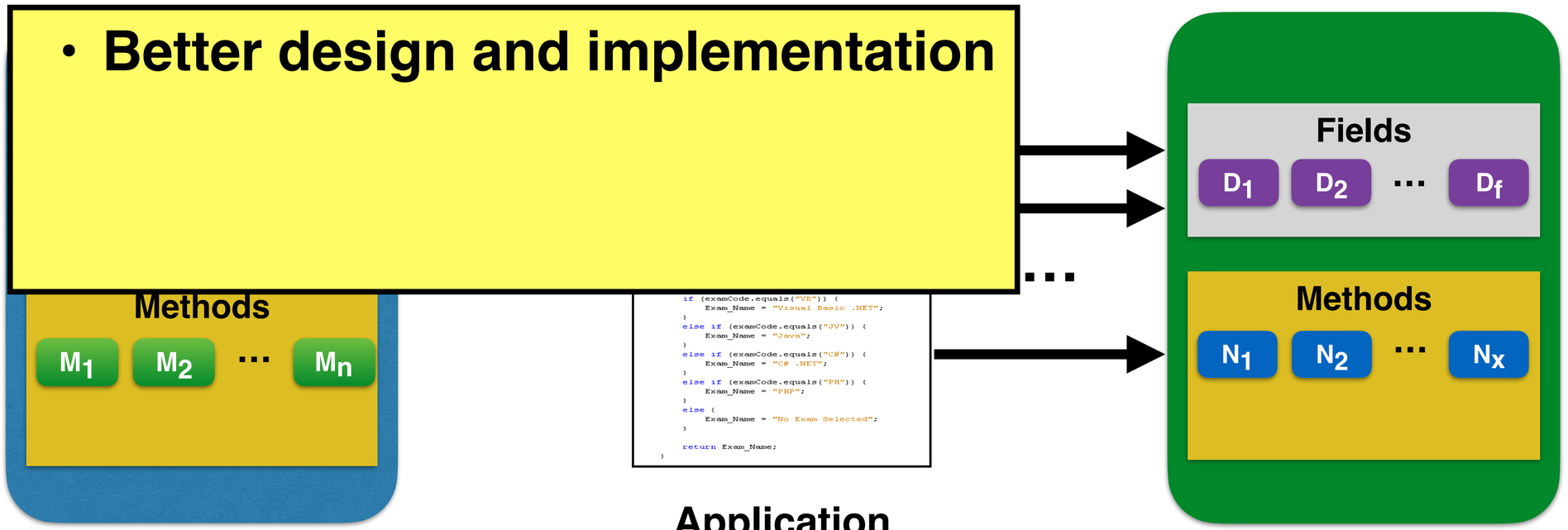
Class Updates for Applications

- **Better design and implementation**



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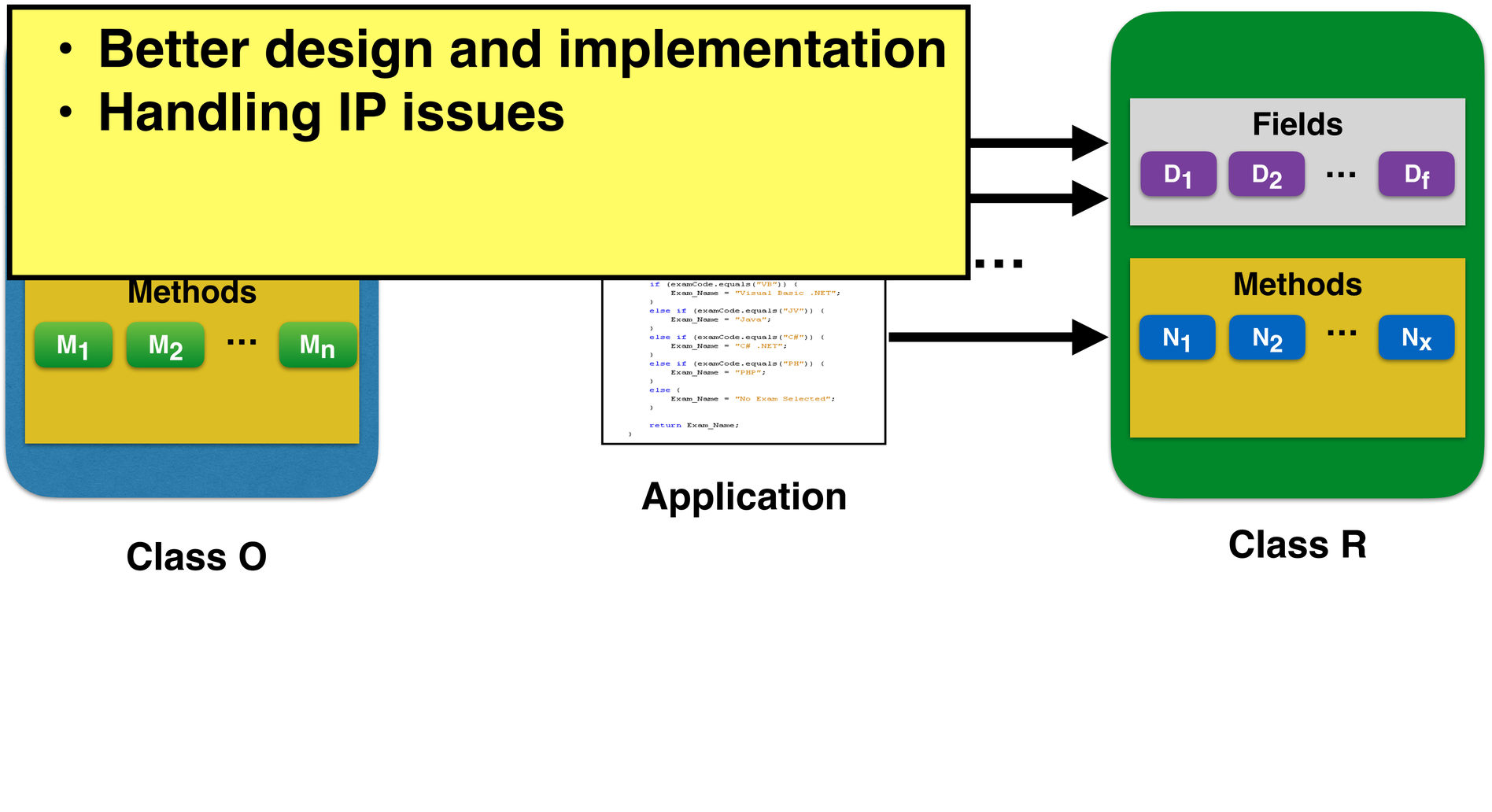
Class Updates for Applications

- **Better design and implementation**
- **Handling IP issues**



Developer

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- **Better design and implementation**
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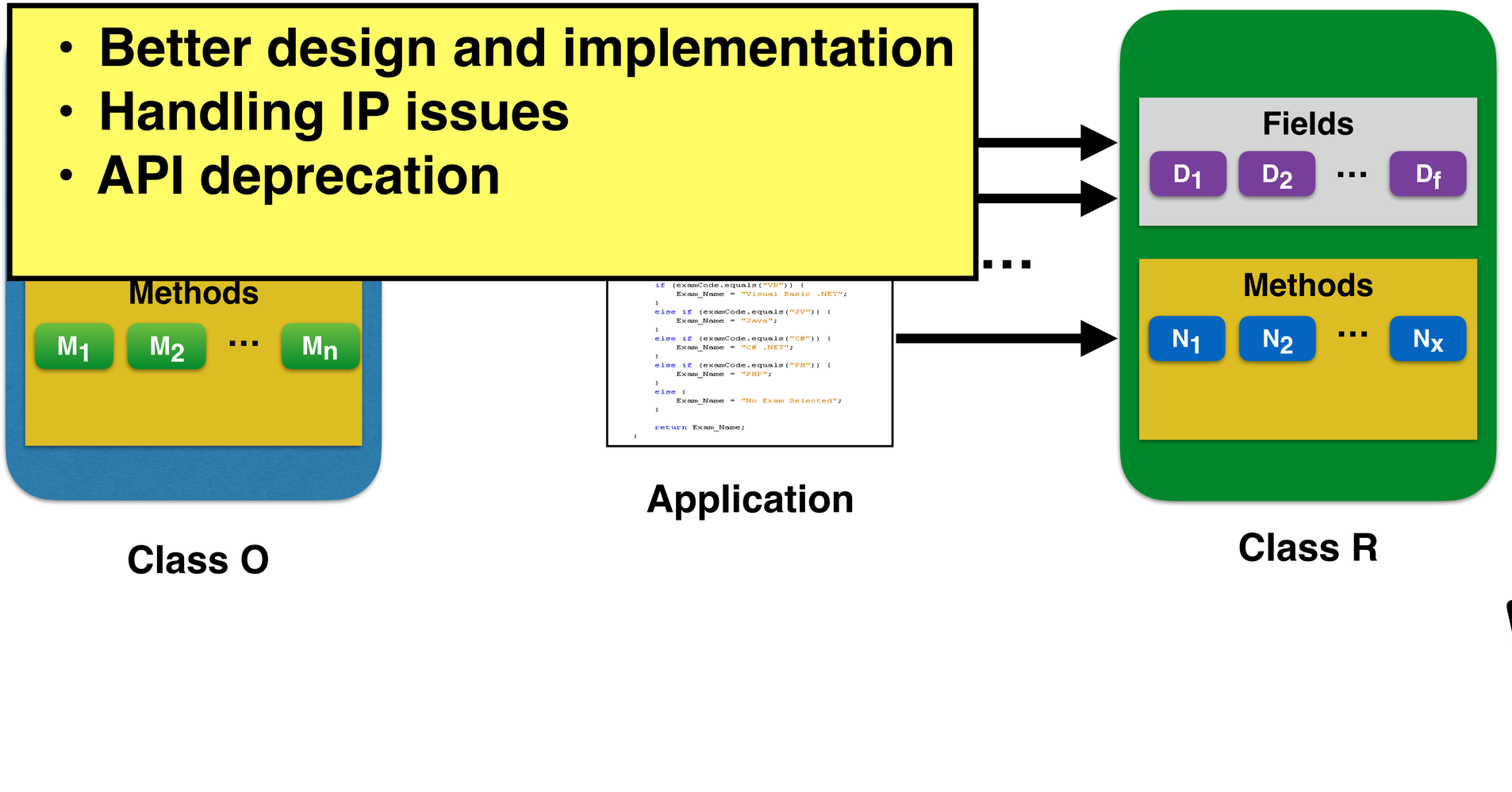
- **API deprecation**



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…

Methods

M_1 M_2 … M_n

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}

return Exam_Name;
}
```

Application

…

Fields

D_1 D_2 … D_f

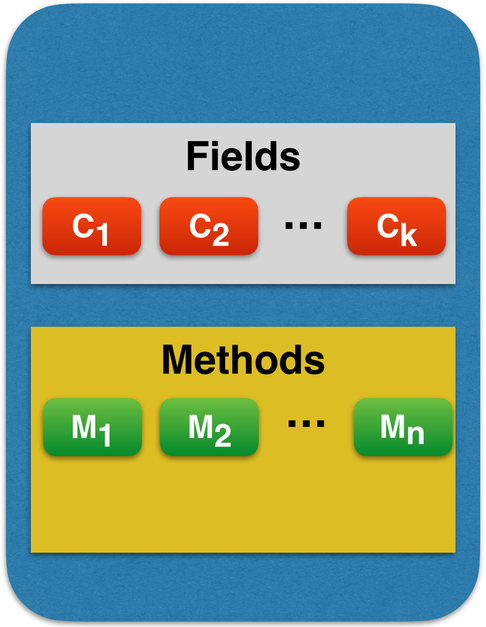
Methods

N_1 N_2 … N_x

Class R

Developer

Class Updates for Applications



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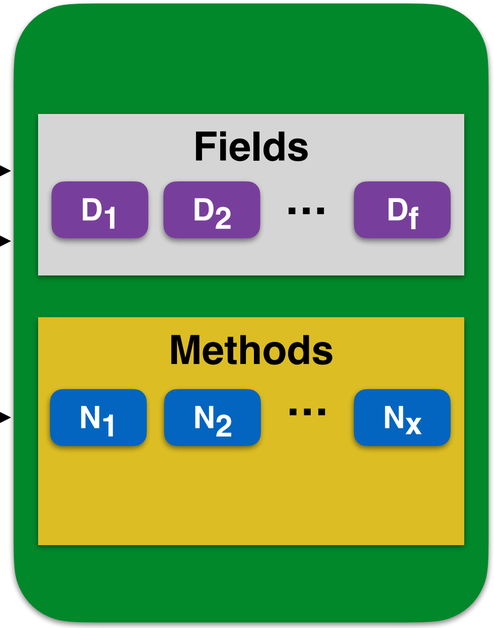

Class R

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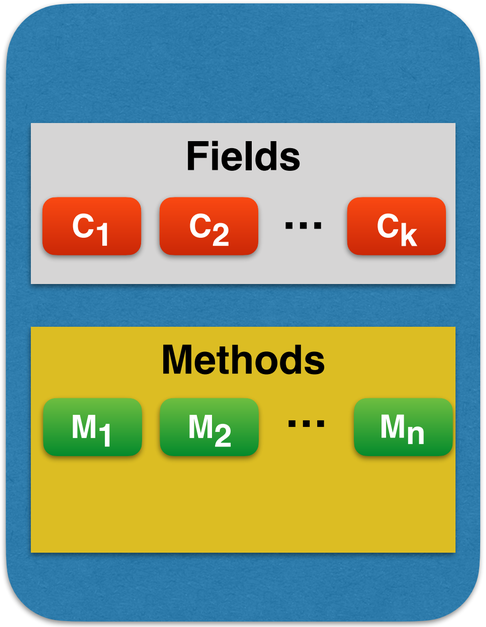

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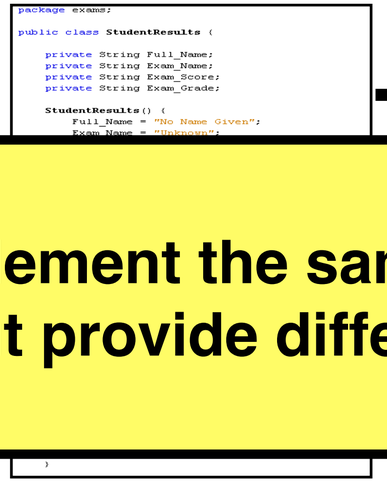
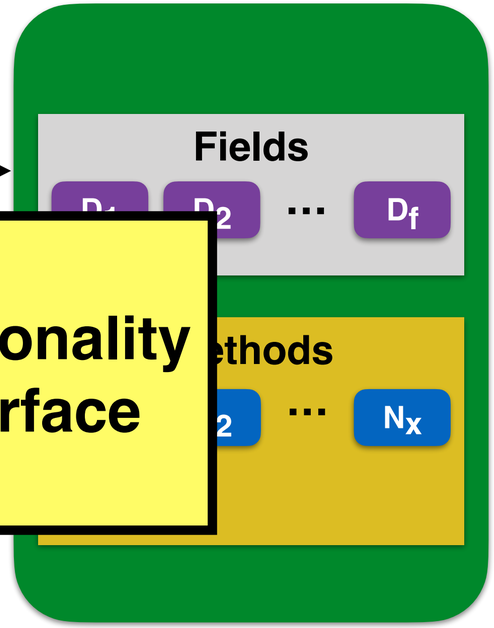


Application

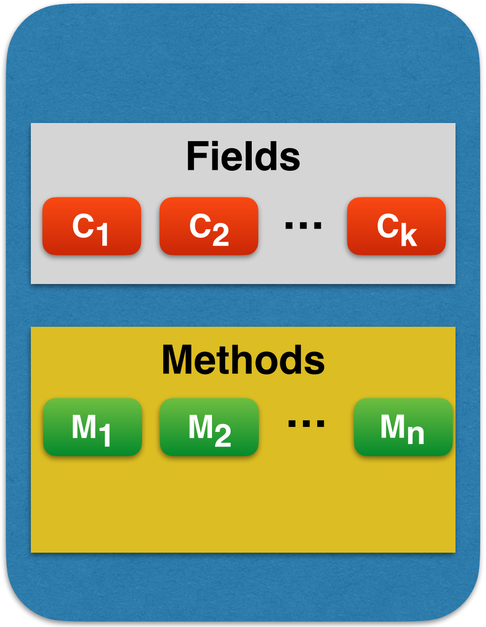
Implement the same functionality but provide different interface



Class R

Developer

Refactoring challenges



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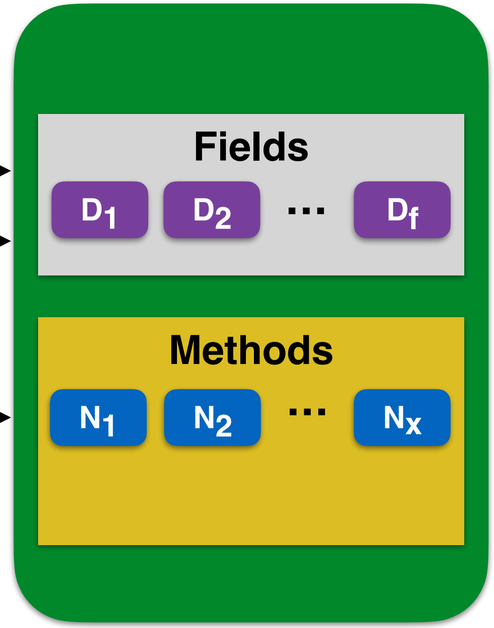
Application



Class R

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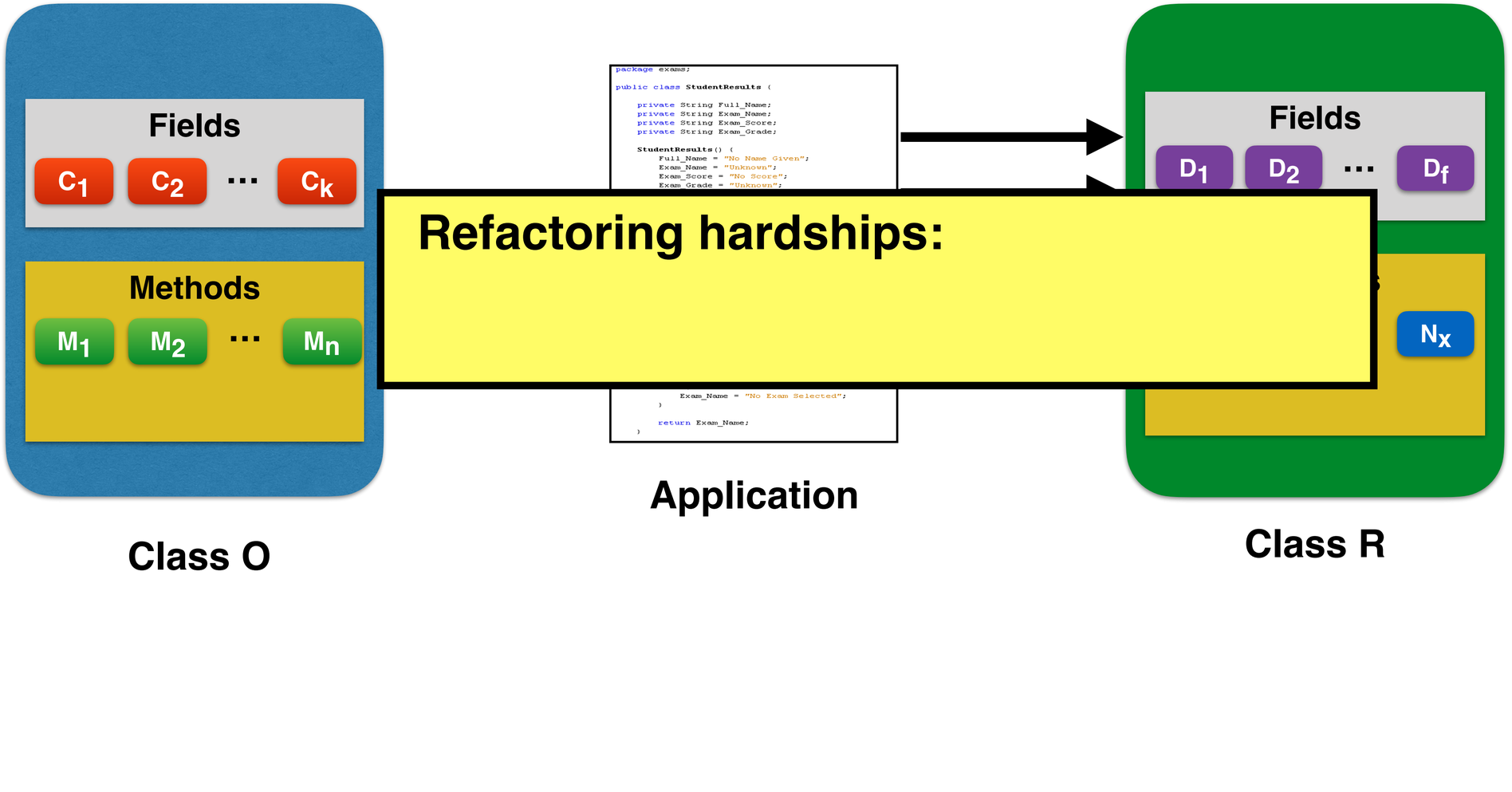

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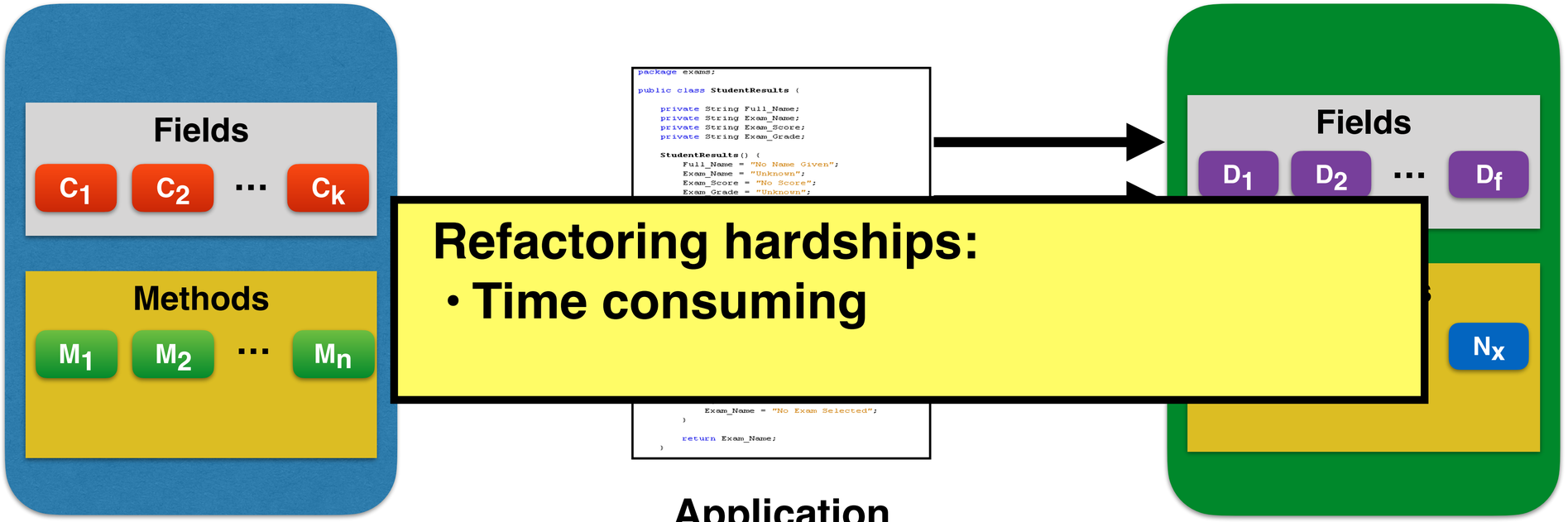

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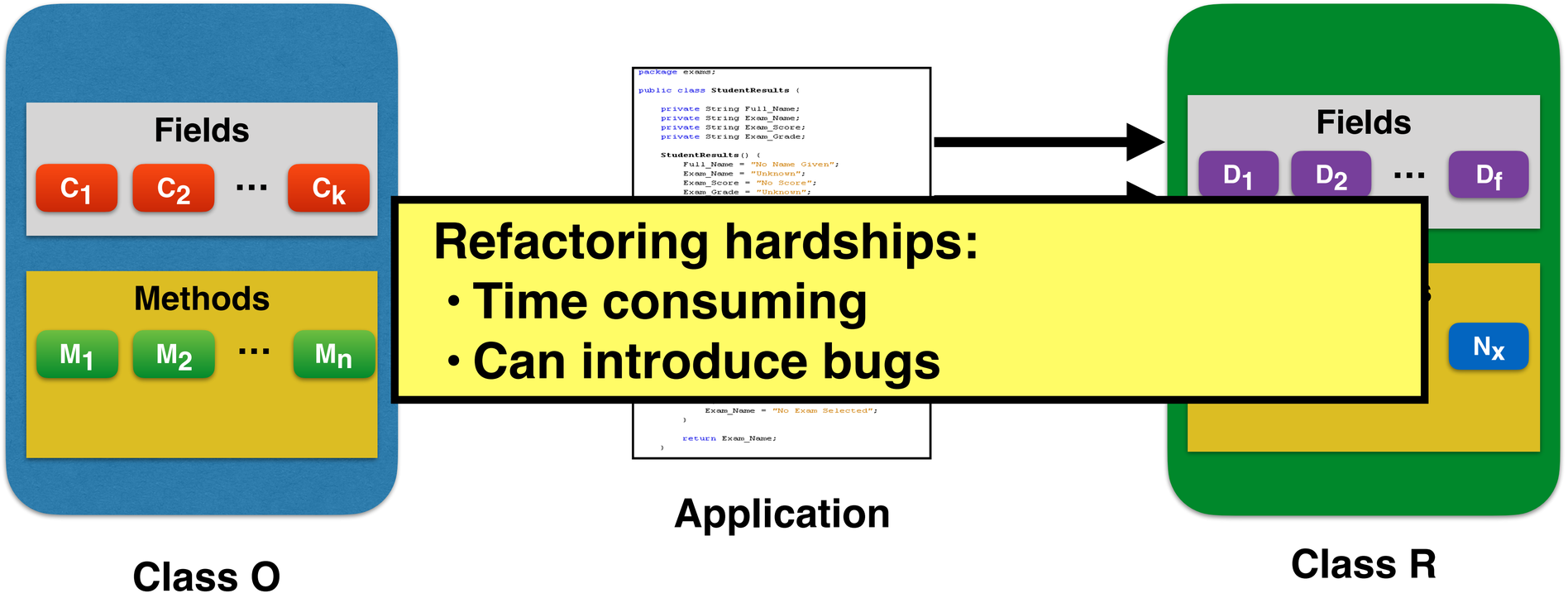
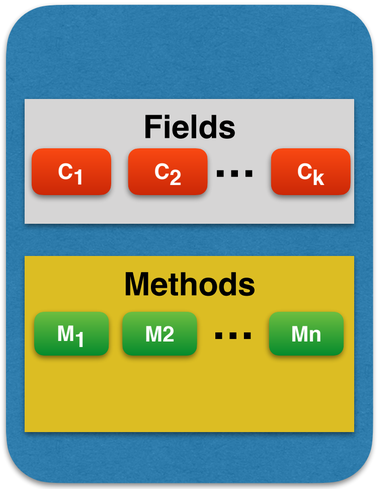
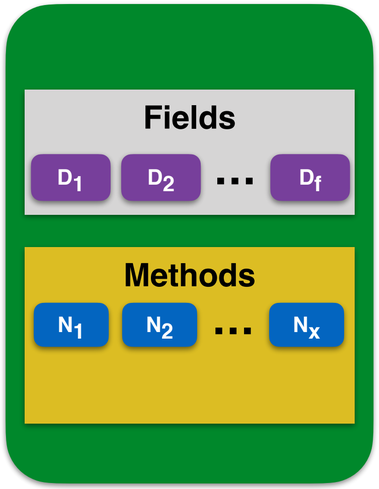


Developer

MASK



Class O



Class R

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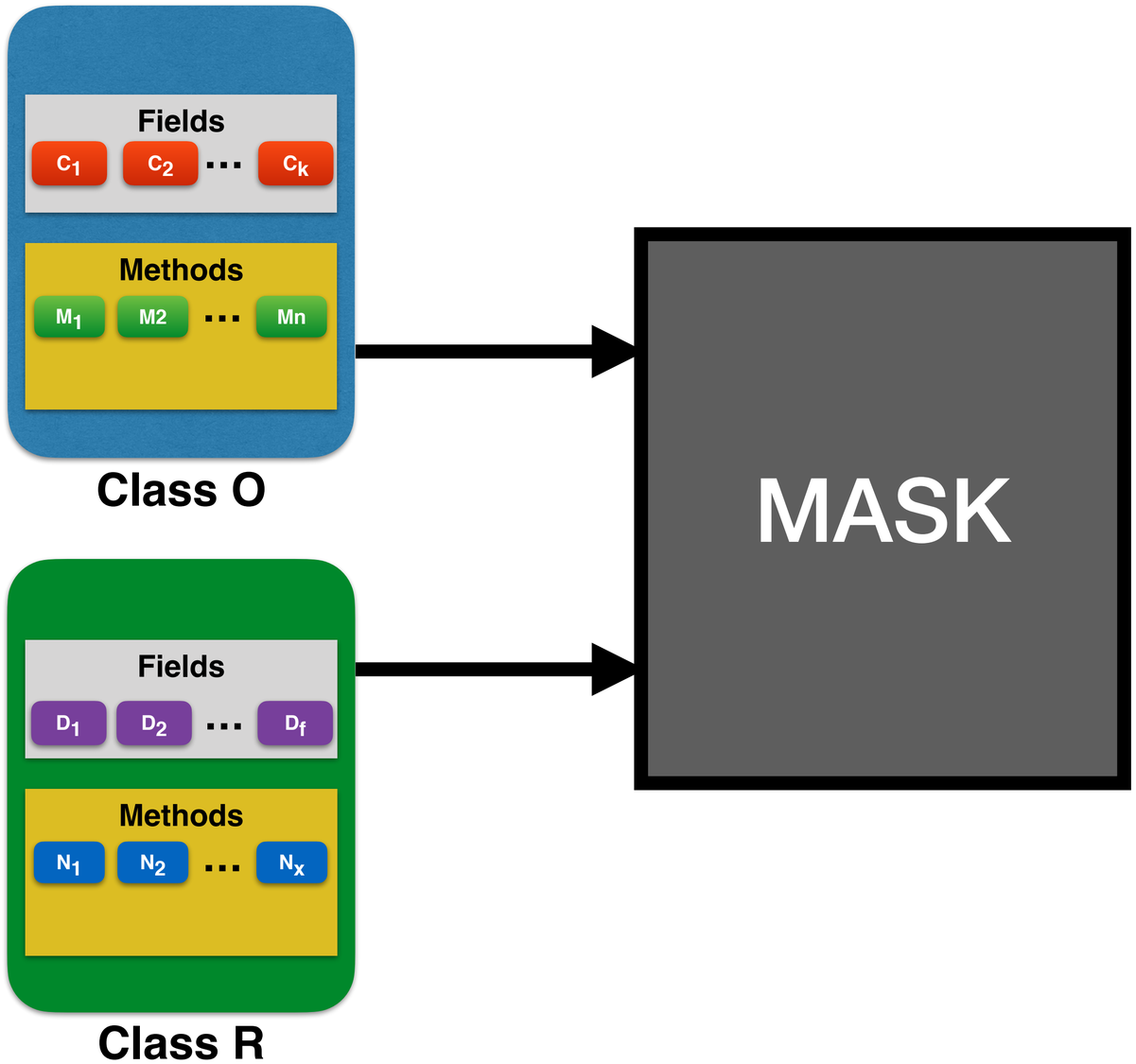
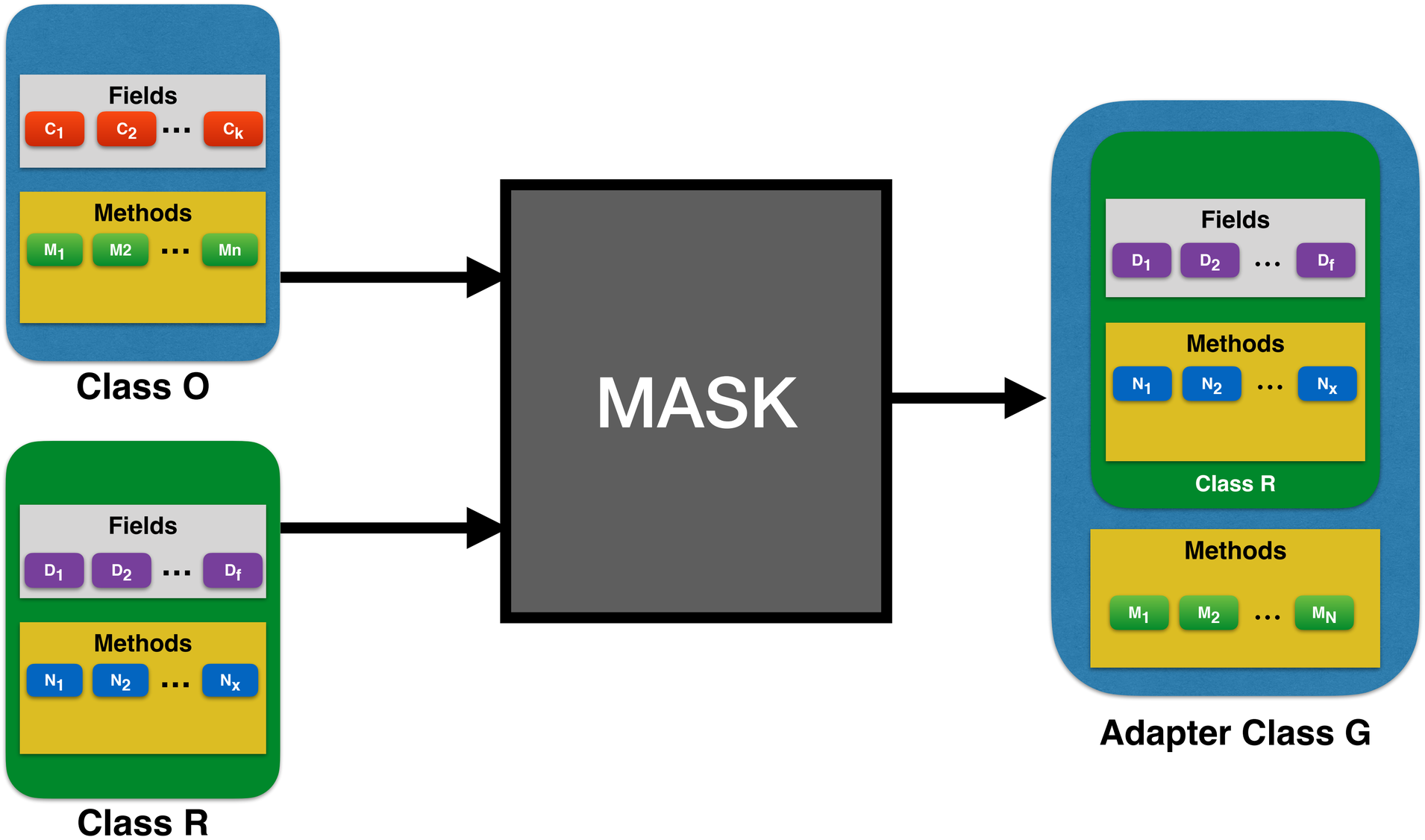

Fields
C1
C2
...
Ck
Methods
M1
M2
...
Mn
Class O
Fields
D1
D2
...
Df
Methods
N1
N2
...
Nx
Class R
MASK

MASK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N2
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Class R
MASK
Fields
D1
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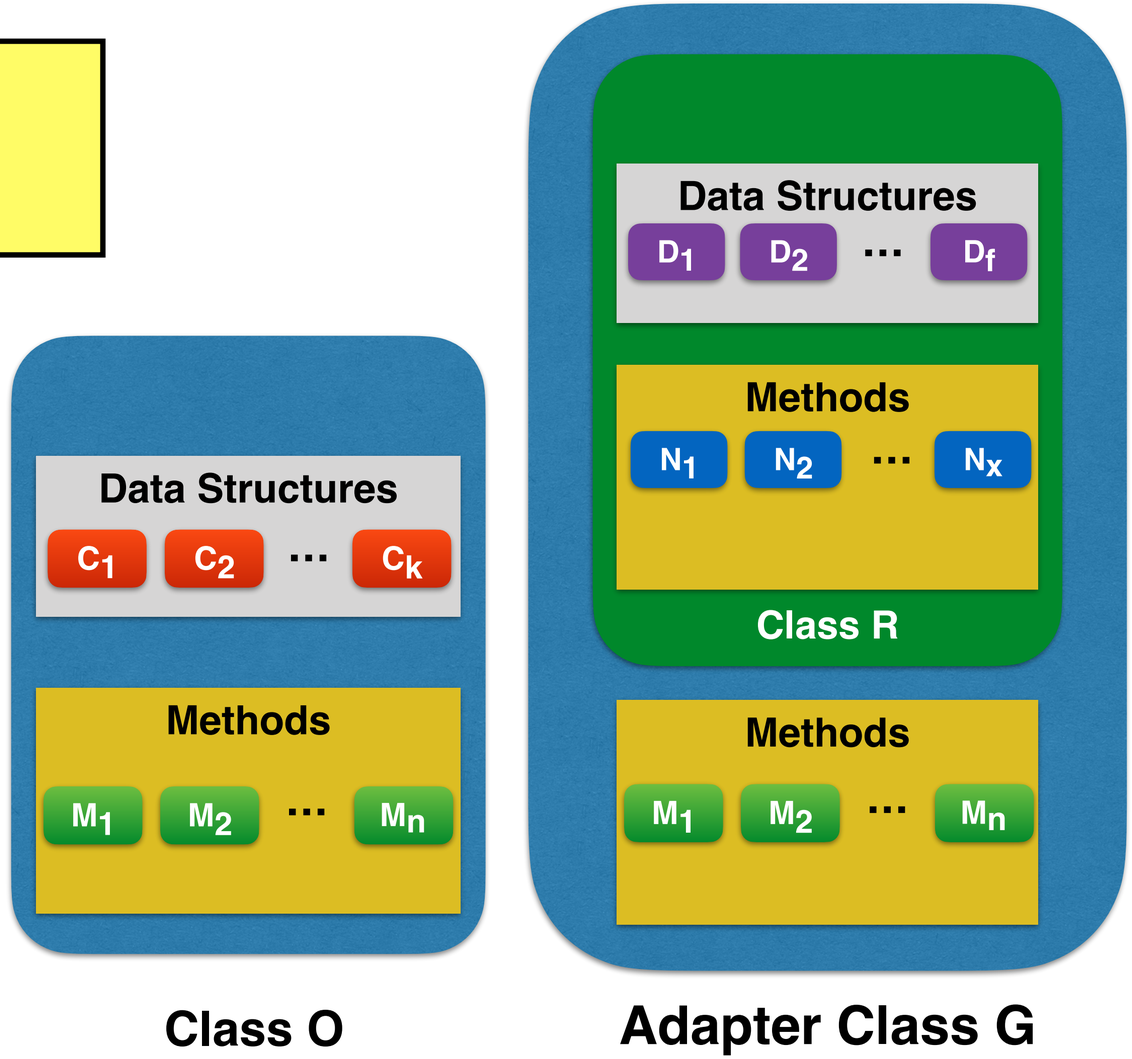
Df
Methods
N1
N2
Nx
Class R
Methods
M1
M2
MN
Adapter Class G

Adapter Class Requirements

1. Identical API signatures
2. Built using APIs from class R
3. API equivalence under all contexts



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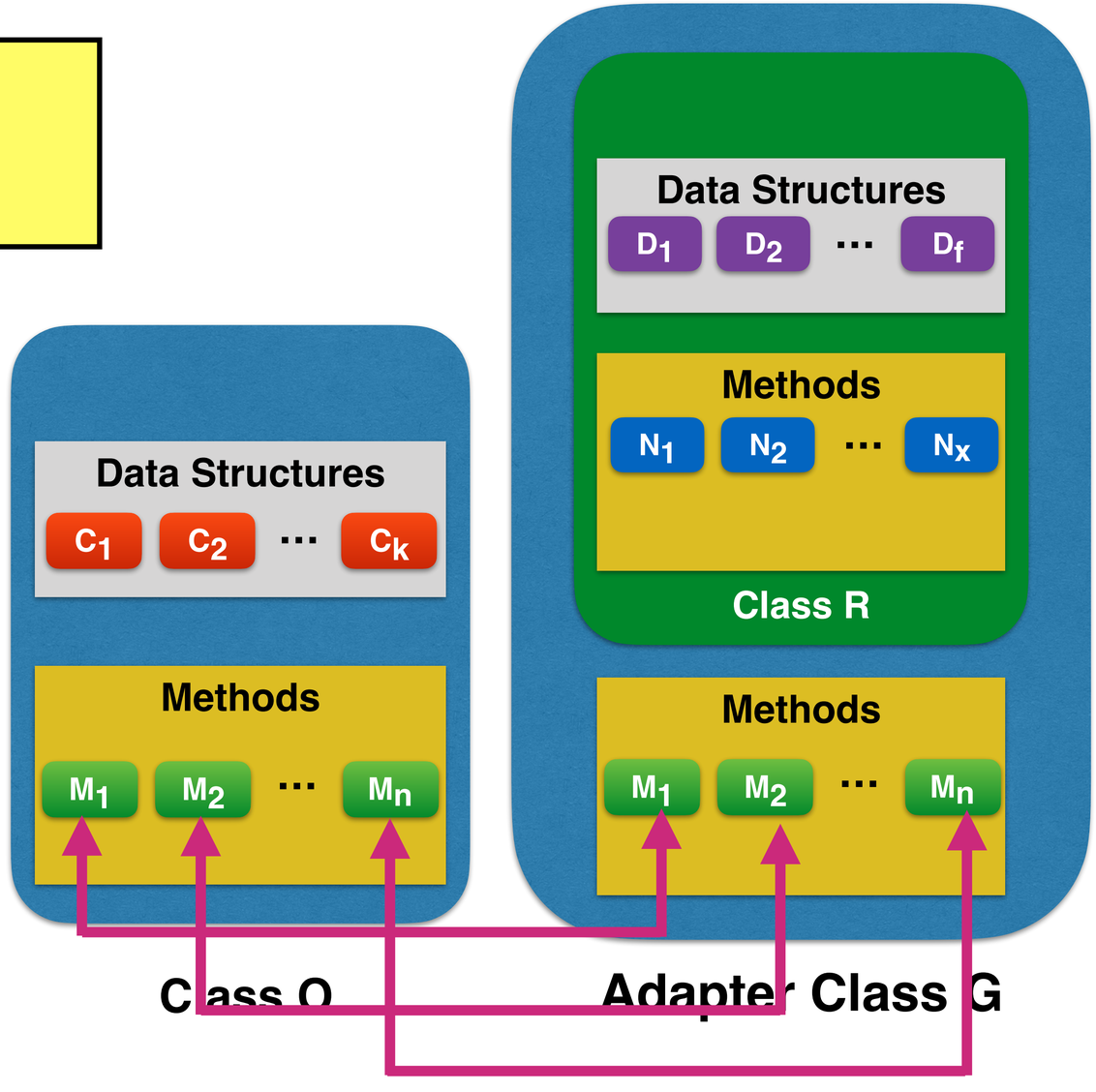

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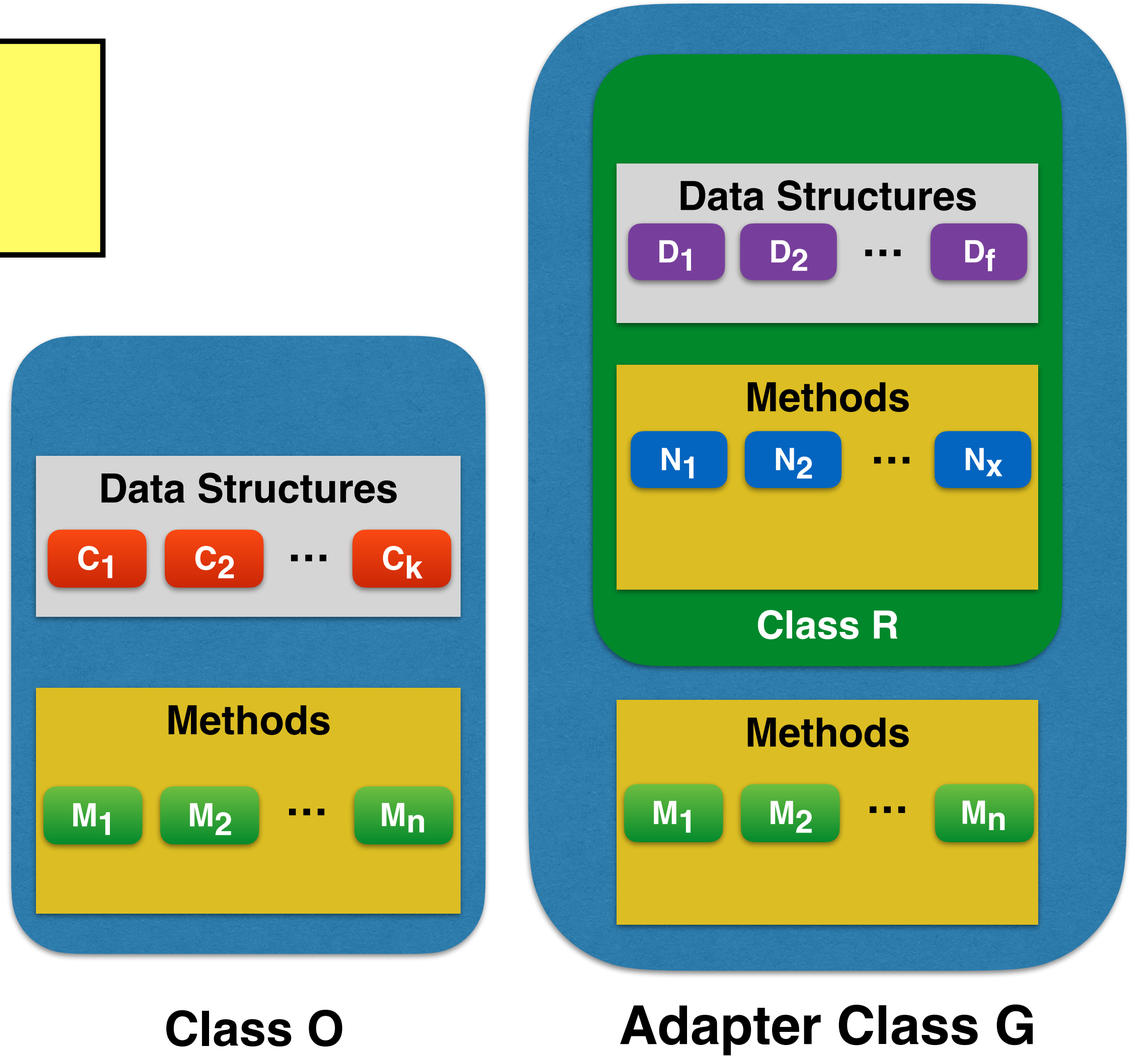

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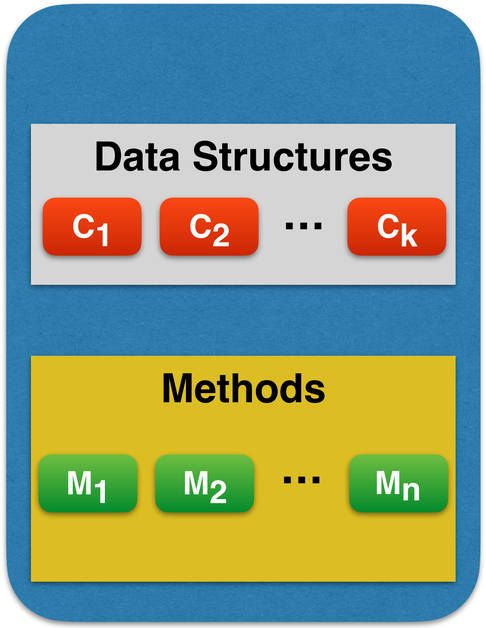

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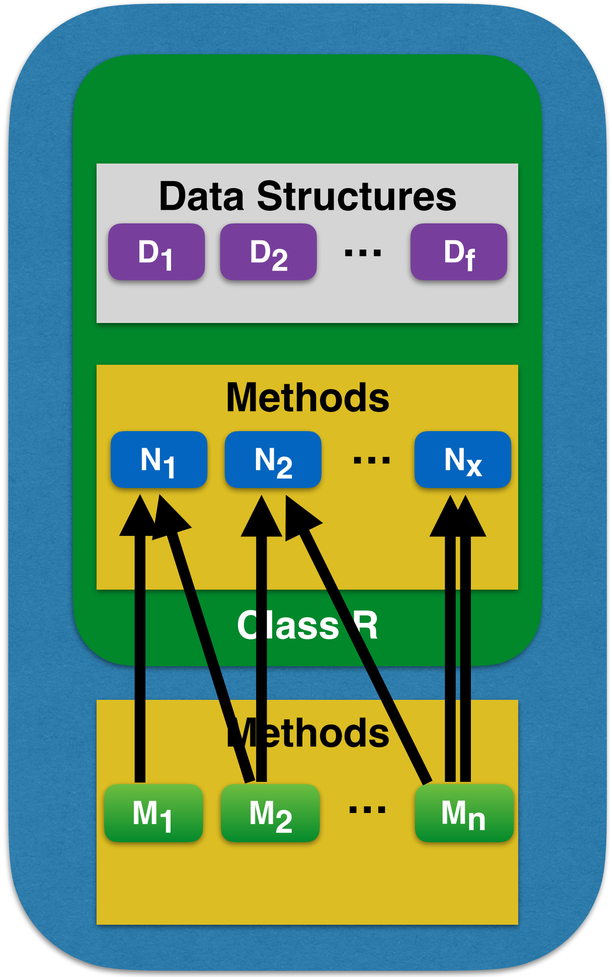

Adapter Class G

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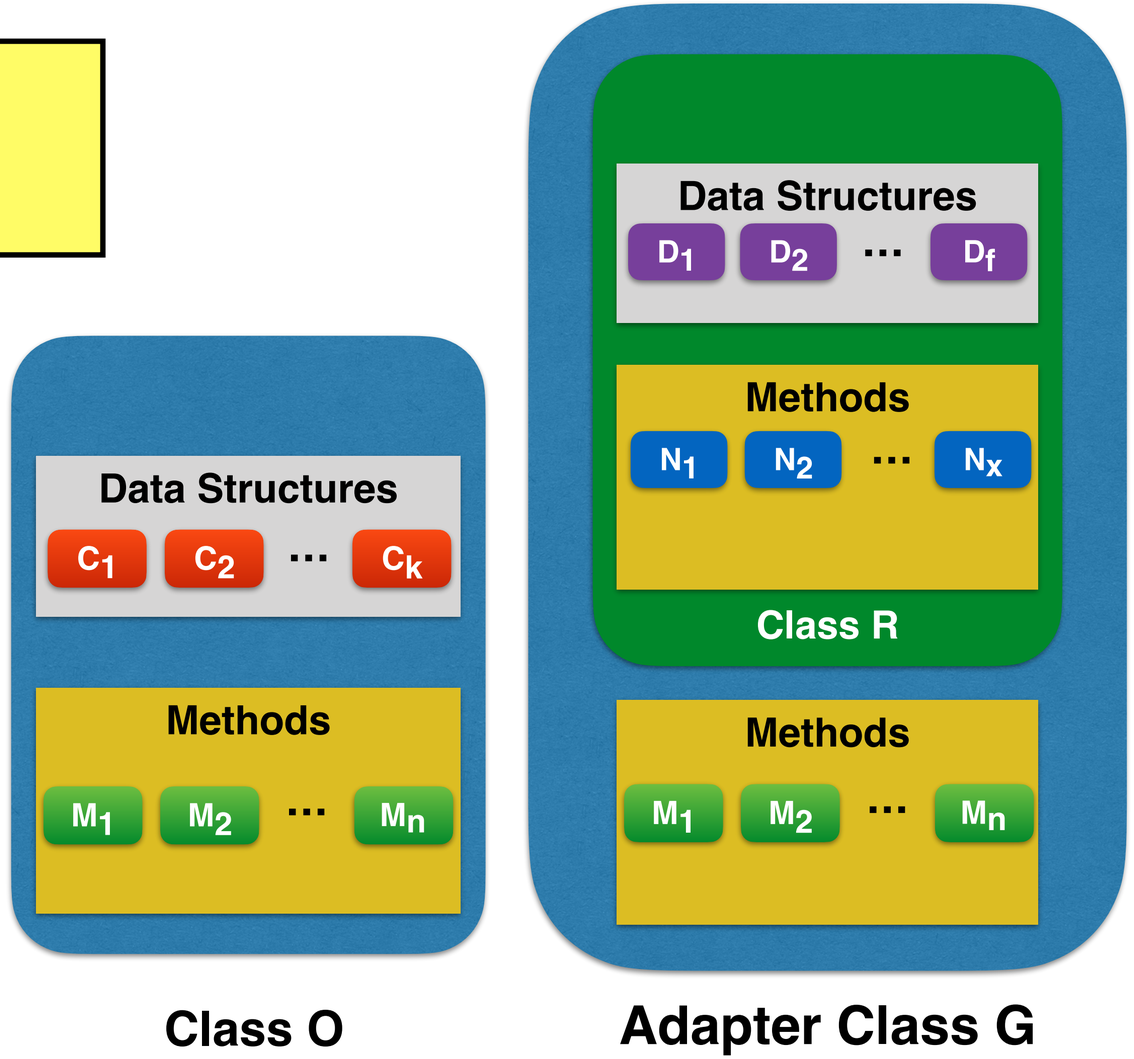

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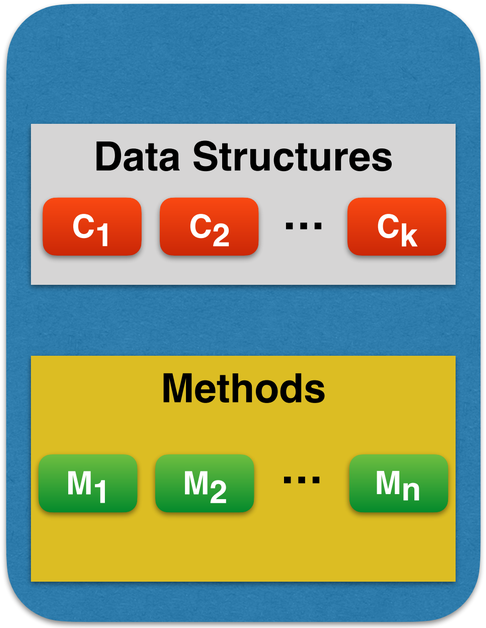

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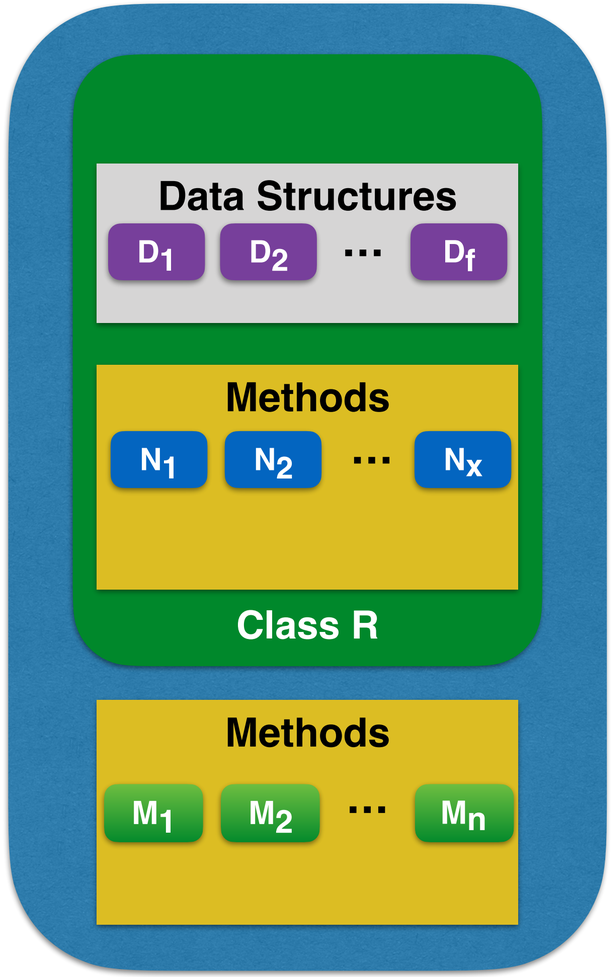

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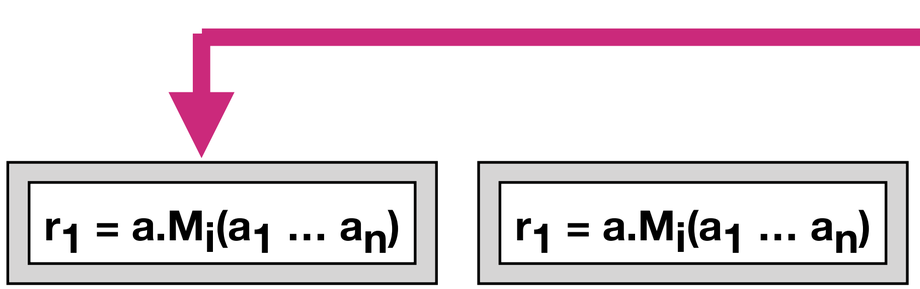

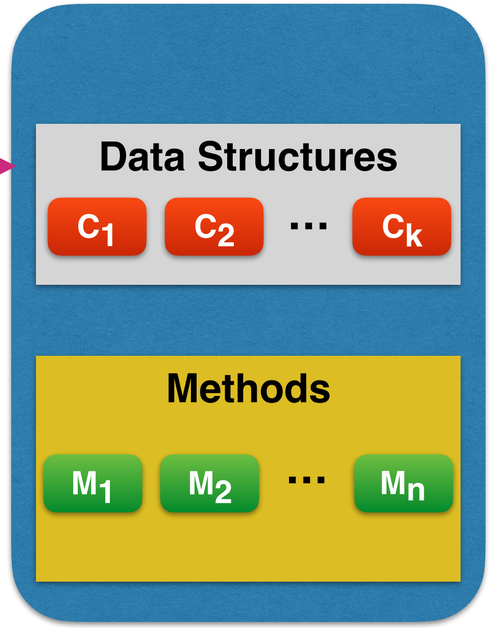

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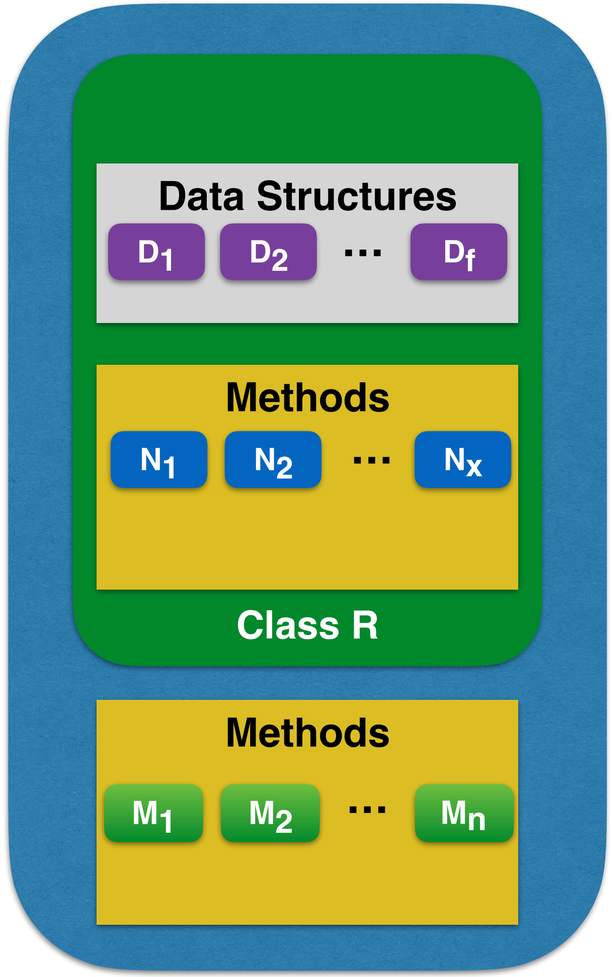

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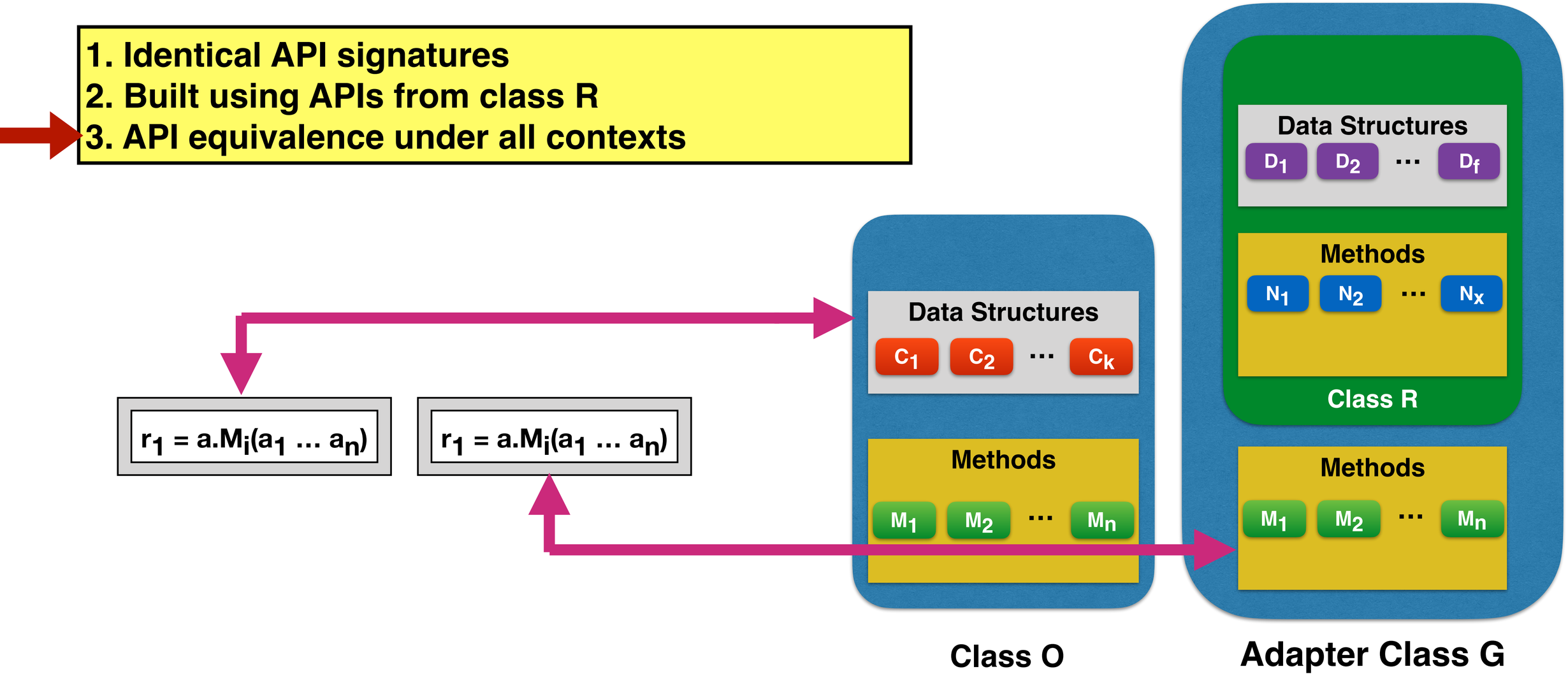

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   a) Return *equivalent value* for equivalent history
   b) Drives *all* objects to *equivalent states*
   c) Creates an equivalent *aliasing* between *all variables* and their *dereferences*

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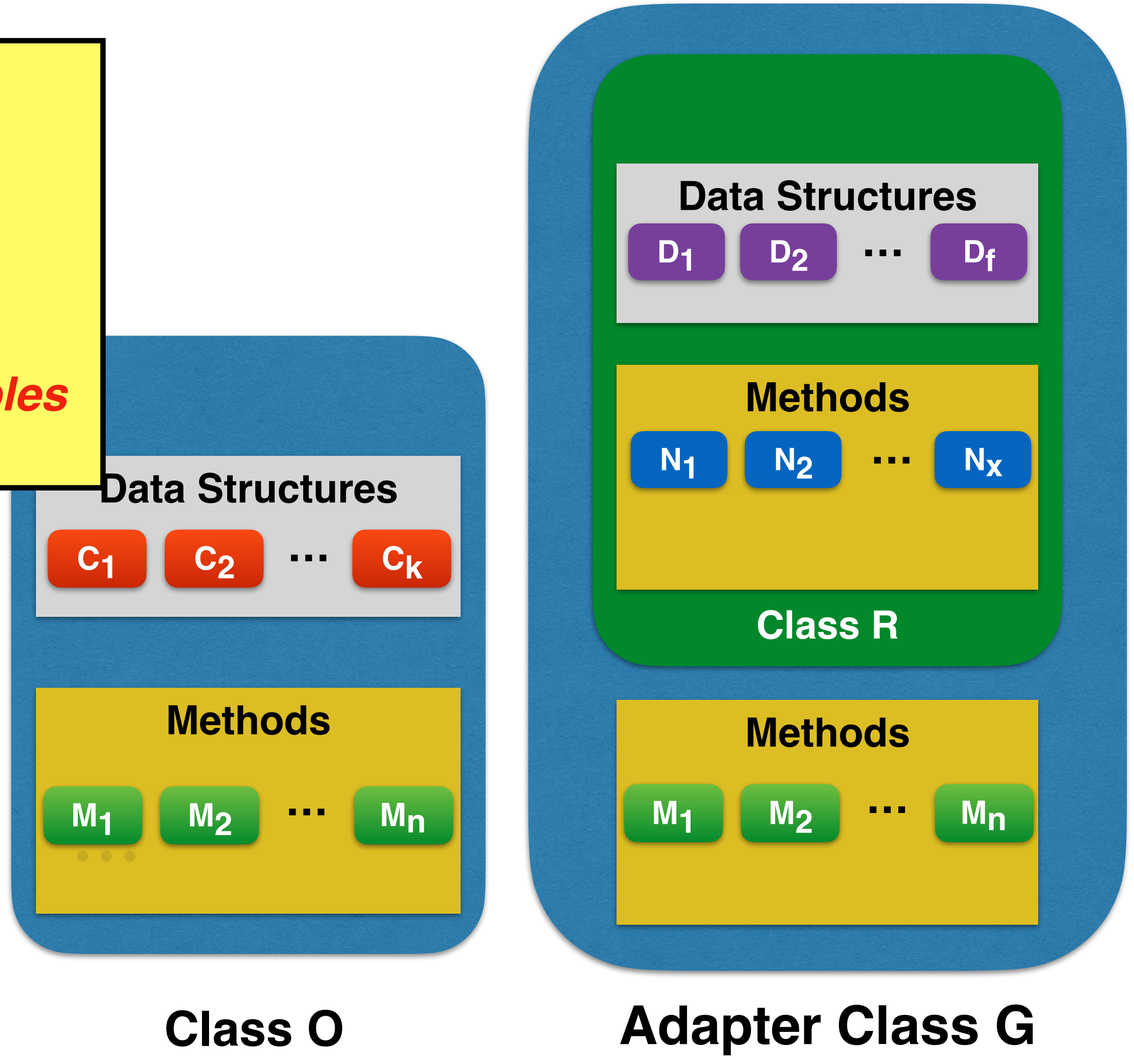

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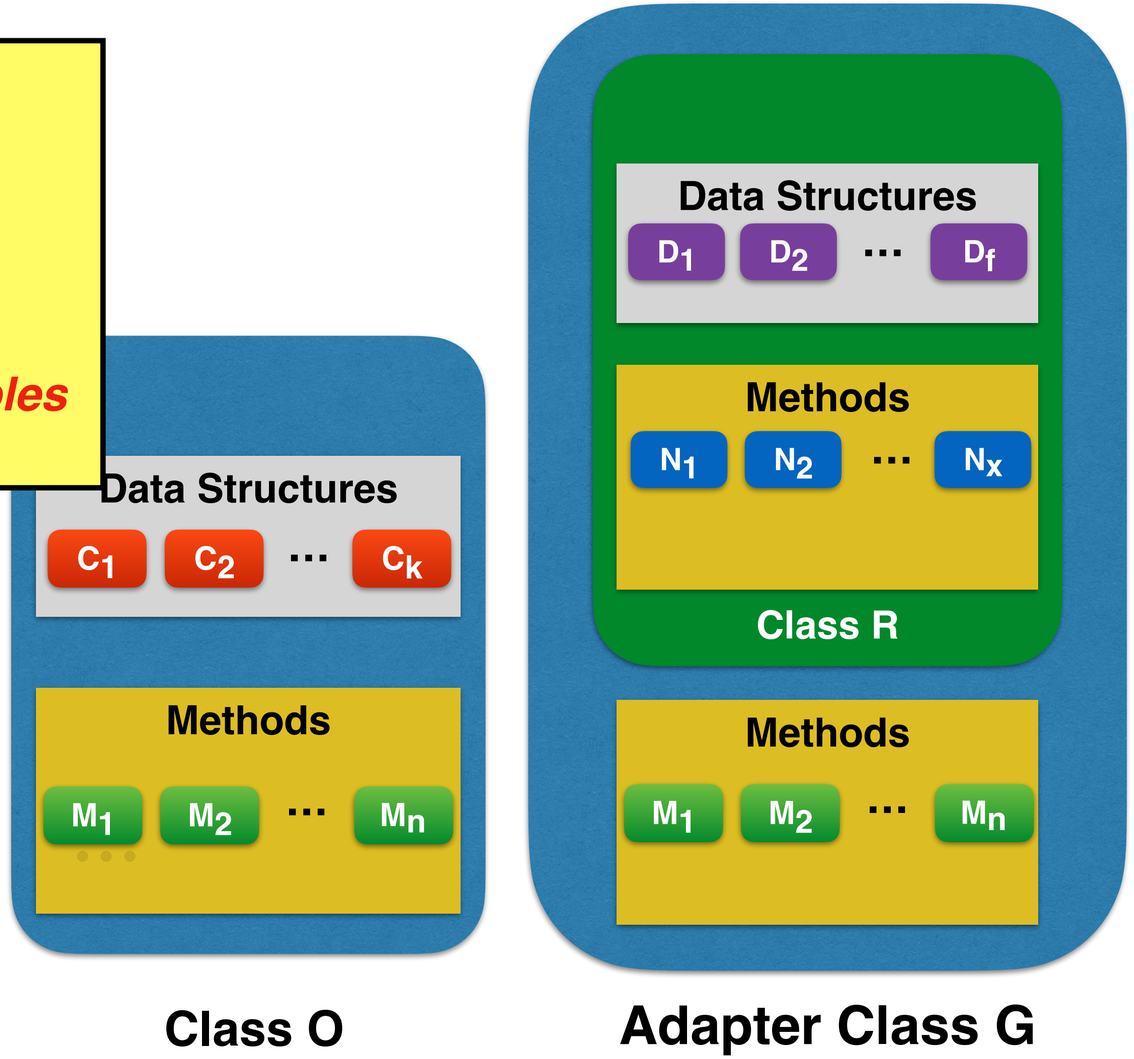
r1 ≡ r1



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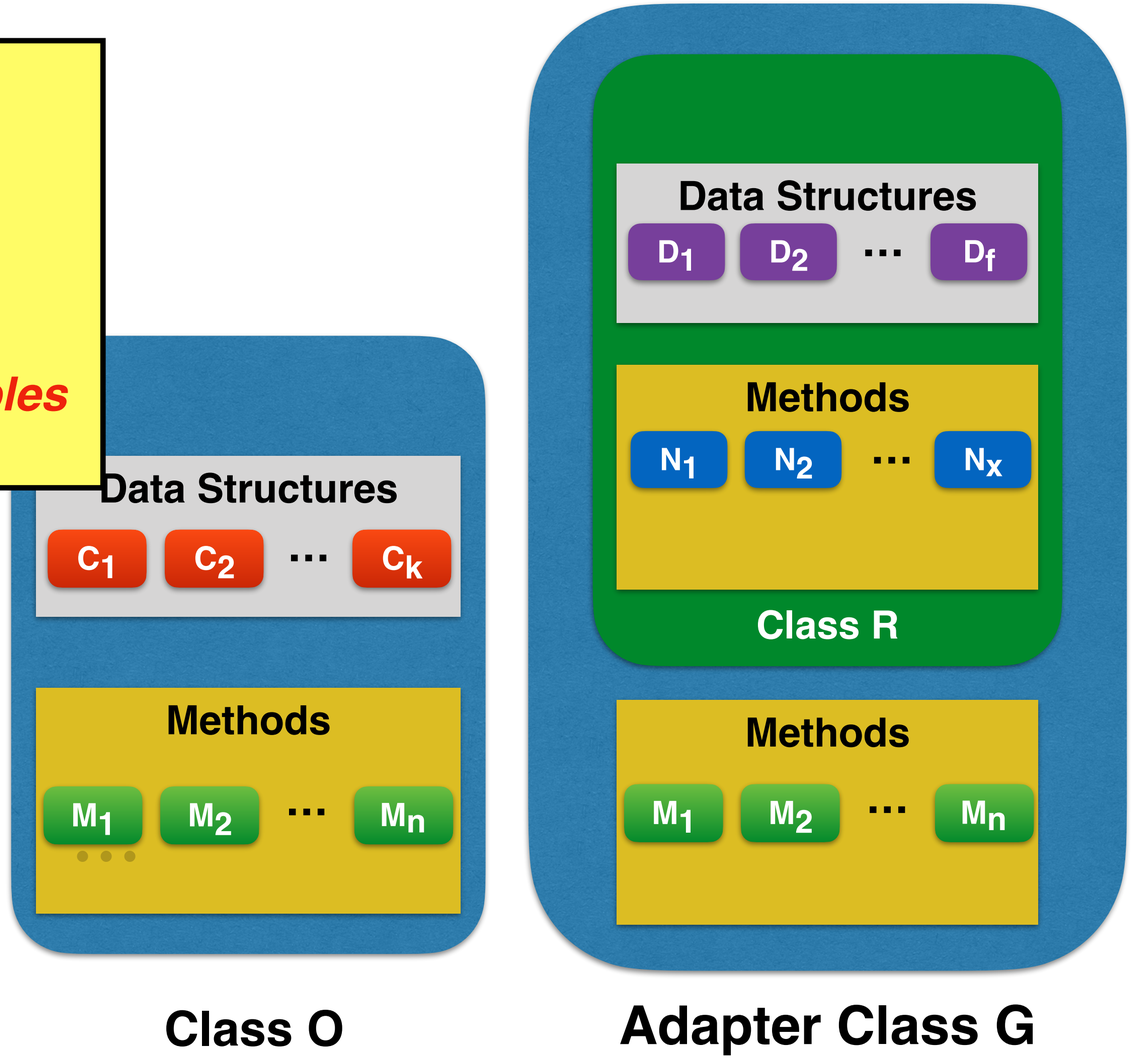
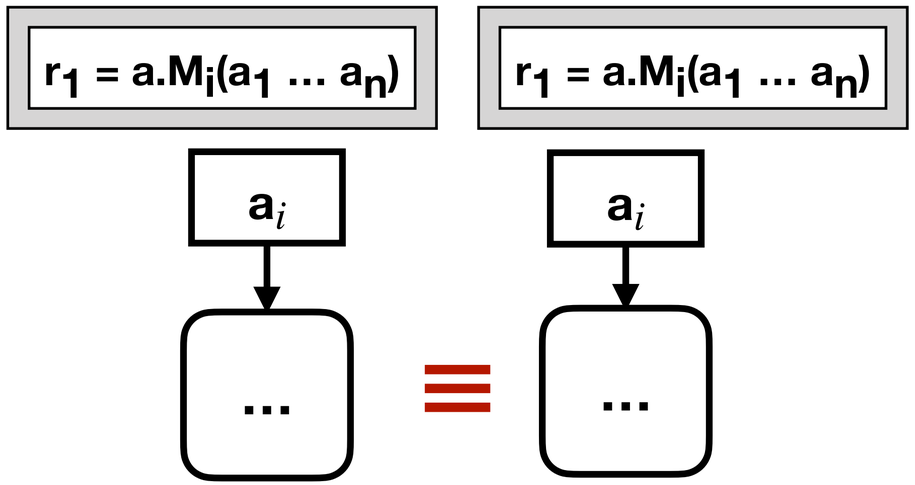
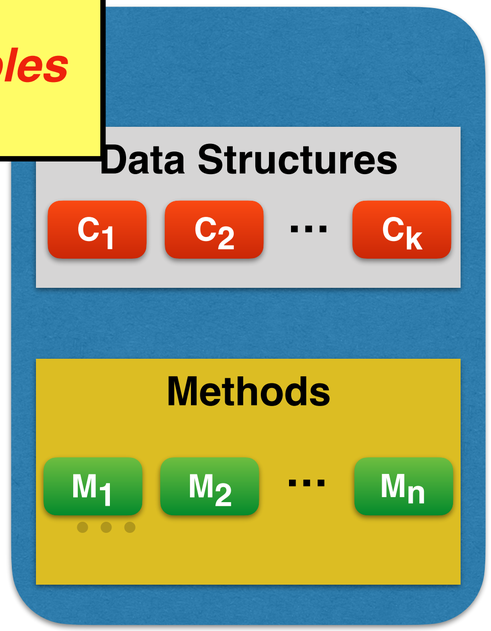


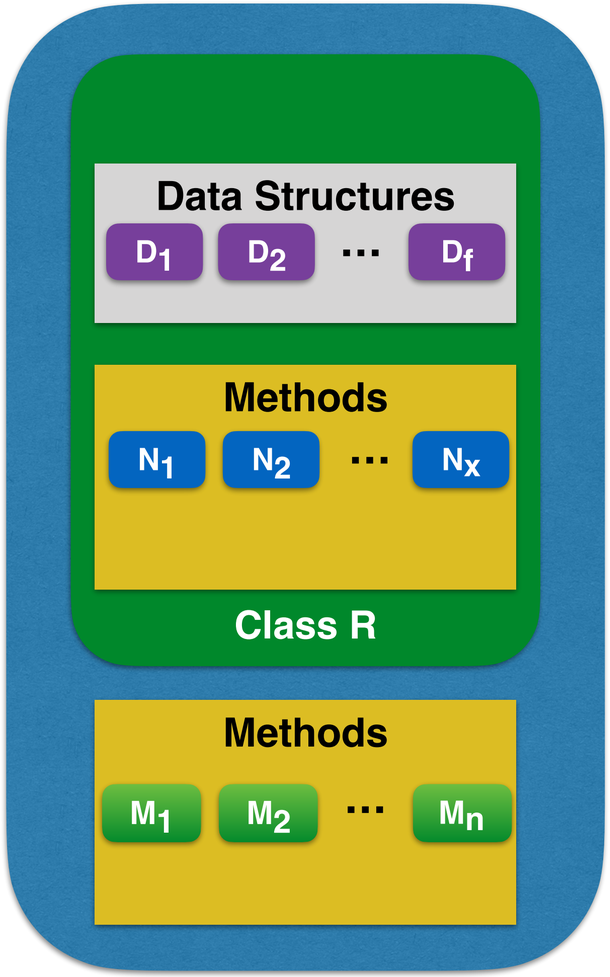
Adapter Class Requirements

1. Identical API signatures
2. Built using APIs from class R
3. API equivalence under all contexts
   a) Return *equivalent value* for equivalent history
   b) Drives *all* objects to *equivalent states*
   c) Creates an equivalent *aliasing* between *all variables* and their *dereferences*





Class O



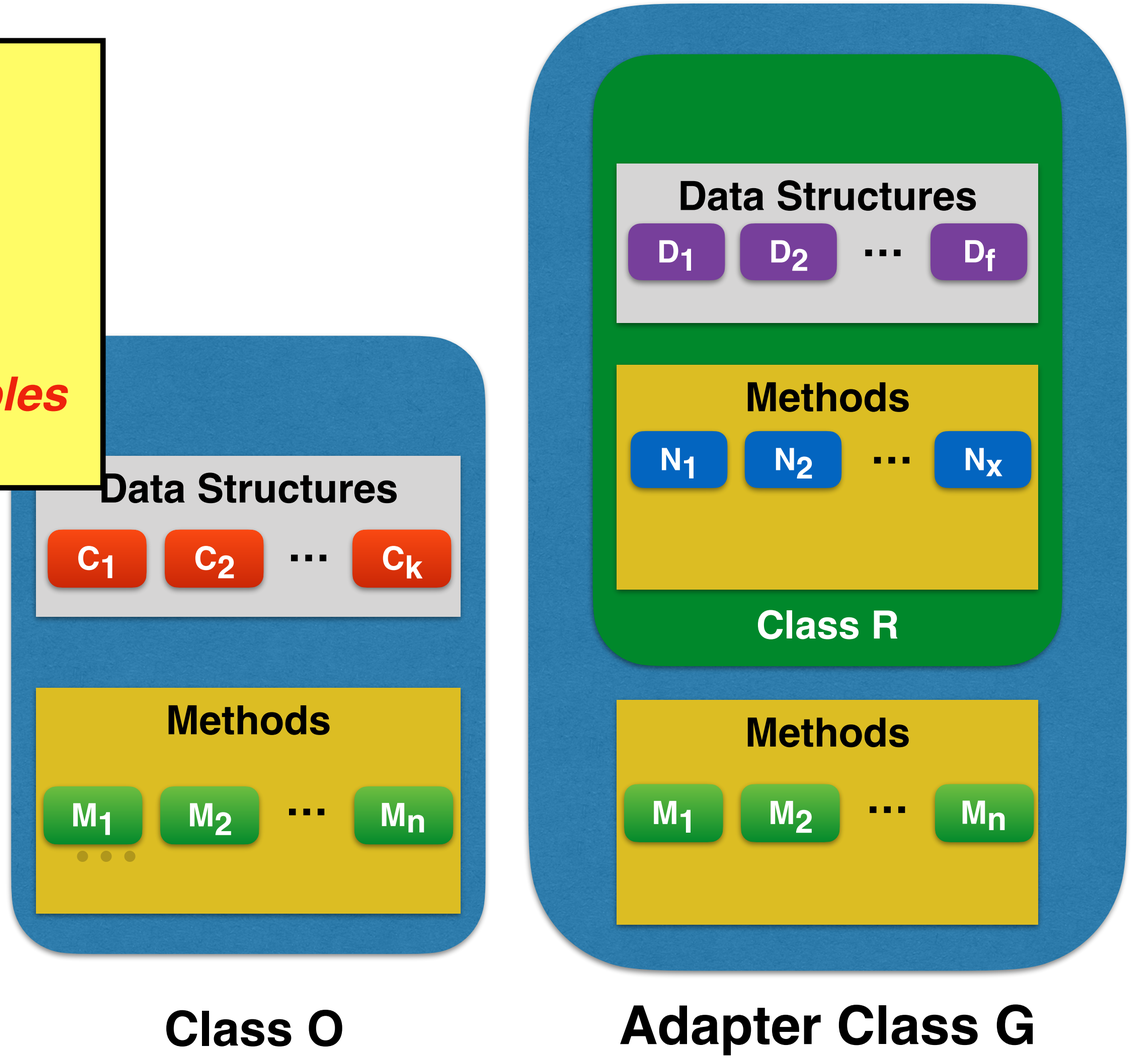
Adapter Class G

Adapter Class Requirements

1. Identical API signatures
2. Built using APIs from class R
3. API equivalence under all contexts
   a) Return *equivalent value* for equivalent history
   b) Drives *all* objects to *equivalent states*
   c) Creates an equivalent *aliasing* between *all variables* and their *dereferences*

$r_1 = a.M_i(a_1 \ldots a_n)$

$r_1 = a.M_i(a_1 \ldots a_n)$



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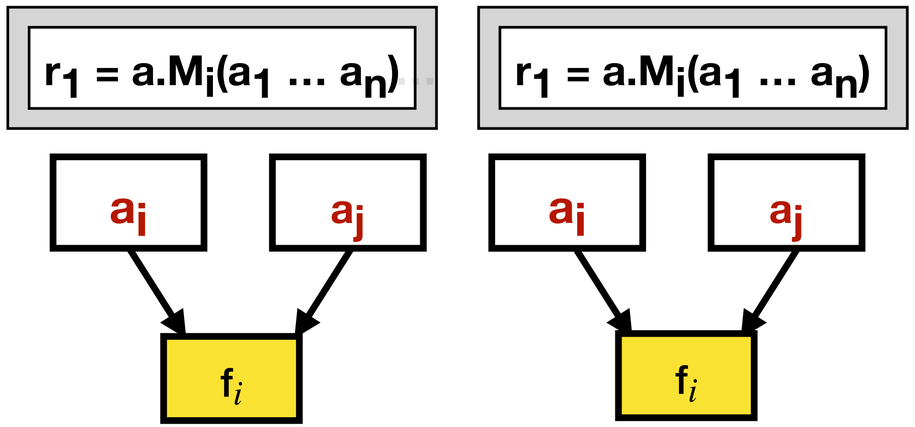

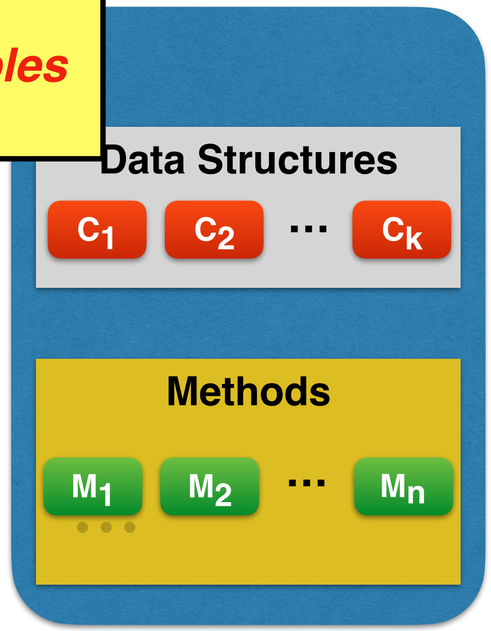

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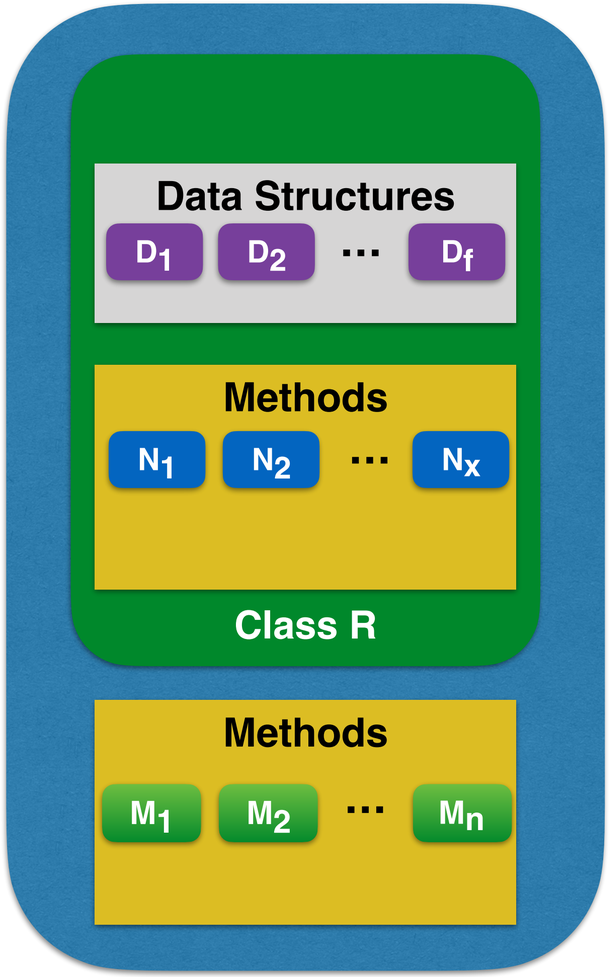

Adapter Class G

Adapter Class Requirements

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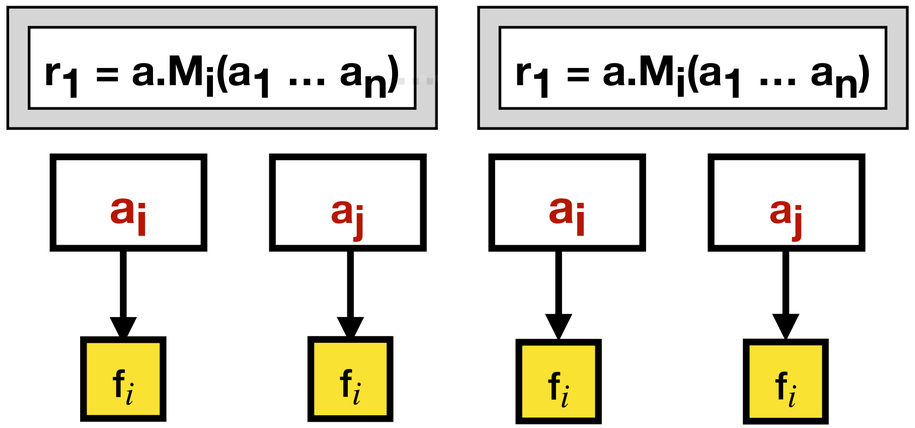
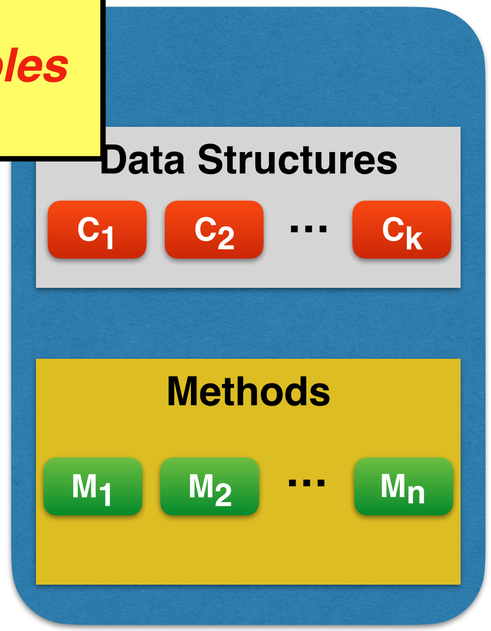
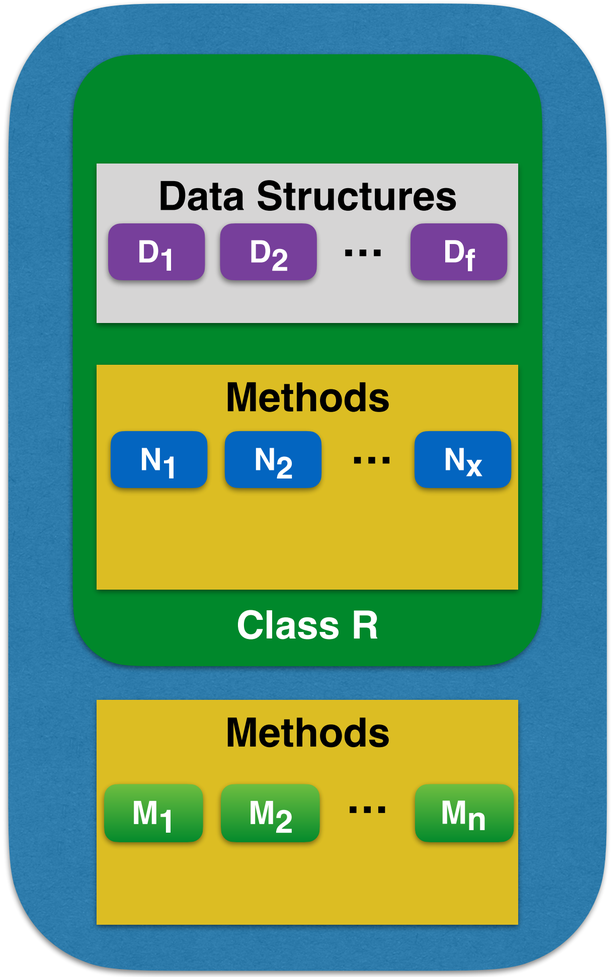




Class O



Adapter Class G

Class replacement example

Class replacement example

```
int x1, y1, x2, y2;

Box (int a, int b, int c, int d) {
   x1 = a; y1 = b;  x2 = c; y2 = d;
}

int length () {
  return x2 - x1;
}

Box expand (int val) {
  Box b = new Box (x1 - val, y1 - val,
                   x2 + val, y2 + val);
  return b;
}

...
```

BOX

Class replacement example

int x1, y1, x2, y2;

```
Box (int a, int b, int c, int d) {
   x1 = a; y1 = b;  x2 = c; y2 = d;
}

int length () {
  return x2 - x1;
}

Box expand (int val) {
  Box b = new Box (x1 - val, y1 - val,
                   x2 + val, y2 + val);
  return b;
}
```

…

BOX

int x, y, width, height;

```
Rectangle (Rectangle r) {
 this (r.x, r.y, r.width, r.height);
}

Rectangle (int a, int b, int c, int d) {
 x = a; y = b; width = c; height = d;
}

int width () { return width;}

Rectangle shrink (int h, int v) {
 x += h; width -= (h+h);
 y += v; height -=(v+v);
 return this;
}
```

…

RECTANGLE

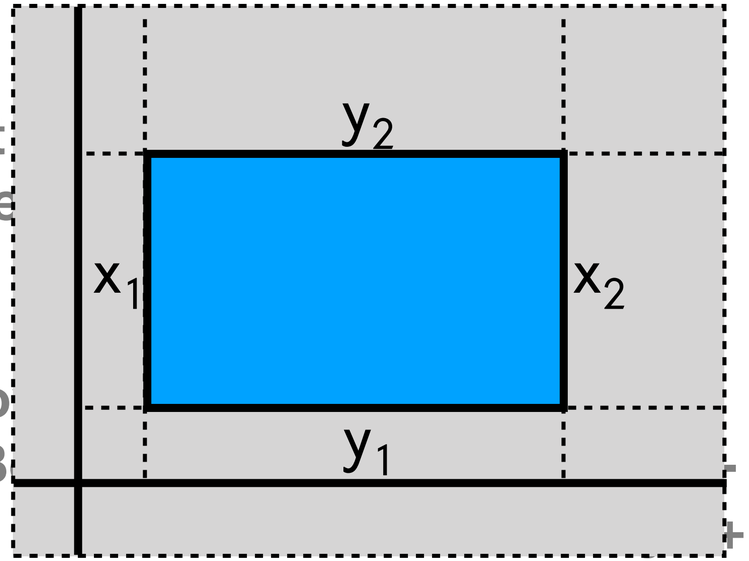
Class replacement example

int x1, y1, x2, y2;

```
Box (int a, int b, int c, int d) {
   x1 = a; y1 = b;  x2 = c; y2 = d;
}

int
  re
}

Bo
  B                                  - val,
                                     + val);
  return b;
}
```



...

BOX

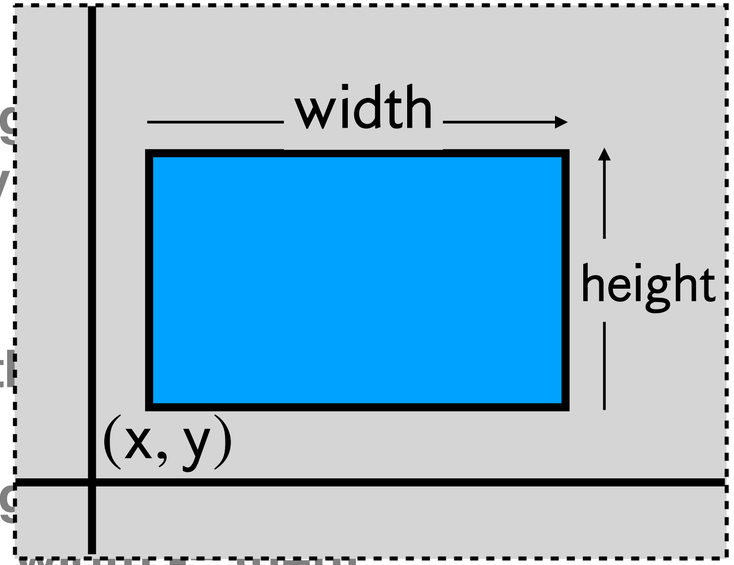
int x, y, width, height;

```
Rectangle (Rectangle r) {
 this (r.x, r.y, r.width, r.height);
}

Rectang
 x = a; y
}

int widt

Rectang
 x += h; width -= (h+h);
 y += v; height -=(v+v);
 return this;
}
```



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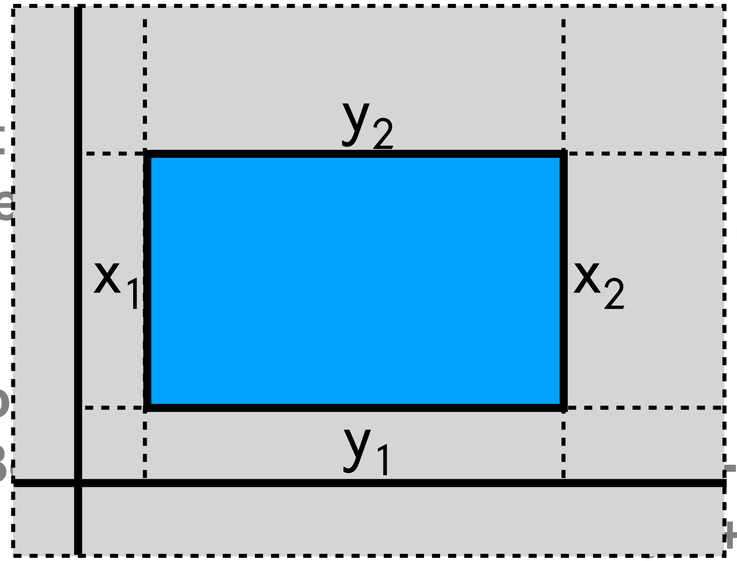


...

BOX

INTER-CLASS EQUIVALENCE PREDICATE

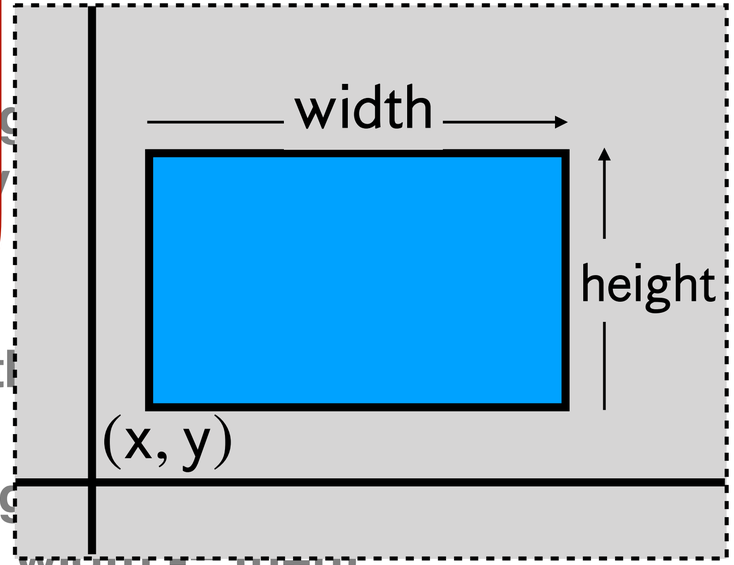
$$x_1 = x$$
$$y_1 = y$$
$$x_2 = x + width$$
$$y_2 = y + height$$

int x, y, width, height;

```
gle (Rectangle r) {
x, r.y, r.width, r.height);

int widt

Rectang
 x += h; width -= (h+h);
 y += v; height -=(v+v);
 return this;
}
```



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RECTANGLE

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```
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}

Box expand (int val) {
  Box b = new Box (x1 - val, y1 - val,
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  return b;
}
```

…

BOX

INTER-CLASS EQUIVALENCE PREDICATE

$$x_1 = x$$
$$y_1 = y$$
$$x_2 = x + \text{width}$$
$$y_2 = y + \text{height}$$

int x, y, width, height;

```
gle (Rectangle r) {
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int width () { return width;}

Rectangle shrink (int h, int v) {
 x += h; width -= (h+h);
 y += v; height -=(v+v);
 return this;
}
```

…

RECTANGLE

Class replacement example

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BOX

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  Box b = new Box (x1 - val, y1 - val,
                   x2 + val, y2 + val);
  return b;
}

...
```

BOX

```
Rectangle rect;

Adapter (Rectangle r) { rect = r; }

Adapter (int a, int b, int c, int d) {
   rect = new Rectangle(a, b, c-a, d-b);
}

int length () {
  int ret = rect.width();
  return ret;
}

Adapter expand (int val) {
  Rectangle ret = new Rectangle (rect);
  ret.shrink (-val, -val);
  return new Adapter (ret);
}

...
```

Adapter

Class replacement example

```
int x1, y1, x2, y2;

Box (int a, int b, int c, int d) {
   x1 = a; y1 = b;  x2 = c; y2 = d;
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  Box b = new Box (x1 - val, y1 - val,
                   x2 + val, y2 + val);
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...
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Adapter

Class replacement example

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                   ...
```

Rectangle rect;

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Class replacement example

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Box expand (int val) {
  Box b = new Box (x1 - val, y1 - val,
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  return b;
}

...
```

Rectangle rect;

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}

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  int ret = rect.width();
  return ret;
}

Adapter expand (int val) {
  Rectangle ret = new Rectangle (rect);
  ret.shrink (-val, -val);
  return new Adapter (ret);
}
                                    Adapter
...
```

Challenges for MASK

1. Establish an inter-class equivalence predicate

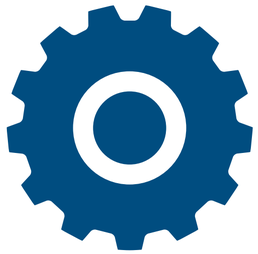
2. Synthesize the adapter class

    Verify correctness of ***all*** adapter methods with inter-class equivalence

Synthesizing the adapter class via Sketching

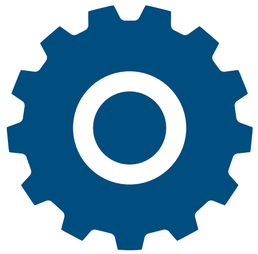
Synthesizing adapter class via sketching

Inter-class Equivalence Predicate

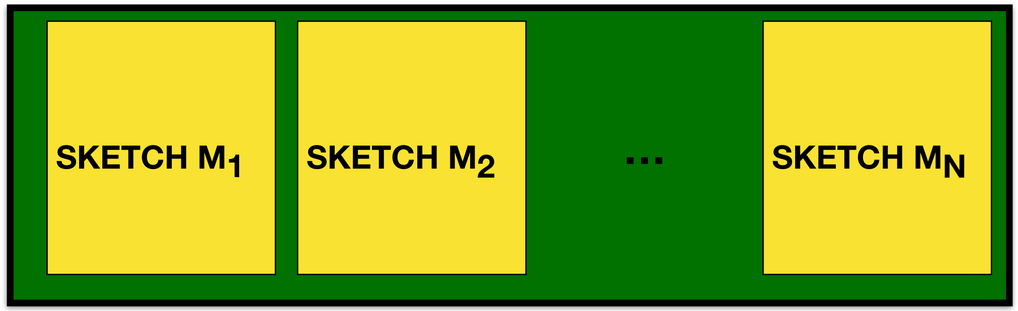


Synthesizing adapter class via sketching

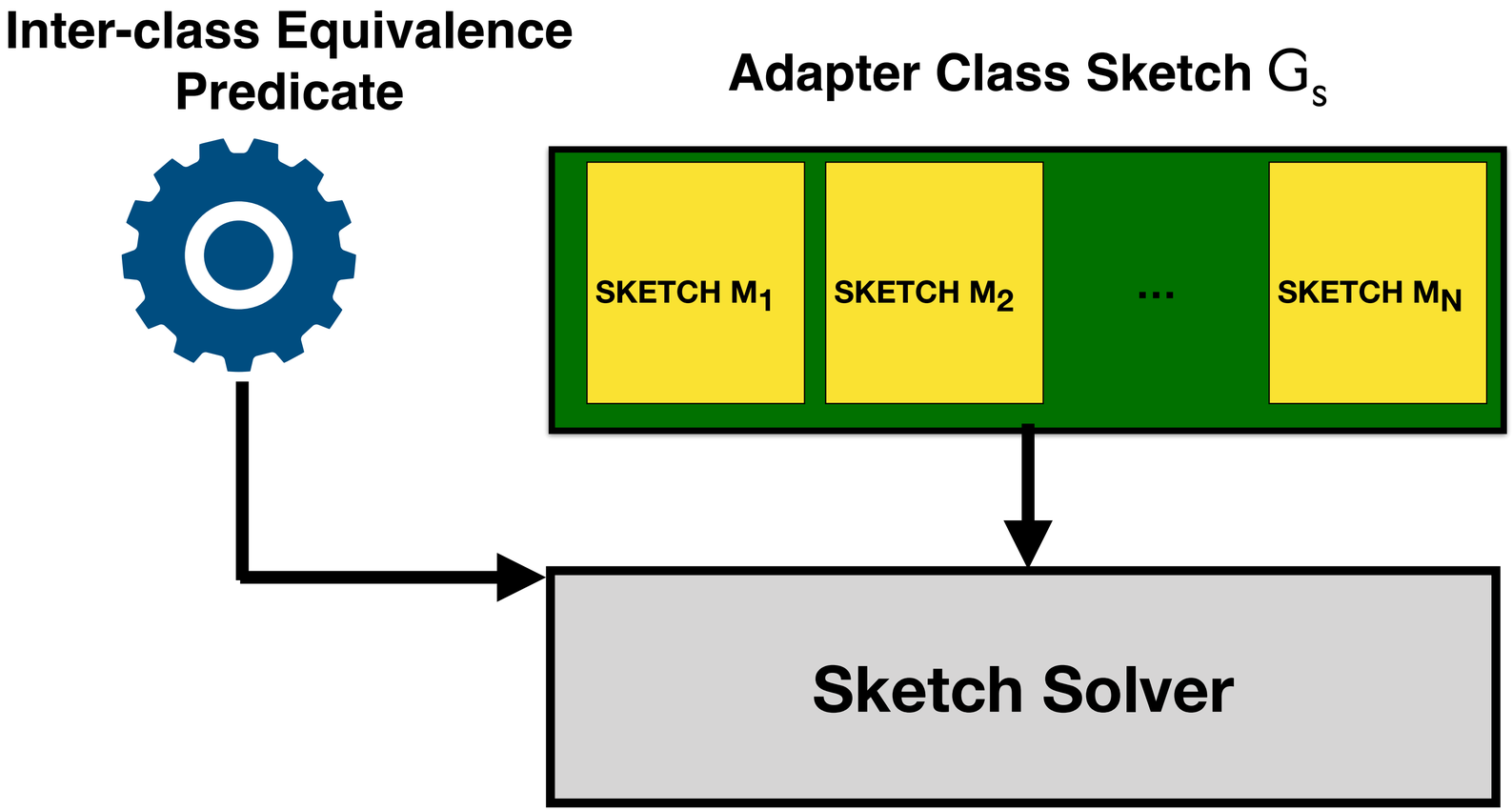
Inter-class Equivalence Predicate



Adapter Class Sketch G_s



Synthesizing adapter class via sketching



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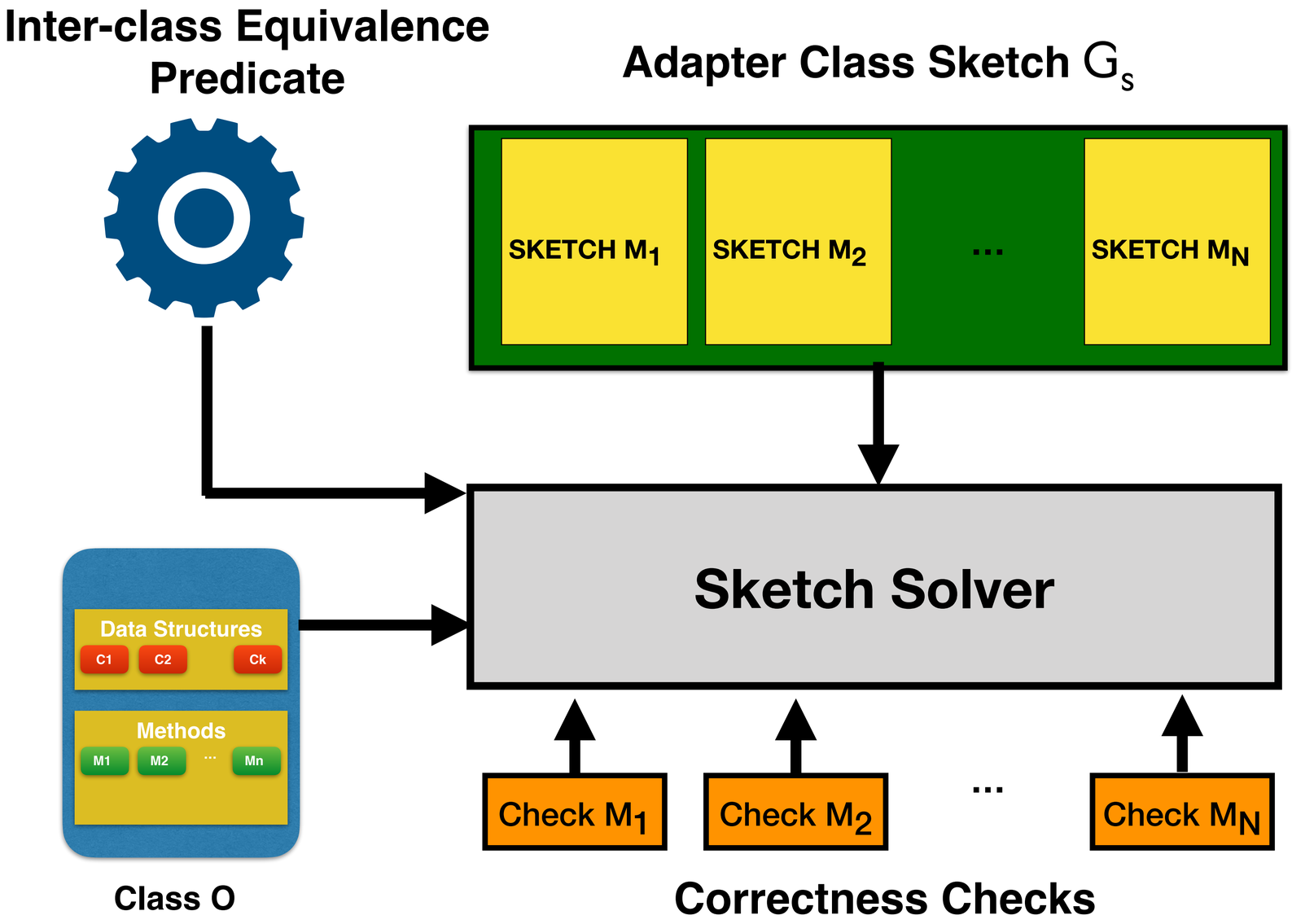

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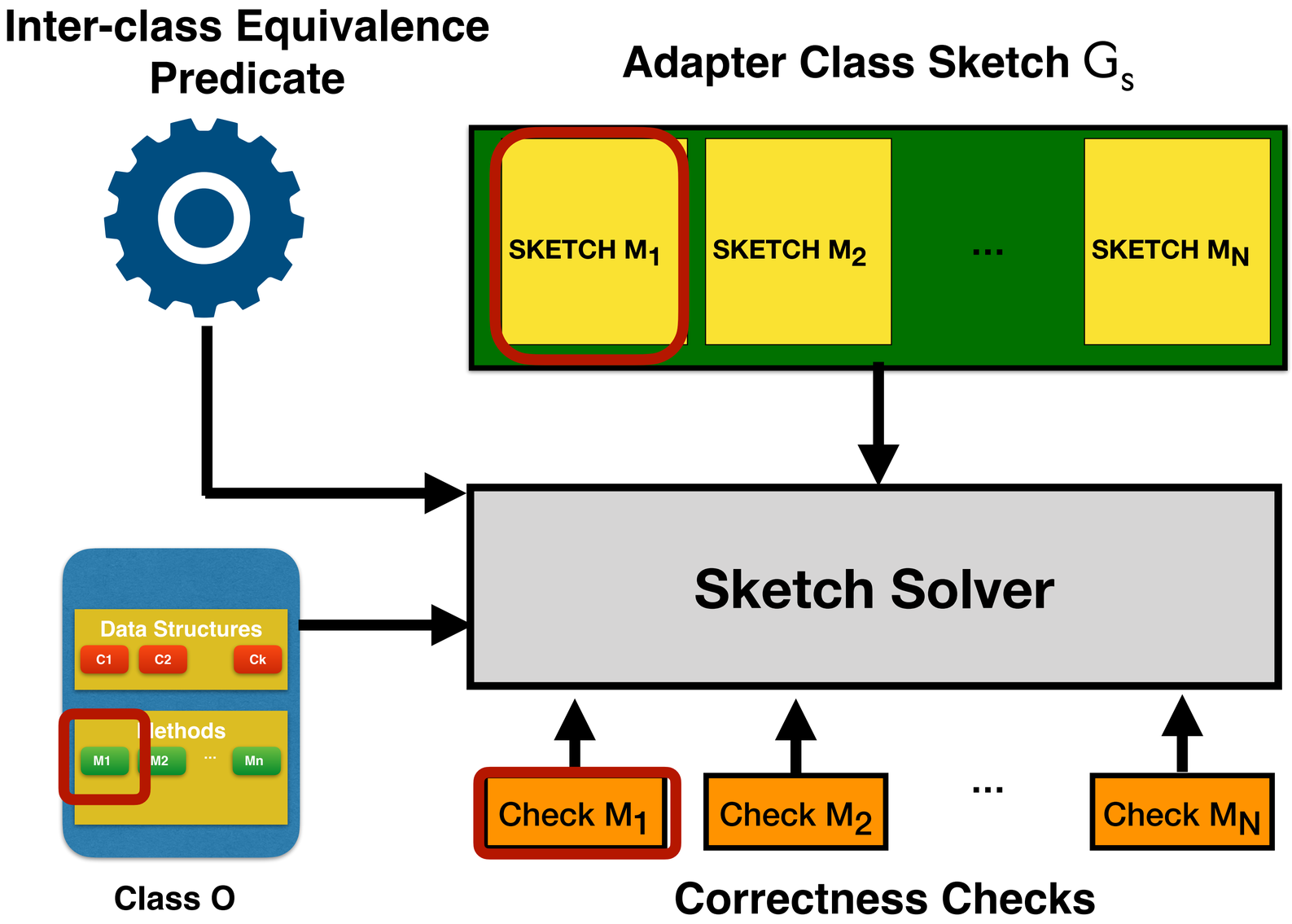
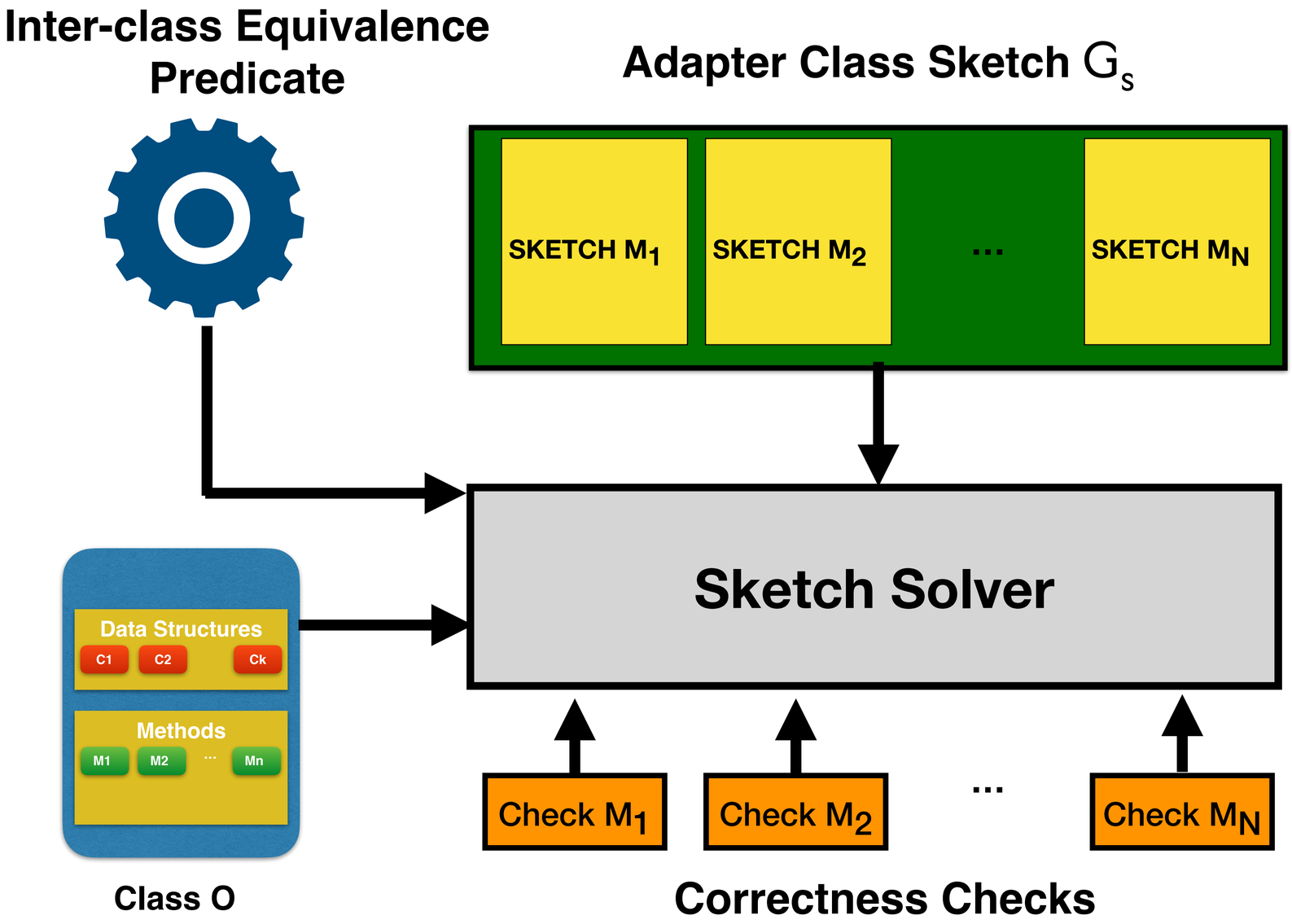


Synthesizing adapter class via sketching



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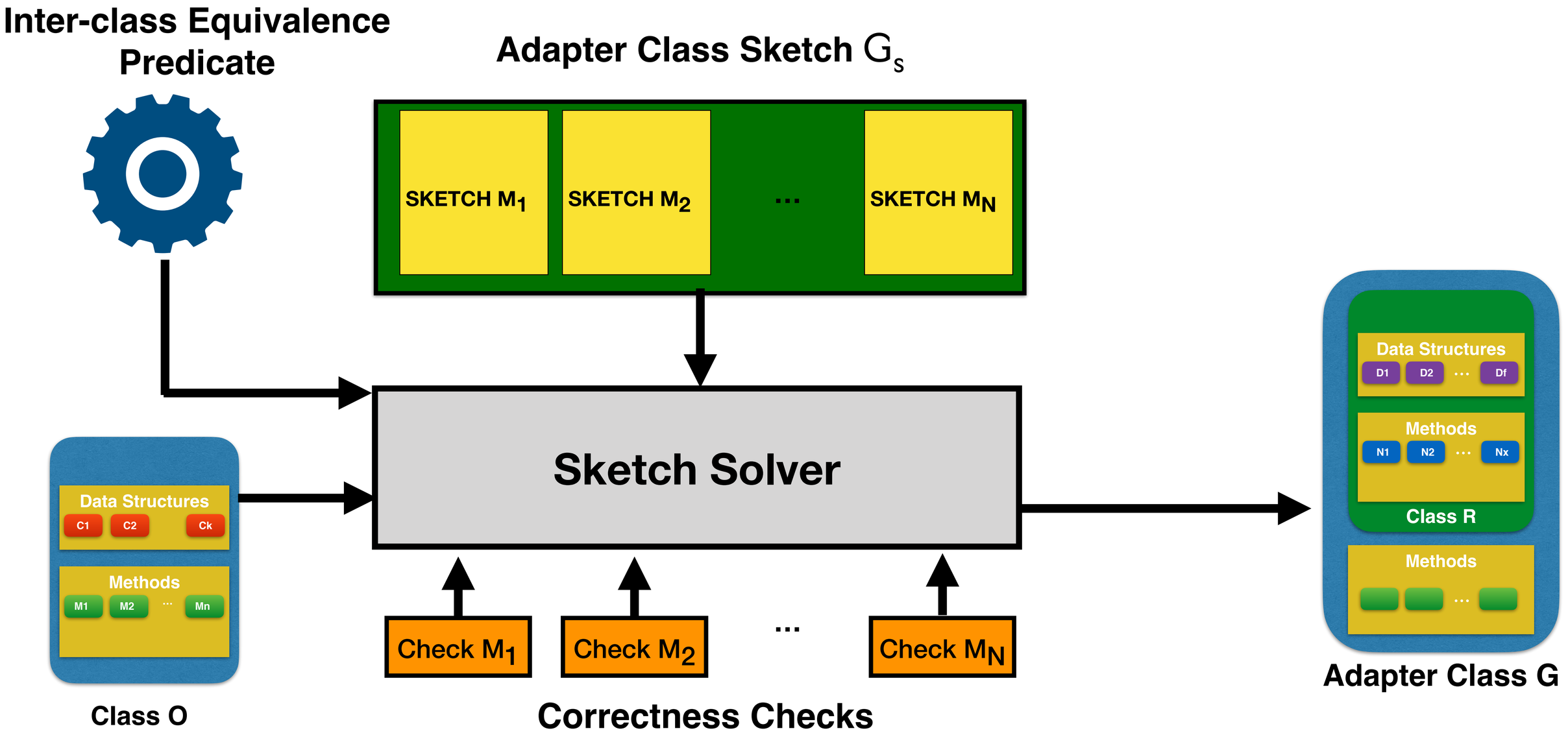
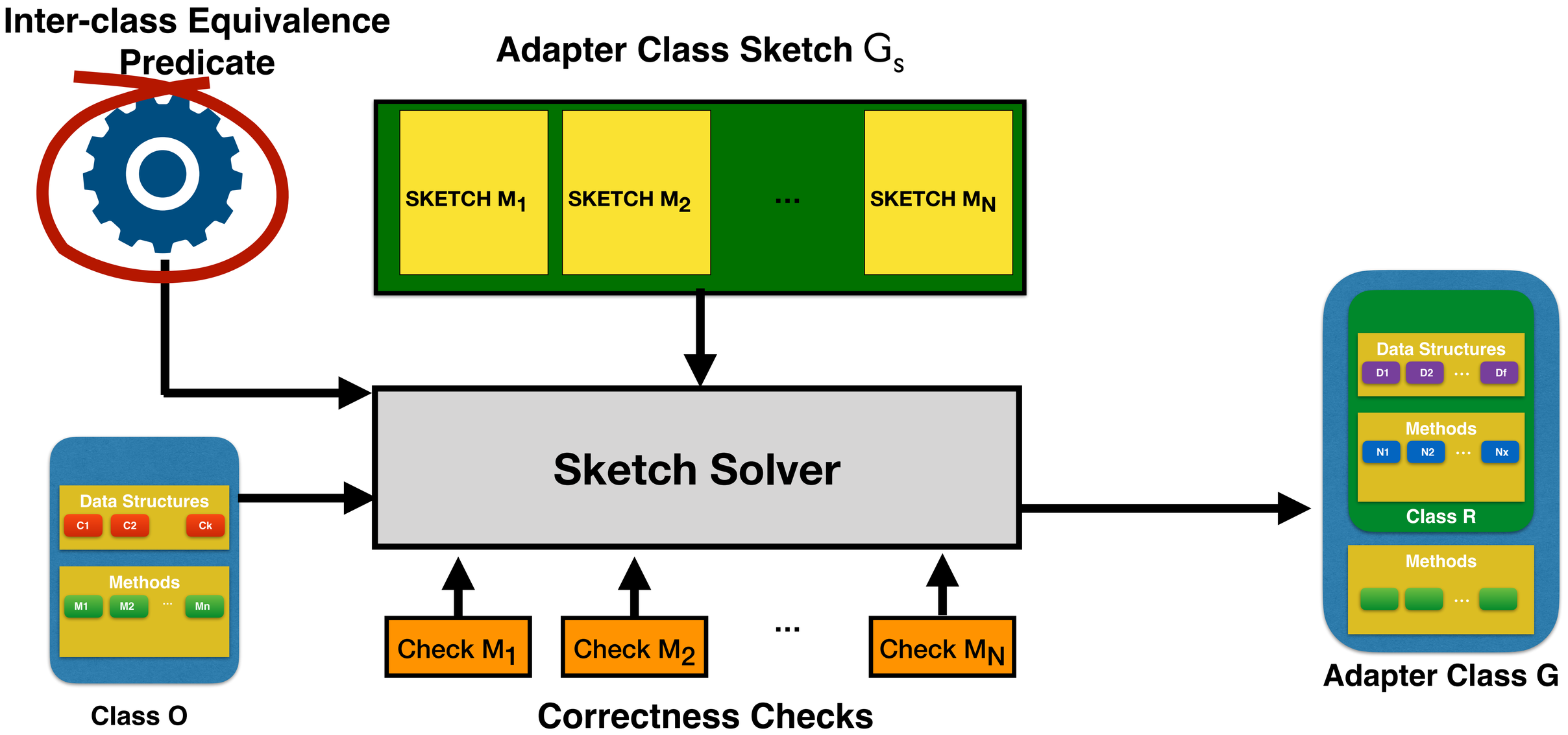


Synthesizing adapter class via sketching



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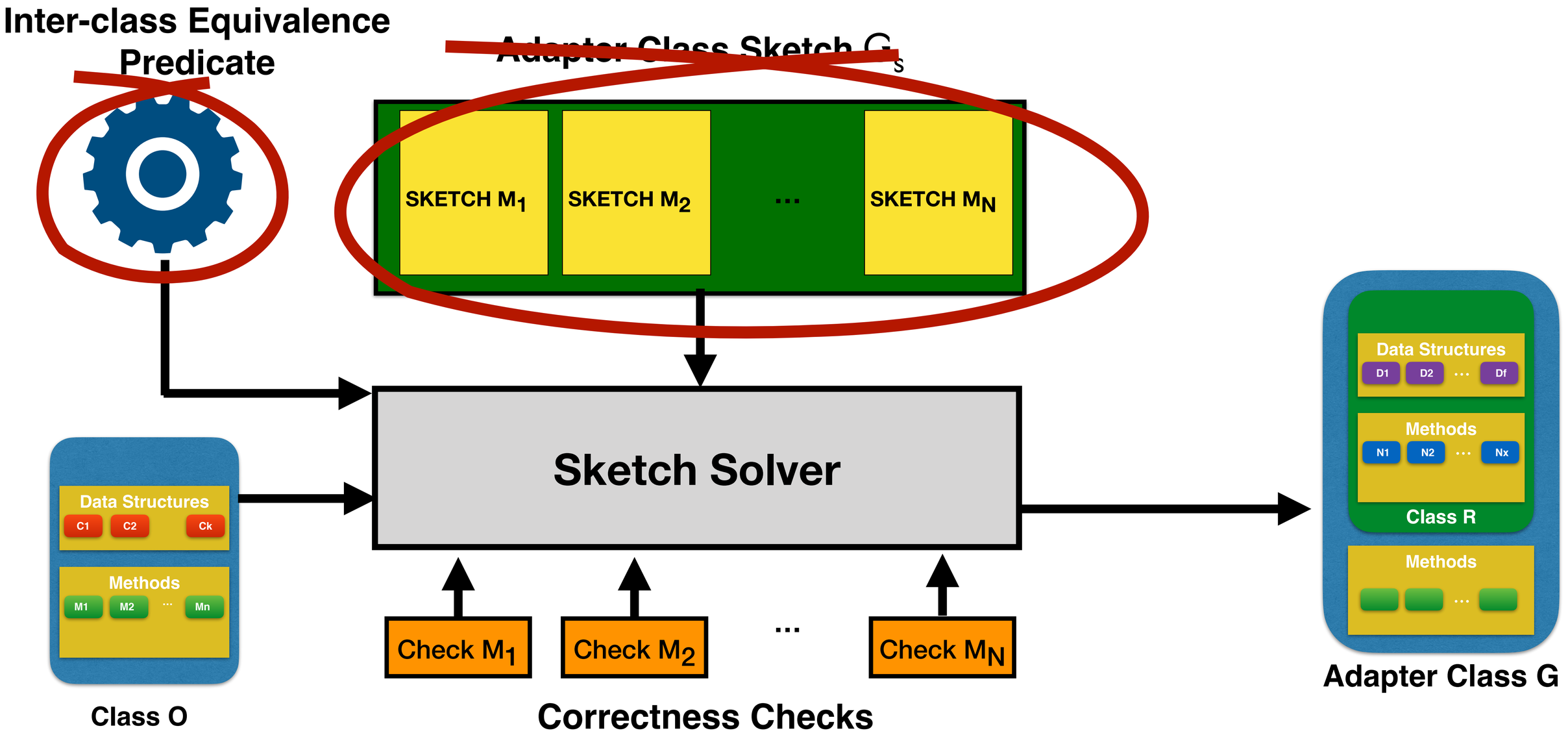

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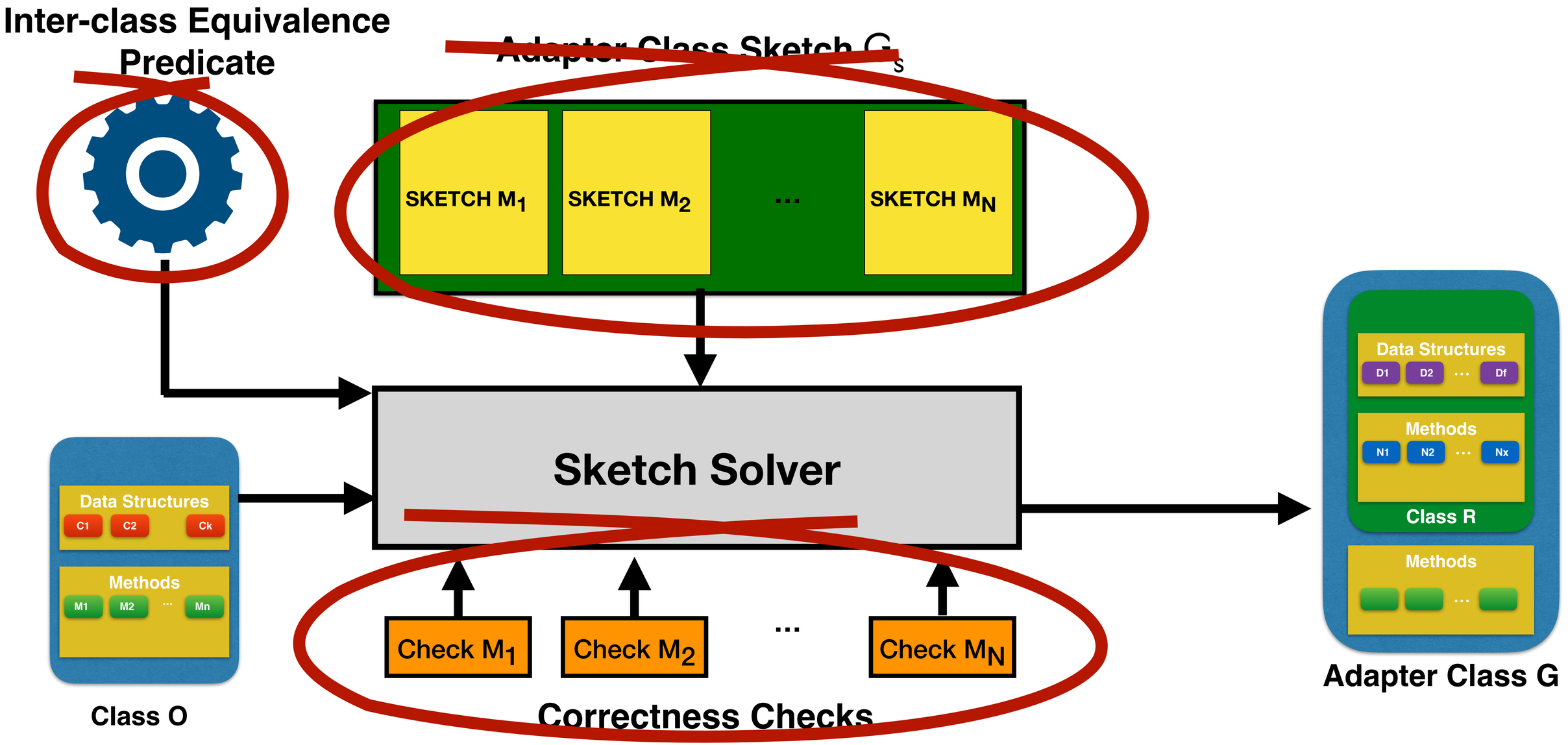
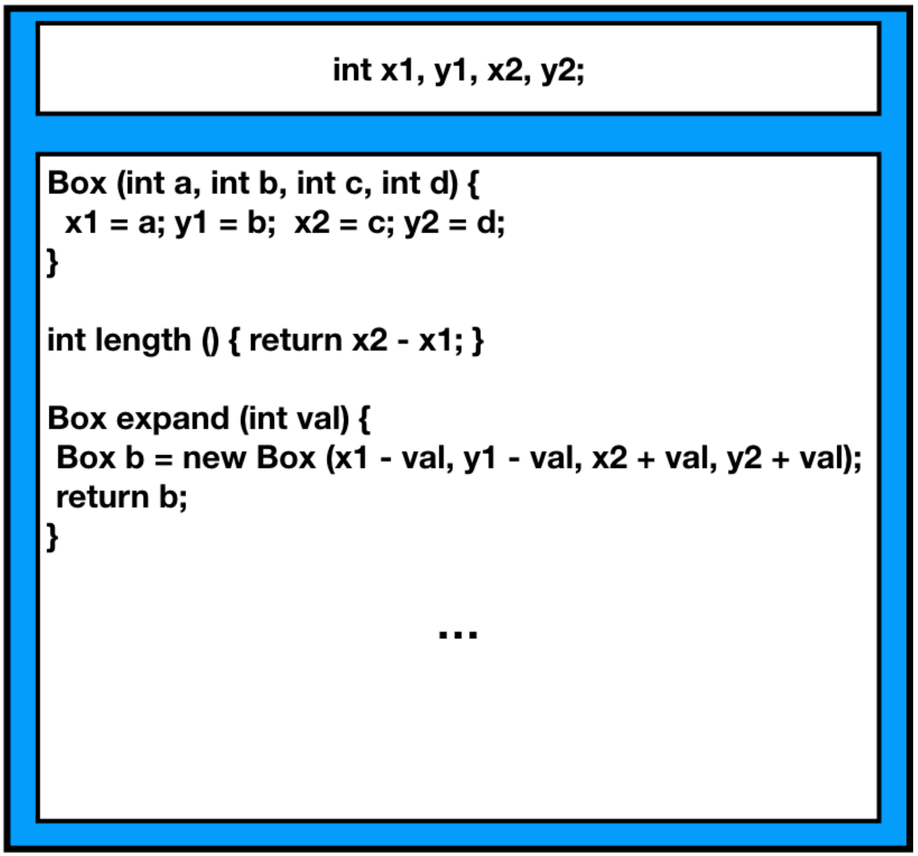
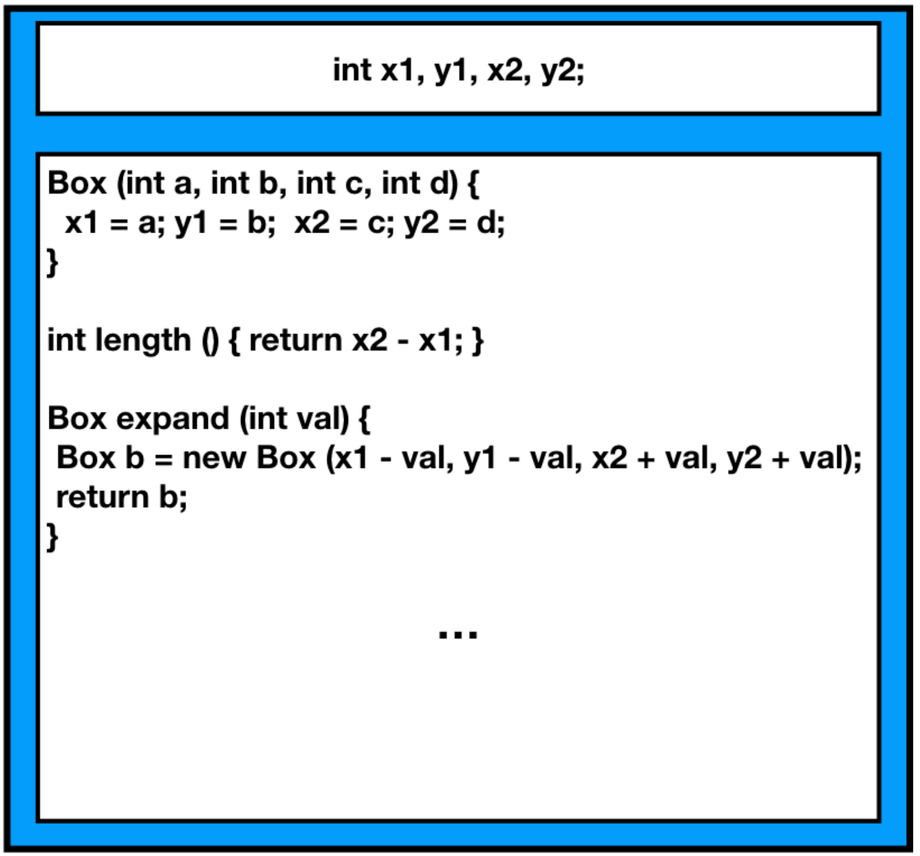


Building the adapter method sketch



Building the adapter method sketch

Box expand(int val)



Box

Building the adapter method sketch

Box expand(int val)

```
int x1, y1, x2, y2;

Box (int a, int b, int c, int d) {
  x1 = a; y1 = b;  x2 = c; y2 = d;
}

int length () { return x2 - x1; }

Box expand (int val) {
 Box b = new Box (x1 - val, y1 - val, x2 + v
 return b;
}

...
```

Box

```
Adapter expand(int val) {
   Rectangle retRect1 = null; int retInt1 = 0;
   switch (??) {
      case 1: retRect1 = new Rectangle ( ); break;
      case 2: retRect1 = new Rectangle (this.rect); break;
      case 3: retInt1 = width(); break;
      case 4: rect.shrink ({val | -val | ??}, {val | -val | ??});
break;
                              ...
      default:
   }

   Rectangle retRect2 = null; int retInt2 = 0;
   switch (??) { ... }

   return new Adapter({this.rect | retRect1 | retRect2 | null});
}
```

SKETCH

Building the adapter method sketch

Box expand(int val)

```
int x1, y1, x2, y2;

Box (int a, int b, int c, int d) {
  x1 = a; y1 = b;  x2 = c; y2 = d;
}

int length () { return x2 - x1; }

Box expand (int val) {
 Box b = new Box (x1 - val, y1 - val, x2 + v
 return b;
}

...
```

Box

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Adapter expand(int val) {
  Rectangle retRect1 = null; int retInt1 = 0;
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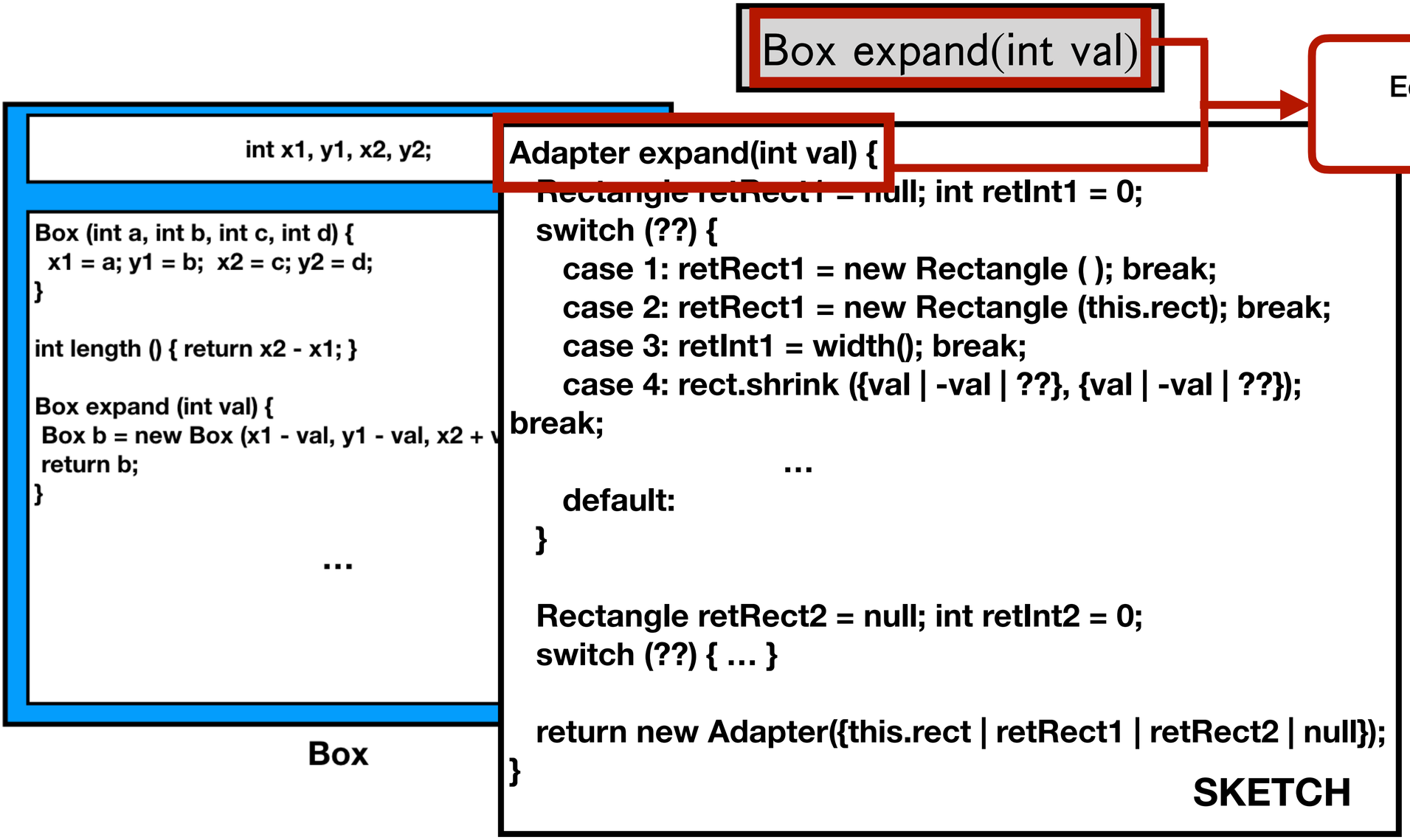
     case 3: retInt1 = width(); break;
     case 4: rect.shrink ({val | -val | ??}, {val | -val | ??});
break;
                          ...
     default:
  }

  Rectangle retRect2 = null; int retInt2 = 0;
  switch (??) { ... }

  return new Adapter({this.rect | retRect1 | retRect2 | null});
}
```

SKETCH

Building the adapter method sketch



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      case 4: rect.shrink ({val | -val | ??}, {val | -val | ??});
break;
                              ...
      default:
   }

   Rectangle retRect2 = null; int retInt2 = 0;
   switch (??) { ... }

   return new Adapter({this.rect | retRect1 | retRect2 | null});
}
```

SKETCH

Building the adapter method sketch

Box expand(int val)

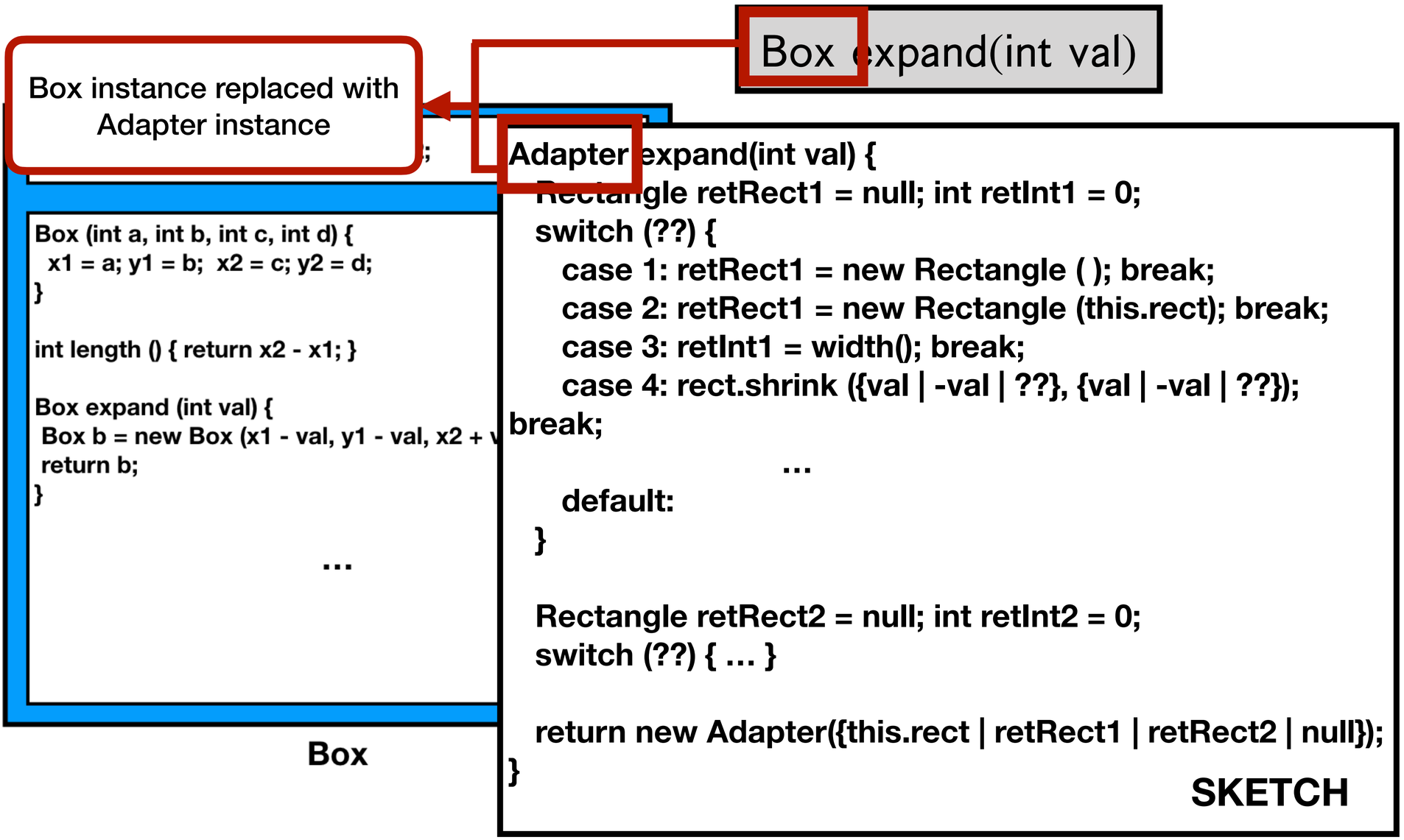
```
int x1, y1, x2, y2;

Box (int a, int b, int c, int d) {
  x1 = a; y1 = b;  x2 = c; y2 = d;
}

int length () { return x2 - x1; }

Box expand (int val) {
 Box b = new Box (x1 - val, y1 - val, x2 + v
 return b;
}

...
```

Box

```
Adapter expand(int val) {
  Rectangle retRect1 = null; int retInt1 = 0;
  switch (??) {
     case 1: retRect1 = new Rectangle ( ); break;
     case 2: retRect1 = new Rectangle (this.rect); break;
     case 3: retInt1 = width(); break;
     case 4: rect.shrink ({val | -val | ??}, {val | -val | ??});
break;
                          ...
     default:
  }

  Rectangle retRect2 = null; int retInt2 = 0;
  switch (??) { ... }

  return new Adapter({this.rect | retRect1 | retRect2 | null});
}
```

SKETCH

Building the adapter method sketch



Building the adapter method sketch

Box expand(int val)

```
int x1, y1, x2, y2;

Box (int a, int b, int c, int d) {
  x1 = a; y1 = b;  x2 = c; y2 = d;
}

int length () { return x2 - x1; }

Box expand (int val) {
 Box b = new Box (x1 - val, y1 - val, x2 + v
 return b;
}

...
```

Box

```
Adapter expand(int val) {
   Rectangle retRect1 = null; int retInt1 = 0;
   switch (??) {
      case 1: retRect1 = new Rectangle ( ); break;
      case 2: retRect1 = new Rectangle (this.rect); break;
      case 3: retInt1 = width(); break;
      case 4: rect.shrink ({val | -val | ??}, {val | -val | ??});
break;
                              ...
      default:
   }

   Rectangle retRect2 = null; int retInt2 = 0;
   switch (??) { ... }

   return new Adapter({this.rect | retRect1 | retRect2 | null});
}
```

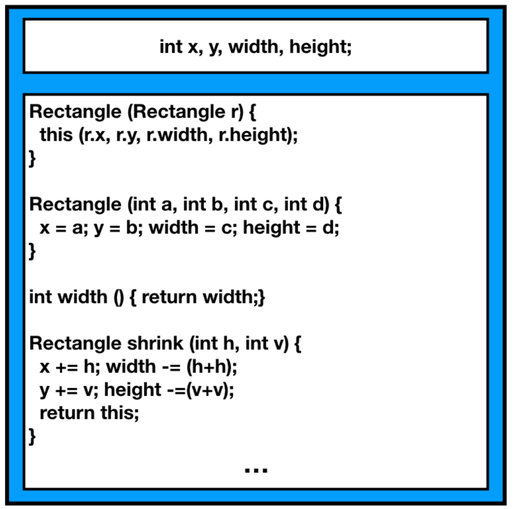
SKETCH

Building the adapter method sketch

Box expand(int c)

```
Adapter expand(int val) {
  Rectangle retRect1 = null; int retInt1 = 0;
  switch (??) {
    case 1: retRect1 = new Rectangle ( ); break;
    case 2: retRect1 = new Rectangle (this.rect); break;
    case 3: retInt1 = width(); break;
    case 4: rect.shrink ({val | -val | ??}, {val | -val | ??});
break;
                          …
    default:
  }

  Rectangle retRect2 = null; int retInt2 = 0;
  switch (??) { … }

  return new Adapter({this.rect | retRect1 | retRect2 | null});
}
```

SKETCH



Rectangle

Building the adapter method sketch

Box expand(int c)

```
Adapter expand(int val) {
  Rectangle retRect1 = null; int retInt1 = 0;
  switch (??) {
    case 1: retRect1 = new Rectangle ( ); break;
    case 2: retRect1 = new Rectangle (this.rect); break;
    case 3: retInt1 = width(); break;
    case 4: rect.shrink ({val | -val | ??}, {val | -val | ??});
break;
                          …
    default:
  }

  Rectangle retRect2 = null; int retInt2 = 0;
  switch (??) { … }

  return new Adapter({this.rect | retRect1 | retRect2 | null});
}
```

SKETCH

```
int x, y, width, height;

Rectangle (Rectangle r) {
  this (r.x, r.y, r.width, r.height);
}

Rectangle (int a, int b, int c, int d) {
  x = a; y = b; width = c; height = d;
}

int width () { return width;}

Rectangle shrink (int h, int v) {
  x += h; width -= (h+h);
  y += v; height -=(v+v);
  return this;
}
                          …
```

Rectangle

Building the adapter method sketch

Box expand(int c)

Choice to invoke a public method from Class R

```
Adapter expand(int val) {
  Rectangle retRect1 = null; int retInt1 = 0;
  switch (??) {
    case 1: retRect1 = new Rectangle ( ); break;
    case 2: retRect1 = new Rectangle (this.rect); break;
    case 3: retInt1 = width(); break;
    case 4: rect.shrink ({val | -val | ??}, {val | -val | ??});
... break;
                          ...
    default:
  }

  Rectangle retRect2 = null; int retInt2 = 0;
  switch (??) { ... }

  return new Adapter({this.rect | retRect1 | retRect2 | null});
}
```

SKETCH

```
int x, y, width, height;

Rectangle (Rectangle r) {
  this (r.x, r.y, r.width, r.height);
}

Rectangle (int a, int b, int c, int d) {
  x = a; y = b; width = c; height = d;
}

int width () { return width;}

Rectangle shrink (int h, int v) {
  x += h; width -= (h+h);
  y += v; height -=(v+v);
  return this;
}
                    ...
```

Rectangle

Building the adapter method sketch

Box expand(int c)

Choice to invoke a public method from Class R

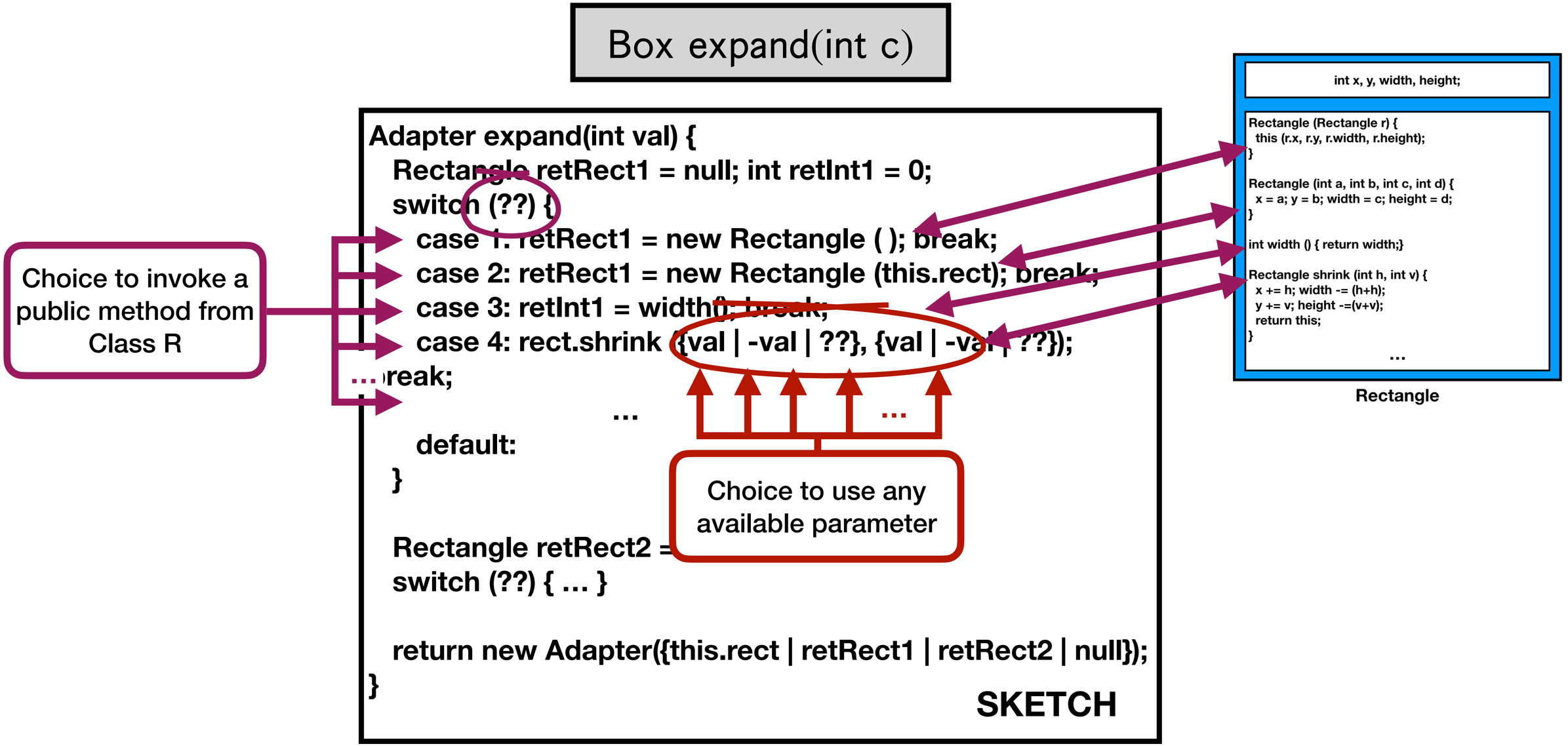
```
Adapter expand(int val) {
  Rectangle retRect1 = null; int retInt1 = 0;
  switch (??) {
    case 1: retRect1 = new Rectangle ( ); break;
    case 2: retRect1 = new Rectangle (this.rect); break;
    case 3: retInt1 = width(); break;
    case 4: rect.shrink ({val | -val | ??}, {val | -val | ??});
... break;
                    ...
    default:
  }

  Rectangle retRect2 = null; int retInt2 = 0;
  switch (??) { ... }

  return new Adapter({this.rect | retRect1 | retRect2 | null});
}
```

SKETCH

```
int x, y, width, height;

Rectangle (Rectangle r) {
  this (r.x, r.y, r.width, r.height);
}

Rectangle (int a, int b, int c, int d) {
  x = a; y = b; width = c; height = d;
}

int width () { return width;}

Rectangle shrink (int h, int v) {
  x += h; width -= (h+h);
  y += v; height -=(v+v);
  return this;
}
                    ...
```

Rectangle

Building the adapter method sketch

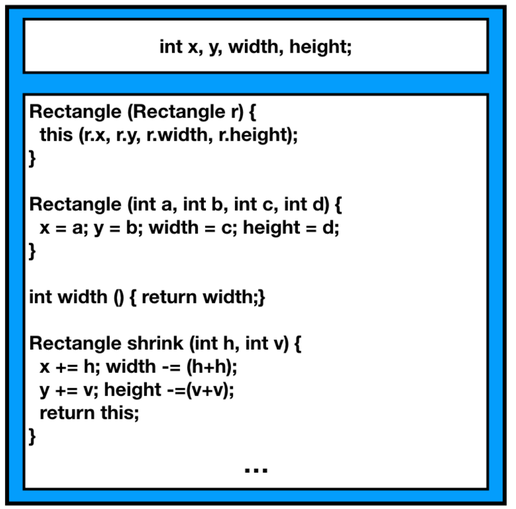


Building the adapter method sketch

Box expand(int c)

```
Adapter expand(int val) {
  Rectangle retRect1 = null; int retInt1 = 0;
  switch (??) {
    case 1: retRect1 = new Rectangle ( ); break;
    case 2: retRect1 = new Rectangle (this.rect); break;
    case 3: retInt1 = width(); break;
    case 4: rect.shrink ({val | -val | ??}, {val | -val | ??});
break;
                          …
    default:
  }

  Rectangle retRect2 = null; int retInt2 = 0;
  switch (??) { … }

  return new Adapter({this.rect | retRect1 | retRect2 | null});
}
```

SKETCH



Rectangle

Building the adapter method sketch

Box expand(int c)

```
Adapter expand(int val) {
  Rectangle retRect1 = null; int retInt1 = 0;
  switch (??) {
    case 1: retRect1 = new Rectangle ( ); break;
    case 2: retRect1 = new Rectangle (this.rect); break;
    case 3: retInt1 = width(); break;
    case 4: rect.shrink ({val | -val | ??}, {val | -val | ??});
break;
                          …
    default:
  }

  Rectangle retRect2 = null; int retInt2 = 0;
  switch (??) { … }

  return new Adapter({this.rect | retRect1 | retRect2 | null});
}
```

SKETCH

Create a invocation sequence

```
int x, y, width, height;

Rectangle (Rectangle r) {
  this (r.x, r.y, r.width, r.height);
}

Rectangle (int a, int b, int c, int d) {
  x = a; y = b; width = c; height = d;
}

int width () { return width;}

Rectangle shrink (int h, int v) {
  x += h; width -= (h+h);
  y += v; height -=(v+v);
  return this;
}
                          …
```

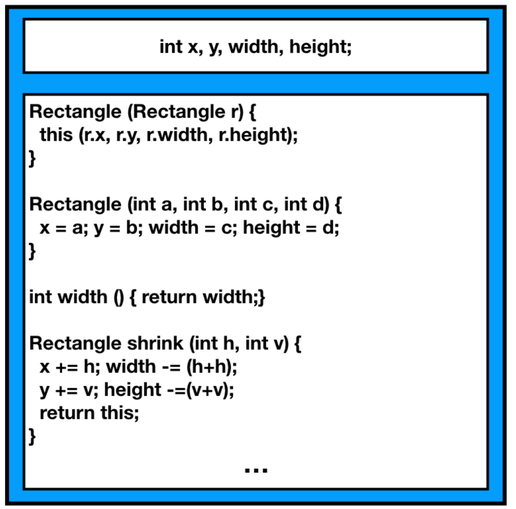
Rectangle

Building the adapter method sketch

Box expand(int c)

```
Adapter expand(int val) {
  Rectangle retRect1 = null; int retInt1 = 0;
  switch (??) {
    case 1: retRect1 = new Rectangle ( ); break;
    case 2: retRect1 = new Rectangle (this.rect); break;
    case 3: retInt1 = width(); break;
    case 4: rect.shrink ({val | -val | ??}, {val | -val | ??});
break;
                          …
    default:
  }

  Rectangle retRect2 = null; int retInt2 = 0;
  switch (??) { … }

  return new Adapter({this.rect | retRect1 | retRect2 | null});
}
```

SKETCH



Rectangle

Building the adapter method sketch

Box expand(int c)

```
Adapter expand(int val) {
   Rectangle retRect1 = null; int retInt1 = 0;
   switch (??) {
      case 1: retRect1 = new Rectangle ( ); break;
      case 2: retRect1 = new Rectangle (this.rect); break;
      case 3: retInt1 = width(); break;
      case 4: rect.shrink ({val | -val | ??}, {val | -val | ??});
break;
                              ...
      default:
   }

   Rectangle retRect2 = null; int retInt2 = 0;
   switch (??) { ... }

   return new Adapter({this.rect | retRect1 | retRect2 | null});
}
```

SKETCH

Choice to return any suitable value

```
int x, y, width, height;

Rectangle (Rectangle r) {
  this (r.x, r.y, r.width, r.height);
}

Rectangle (int a, int b, int c, int d) {
  x = a; y = b; width = c; height = d;
}

int width () { return width;}

Rectangle shrink (int h, int v) {
  x += h; width -= (h+h);
  y += v; height -=(v+v);
  return this;
}
                              ...
```

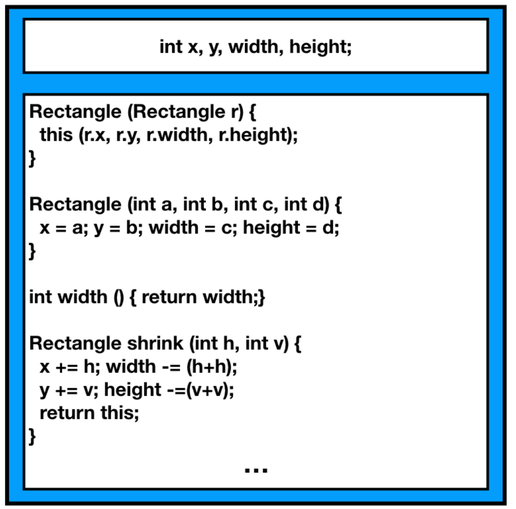
Rectangle

Building the adapter method sketch

Box expand(int c)

```
Adapter expand(int val) {
  Rectangle retRect1 = null; int retInt1 = 0;
  switch (??) {
    case 1: retRect1 = new Rectangle ( ); break;
    case 2: retRect1 = new Rectangle (this.rect); break;
    case 3: retInt1 = width(); break;
    case 4: rect.shrink ({val | -val | ??}, {val | -val | ??});
break;
                          …
    default:
  }

  Rectangle retRect2 = null; int retInt2 = 0;
  switch (??) { … }

  return new Adapter({this.rect | retRect1 | retRect2 | null});
}
```

SKETCH



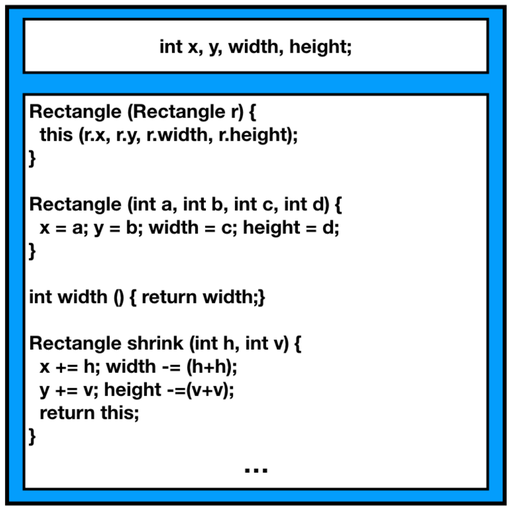
Rectangle

Building the correctness check/harness

ASSUME AVAILABILITY OF INTER-CLASS EQUIVALENCE PREDICATE

$$x_1 = x$$
$$y_1 = y$$
$$x_2 = x + \text{width}$$
$$y_2 = y + \text{height}$$

```
harness static void check-expand ( int s[], int r[] ) {
  Box a1 = new Box (); a1.x1 = s[0]; a1.y1 = s[1];
  a1.x2 = s[2]; a1.y2 = s[3];
  int a2 = s[4];

  Rectangle b1 = new Rectangle(); b1.x = r[0]; b1.y = r[1];
  b1.width = r[2]; b1.height = r[3];
  Adapter w1 = new Adapter(b1);
  int b2 = r[4];

  assume(a1.x1 == b1.x && a1.y1 = b1.y
  && a1.x2 == b1.x+b1.width && a1.y2 == b1.y+b1.height);
  assume(a2 == b2);

  Box2 a3 = a1.expand(a2);  Adapter w3 = w1.expand(b2);

  Rectangle b3 = w3.rect;
  assert(a1.x1 == b1.x && a1.y1 = b1.y
  && a1.x2 == b1.x+b1.width && a1.y2 == b1.y+b1.height);
  assert(a2 == b2);
  assert(a3.x1 == b3.x && a3.y1 = b3.y
  && a3.x2 == b3.x+ b3.width && a3.y2 == b3.y+ b3.height);
  assert((a1 == a3 && b1 == b3) || (a1 != a3 && b1 != b3) );
}
```



Rectangle

Building the correctness check/harness

ASSUME AVAILABILITY OF INTER-CLASS EQUIVALENCE PREDICATE

$$x_1 = x$$
$$y_1 = y$$
$$x_2 = x + \text{width}$$
$$y_2 = y + \text{height}$$

```
harness static void check-expand ( int s[], int r[] ) {
  Box a1 = new Box (); a1.x1 = s[0]; a1.y1 = s[1];
  a1.x2 = s[2]; a1.y2 = s[3];
  int a2 = s[4];

  Rectangle b1 = new Rectangle(); b1.x = r[0]; b1.y = r[1];
  b1.width = r[2]; b1.height = r[3];
  Adapter w1 = new Adapter(b1);
  int b2 = r[4];

  assume(a1.x1 == b1.x && a1.y1 = b1.y
  && a1.x2 == b1.x+b1.width && a1.y2 == b1.y+b1.height);
  assume(a2 == b2);

  Box2 a3 = a1.expand(a2);  Adapter w3 = w1.expand(b2);

  Rectangle b3 = w3.rect;
  assert(a1.x1 == b1.x && a1.y1 = b1.y
  && a1.x2 == b1.x+b1.width && a1.y2 == b1.y+b1.height);
  assert(a2 == b2);
  assert(a3.x1 == b3.x && a3.y1 = b3.y
  && a3.x2 == b3.x+ b3.width && a3.y2 == b3.y+ b3.height);
  assert((a1 == a3 && b1 == b3) || (a1 != a3 && b1 != b3) );
}
```

Create parameters for the original method and symbolize them.

```
Rectangle (int a, int b, int c, int d) {
  x = a; y = b; width = c; height = d;
}

int width () { return width;}

Rectangle shrink (int h, int v) {
  x += h; width -= (h+h);
  y += v; height -=(v+v);
  return this;
}
                ...
```

Rectangle

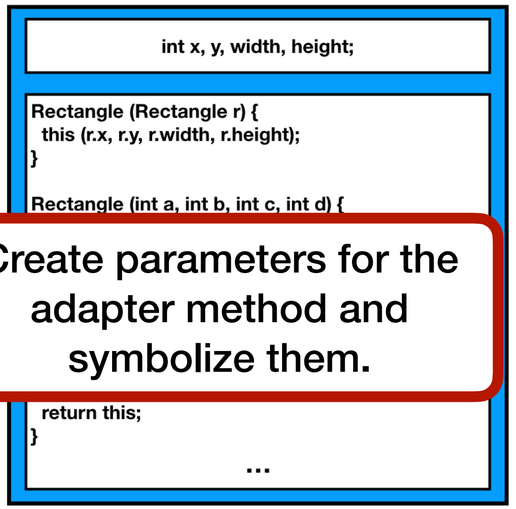
Building the correctness check/harness

ASSUME AVAILABILITY OF INTER-CLASS EQUIVALENCE PREDICATE

$$x_1 = x$$
$$y_1 = y$$
$$x_2 = x + \text{width}$$
$$y_2 = y + \text{height}$$

```
harness static void check-expand ( int s[], int r[] ) {
  Box a1 = new Box (); a1.x1 = s[0]; a1.y1 = s[1];
  a1.x2 = s[2]; a1.y2 = s[3];
  int a2 = s[4];

  Rectangle b1 = new Rectangle(); b1.x = r[0]; b1.y = r[1];
  b1.width = r[2]; b1.height = r[3];
  Adapter w1 = new Adapter(b1);
  int b2 = r[4];

  assume(a1.x1 == b1.x && a1.y1 = b1.y
  && a1.x2 == b1.x+b1.width && a1.y2 == b1.y+b1.height);
  assume(a2 == b2);

  Box2 a3 = a1.expand(a2);  Adapter w3 = w1.expand(b2);

  Rectangle b3 = w3.rect;
  assert(a1.x1 == b1.x && a1.y1 = b1.y
  && a1.x2 == b1.x+b1.width && a1.y2 == b1.y+b1.height);
  assert(a2 == b2);
  assert(a3.x1 == b3.x && a3.y1 = b3.y
  && a3.x2 == b3.x+ b3.width && a3.y2 == b3.y+ b3.height);
  assert((a1 == a3 && b1 == b3) || (a1 != a3 && b1 != b3) );
}
```

Create parameters for the adapter method and symbolize them.



Rectangle

Building the correctness check/harness

ASSUME AVAILABILITY OF INTER-CLASS EQUIVALENCE PREDICATE

$$x_1 = x$$
$$y_1 = y$$
$$x_2 = x + \text{width}$$
$$y_2 = y + \text{height}$$

```
harness static void check-expand ( int s[], int r[] ) {
  Box a1 = new Box (); a1.x1 = s[0]; a1.y1 = s[1];
  a1.x2 = s[2]; a1.y2 = s[3];
  int a2 = s[4];

  Rectangle b1 = new Rectangle(); b1.x = r[0]; b1.y = r[1];
  b1.width = r[2]; b1.height = r[3];
  Adapter w1 = new Adapter(b1);
  int b2 = r[4];

  assume(a1.x1 == b1.x && a1.y1 = b1.y
  && a1.x2 == b1.x+b1.width && a1.y2 == b1.y+b1.height);
  assume(a2 == b2);

  Box2 a3 = a1.expand(a2);  Adapter w3 = w1.expand(b2);

  Rectangle b3 = w3.rect;
  assert(a1.x1 == b1.x && a1.y1 = b1.y
  && a1.x2 == b1.x+b1.width && a1.y2 == b1.y+b1.height);
  assert(a2 == b2);
  assert(a3.x1 == b3.x && a3.y1 = b3.y
  && a3.x2 == b3.x+ b3.width && a3.y2 == b3.y+ b3.height);
  assert((a1 == a3 && b1 == b3) || (a1 != a3 && b1 != b3) );
}
```

```
int x, y, width, height;

Rectangle (Rectangle r) {
  this (r.x, r.y, r.width, r.height);
}

Rectangle (int a, int b, int c, int d) {
  x = a; y = b; width = c; height = d;
}

int width () { return width;}

Rectangle shrink (int h, int v) {
  x += h; width -= (h+h);
  y += v; height -=(v+v);
  return this;
```

Enforce the equivalence between corresponding parameters

Building the correctness check/harness

ASSUME AVAILABILITY OF INTER-CLASS EQUIVALENCE PREDICATE

$$x_1 = x$$
$$y_1 = y$$
$$x_2 = x + \text{width}$$
$$y_2 = y + \text{height}$$

```
harness static void check-expand ( int s[], int r[] ) {
  Box a1 = new Box (); a1.x1 = s[0]; a1.y1 = s[1];
  a1.x2 = s[2]; a1.y2 = s[3];
  int a2 = s[4];

  Rectangle b1 = new Rectangle(); b1.x = r[0]; b1.y = r[1];
  b1.width = r[2]; b1.height = r[3];
  Adapter w1 = new Adapter(b1);
  int b2 = r[4];

  assume(a1.x1 == b1.x && a1.y1 = b1.y
  && a1.x2 == b1.x+b1.width && a1.y2 == b1.y+b1.height);
  assume(a2 == b2);

  Box2 a3 = a1.expand(a2);  Adapter w3 = w1.expand(b2);

  Rectangle b3 = w3.rect;
  assert(a1.x1 == b1.x && a1.y1 = b1.y
  && a1.x2 == b1.x+b1.width && a1.y2 == b1.y+b1.height);
  assert(a2 == b2);
  assert(a3.x1 == b3.x && a3.y1 = b3.y
  && a3.x2 == b3.x+ b3.width && a3.y2 == b3.y+ b3.height);
  assert((a1 == a3 && b1 == b3) || (a1 != a3 && b1 != b3) );
}
```

```
int x, y, width, height;

Rectangle (Rectangle r) {
  this (r.x, r.y, r.width, r.height);
}

Rectangle (int a, int b, int c, int d) {
  x = a; y = b; width = c; height = d;
}

int width () { return width;}

Rectangle shrink (int h, int v) {
  x += h; width -= (h+h);
  y += v; height -=(v+v);
  return this;
```

Enforce the equivalence between corresponding parameters

Building the correctness check/harness

ASSUME AVAILABILITY OF INTER-CLASS EQUIVALENCE PREDICATE

$$x_1 = x$$
$$y_1 = y$$
$$x_2 = x + \text{width}$$
$$y_2 = y + \text{height}$$

```
harness static void check-expand ( int s[], int r[] ) {
  Box a1 = new Box (); a1.x1 = s[0]; a1.y1 = s[1];
  a1.x2 = s[2]; a1.y2 = s[3];
  int a2 = s[4];

  Rectangle b1 = new Rectangle(); b1.x = r[0]; b1.y = r[1];
  b1.width = r[2]; b1.height = r[3];
  Adapter w1 = new Adapter(b1);
  int b2 = r[4];

  assume(a1.x1 == b1.x && a1.y1 = b1.y
  && a1.x2 == b1.x+b1.width && a1.y2 == b1.y+b1.height);
  assume(a2 == b2);

  Box2 a3 = a1.expand(a2);  Adapter w3 = w1.expand(b2);

  Rectangle b3 = w3.rect;
  assert(a1.x1 == b1.x && a1.y1 = b1.y
  && a1.x2 == b1.x+b1.width && a1.y2 == b1.y+b1.height);
  assert(a2 == b2);
  assert(a3.x1 == b3.x && a3.y1 = b3.y
  && a3.x2 == b3.x+ b3.width && a3.y2 == b3.y+ b3.height);
  assert((a1 == a3 && b1 == b3) || (a1 != a3 && b1 != b3) );
}
```

```
int x, y, width, height;

Rectangle (Rectangle r) {
  this (r.x, r.y, r.width, r.height);
}

Rectangle (int a, int b, int c, int d) {
  x = a; y = b; width = c; height = d;
}

int width () { return width;}

Rectangle shrink (int h, int v) {
  x += h; width -= (h+h);
  y += v; height -=(v+v);
  return this;
```

Enforce the equivalence between corresponding parameters

Building the correctness check/harness

ASSUME AVAILABILITY OF INTER-CLASS EQUIVALENCE PREDICATE

$$x_1 = x$$
$$y_1 = y$$
$$x_2 = x + \text{width}$$
$$y_2 = y + \text{height}$$

```
harness static void check-expand ( int s[], int r[] ) {
  Box a1 = new Box (); a1.x1 = s[0]; a1.y1 = s[1];
  a1.x2 = s[2]; a1.y2 = s[3];
  int a2 = s[4];

  Rectangle b1 = new Rectangle(); b1.x = r[0]; b1.y = r[1];
  b1.width = r[2]; b1.height = r[3];
  Adapter w1 = new Adapter(b1);
  int b2 = r[4];

  assume(a1.x1 == b1.x && a1.y1 = b1.y
  && a1.x2 == b1.x+b1.width && a1.y2 == b1.y+b1.height);
  assume(a2 == b2);

  Box2 a3 = a1.expand(a2);  Adapter w3 = w1.expand(b2);

  Rectangle b3 = w3.rect;
  assert(a1.x1 == b1.x && a1.y1 = b1.y
  && a1.x2 == b1.x+b1.width && a1.y2 == b1.y+b1.height);
  assert(a2 == b2);
  assert(a3.x1 == b3.x && a3.y1 = b3.y
  && a3.x2 == b3.x+ b3.width && a3.y2 == b3.y+ b3.height);
  assert((a1 == a3 && b1 == b3) || (a1 != a3 && b1 != b3) );
}
```

```
int x, y, width, height;

Rectangle (Rectangle r) {
  this (r.x, r.y, r.width, r.height);
}

Rectangle (int a, int b, int c, int d) {
  x = a; y = b; width = c; height = d;
}

int width () { return width;}

Rectangle shrink (int h, int v) {
  x += h; width -= (h+h);
  y += v; height -=(v+v);
  return this;
```

Enforce the equivalence between corresponding parameters

Building the correctness check/harness

ASSUME AVAILABILITY OF INTER-CLASS EQUIVALENCE PREDICATE

$$x_1 = x$$
$$y_1 = y$$
$$x_2 = x + \text{width}$$
$$y_2 = y + \text{height}$$

```
harness static void check-expand ( int s[], int r[] ) {
  Box a1 = new Box (); a1.x1 = s[0]; a1.y1 = s[1];
  a1.x2 = s[2]; a1.y2 = s[3];
  int a2 = s[4];

  Rectangle b1 = new Rectangle(); b1.x = r[0]; b1.y = r[1];
  b1.width = r[2]; b1.height = r[3];
  Adapter w1 = new Adapter(b1);
  int b2 = r[4];

  assume(a1.x1 == b1.x && a1.y1 = b1.y
  && a1.x2 == b1.x+b1.width && a1.y2 == b1.y+b1.height);
  assume(a2 == b2);

  Box2 a3 = a1.expand(a2);  Adapter w3 = w1.expand(b2);

  Rectangle b3 = w3.rect;
  assert(a1.x1 == b1.x && a1.y1 = b1.y
  && a1.x2 == b1.x+b1.width && a1.y2 == b1.y+b1.height);
  assert(a2 == b2);
  assert(a3.x1 == b3.x && a3.y1 = b3.y
  && a3.x2 == b3.x+ b3.width && a3.y2 == b3.y+ b3.height);
  assert((a1 == a3 && b1 == b3) || (a1 != a3 && b1 != b3) );
}
```

```
int x, y, width, height;

Rectangle (Rectangle r) {
  this (r.x, r.y, r.width, r.height);
}

Rectangle (int a, int b, int c, int d) {
  x = a; y = b; width = c; height = d;
}

int width () { return width;}

Rectangle shrink (int h, int v) {
  x += h; width -= (h+h);
  y += v; height -=(v+v);
  return this;
```

Enforce the equivalence between corresponding parameters

Building the correctness check/harness

ASSUME AVAILABILITY OF INTER-CLASS EQUIVALENCE PREDICATE

$$x_1 = x$$
$$y_1 = y$$
$$x_2 = x + \text{width}$$
$$y_2 = y + \text{height}$$

```
harness static void check-expand ( int s[], int r[] ) {
  Box a1 = new Box (); a1.x1 = s[0]; a1.y1 = s[1];
  a1.x2 = s[2]; a1.y2 = s[3];
  int a2 = s[4];

  Rectangle b1 = new Rectangle(); b1.x = r[0]; b1.y = r[1];
  b1.width = r[2]; b1.height = r[3];
  Adapter w1 = new Adapter(b1);
  int b2 = r[4];

  assume(a1.x1 == b1.x && a1.y1 = b1.y
  && a1.x2 == b1.x+b1.width && a1.y2 == b1.y+b1.height);
  assume(a2 == b2);

  Box2 a3 = a1.expand(a2);  Adapter w3 = w1.expand(b2);

  Rectangle b3 = w3.rect;
  assert(a1.x1 == b1.x && a1.y1 = b1.y
  && a1.x2 == b1.x+b1.width && a1.y2 == b1.y+b1.height);
  assert(a2 == b2);
  assert(a3.x1 == b3.x && a3.y1 = b3.y
  && a3.x2 == b3.x+ b3.width && a3.y2 == b3.y+ b3.height);
  assert((a1 == a3 && b1 == b3) || (a1 != a3 && b1 != b3) );
}
```

Execute original method and the adapter method

Building the correctness check/harness

ASSUME AVAILABILITY OF INTER-CLASS EQUIVALENCE PREDICATE

$$x_1 = x$$
$$y_1 = y$$
$$x_2 = x + \text{width}$$
$$y_2 = y + \text{height}$$

```
harness static void check-expand ( int s[], int r[] ) {
  Box a1 = new Box (); a1.x1 = s[0]; a1.y1 = s[1];
  a1.x2 = s[2]; a1.y2 = s[3];
  int a2 = s[4];

  Rectangle b1 = new Rectangle(); b1.x = r[0]; b1.y = r[1];
  b1.width = r[2]; b1.height = r[3];
  Adapter w1 = new Adapter(b1);
  int b2 = r[4];

  assume(a1.x1 == b1.x && a1.y1 = b1.y
  && a1.x2 == b1.x+b1.width && a1.y2 == b1.y+b1.height);
  assume(a2 == b2);

  Box2 a3 = a1.expand(a2);  Adapter w3 = w1.expand(b2);

  Rectangle b3 = w3.rect;
  assert(a1.x1 == b1.x && a1.y1 = b1.y
  && a1.x2 == b1.x+b1.width && a1.y2 == b1.y+b1.height);
  assert(a2 == b2);
  assert(a3.x1 == b3.x && a3.y1 = b3.y
  && a3.x2 == b3.x+ b3.width && a3.y2 == b3.y+ b3.height);
  assert((a1 == a3 && b1 == b3) || (a1 != a3 && b1 != b3) );
}
```

Assert Equivalence between corresponding values

Building the correctness check/harness

ASSUME AVAILABILITY OF INTER-CLASS EQUIVALENCE PREDICATE

$$x_1 = x$$
$$y_1 = y$$
$$x_2 = x + \text{width}$$
$$y_2 = y + \text{height}$$

```
harness static void check-expand ( int s[], int r[] ) {
  Box a1 = new Box (); a1.x1 = s[0]; a1.y1 = s[1];
  a1.x2 = s[2]; a1.y2 = s[3];
  int a2 = s[4];

  Rectangle b1 = new Rectangle(); b1.x = r[0]; b1.y = r[1];
```

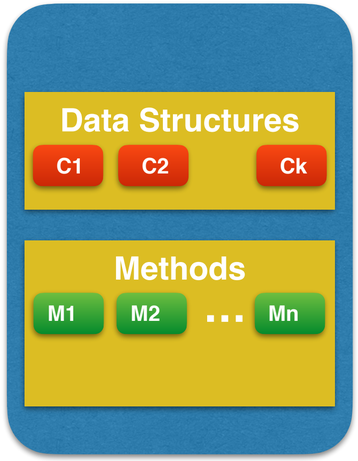
- **Reference class fields**
- **Reference method parameters**
- **Aliasing between variables and other side effects**

```
  Box2 a3 = a1.expand(a2);  Adapter w3 = w1.expand(b2);

  Rectangle b3 = w3.rect;
  assert(a1.x1 == b1.x && a1.y1 = b1.y
  && a1.x2 == b1.x+b1.width && a1.y2 == b1.y+b1.height);
  assert(a2 == b2);
  assert(a3.x1 == b3.x && a3.y1 = b3.y
  && a3.x2 == b3.x+ b3.width && a3.y2 == b3.y+ b3.height);
  assert((a1 == a3 && b1 == b3) || (a1 != a3 && b1 != b3) );
}
```

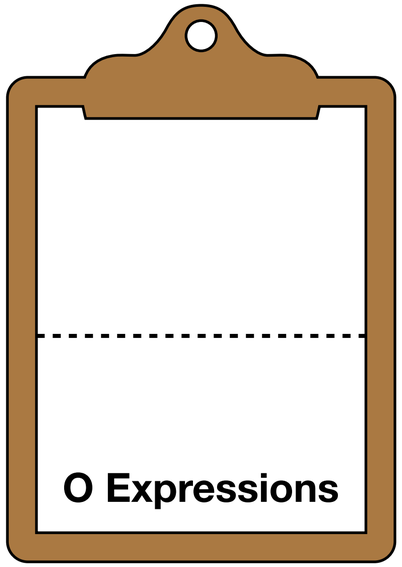
Assert Equivalence between corresponding values

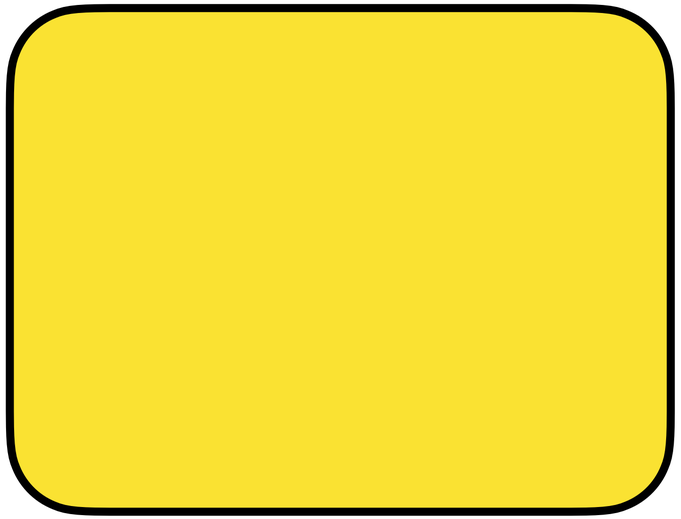
Building Inter-class Equivalence

Step 1:Symbolic Execution



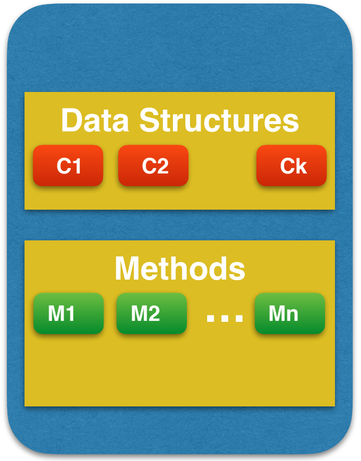
Class O



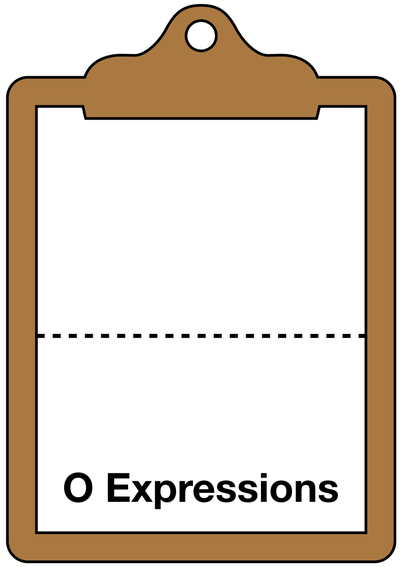


Step 1:Symbolic Execution

- ***All*** public methods in class O are symbolically executed



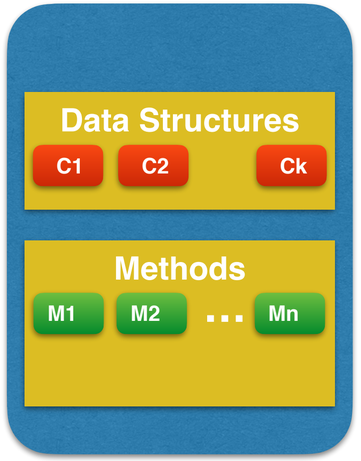
Class O



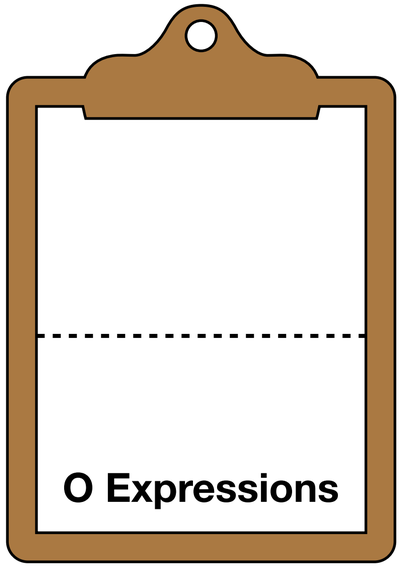
Method : m_i

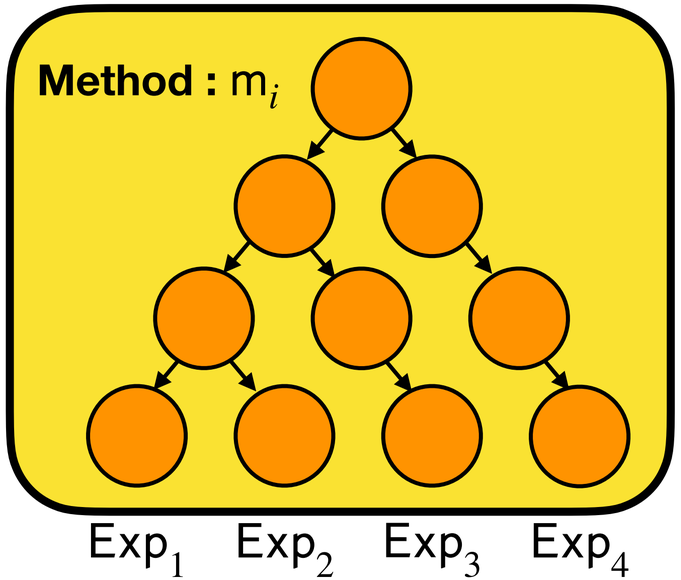
Step 1:Symbolic Execution

- ***All*** public methods in class O are symbolically executed



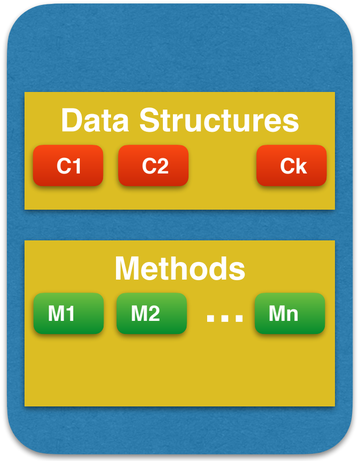
Class O



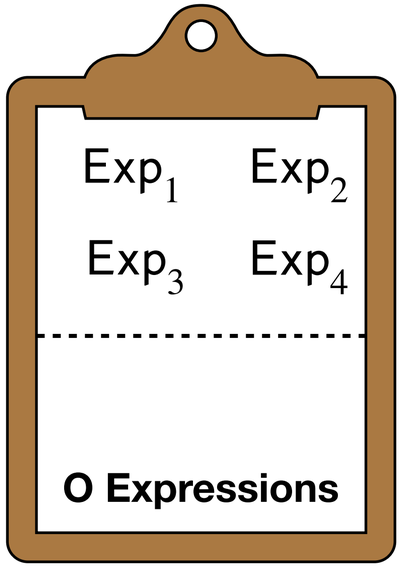


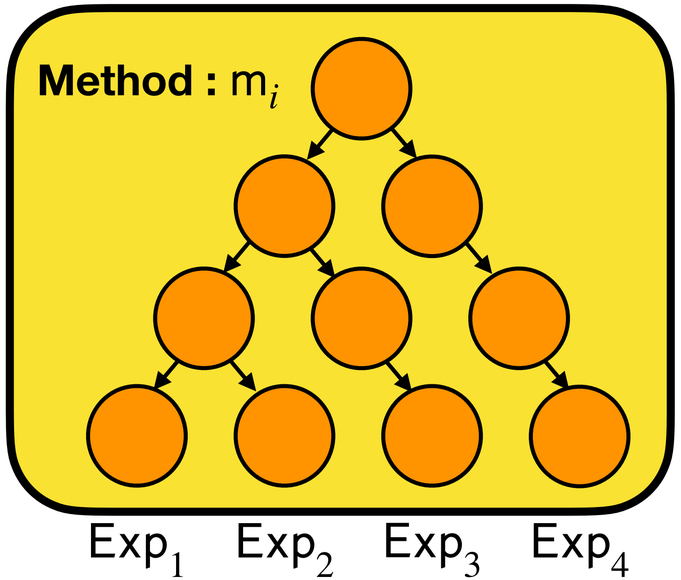
Step 1:Symbolic Execution

- ***All*** public methods in class O are symbolically executed
- Identify all symbolic expressions ***returned***



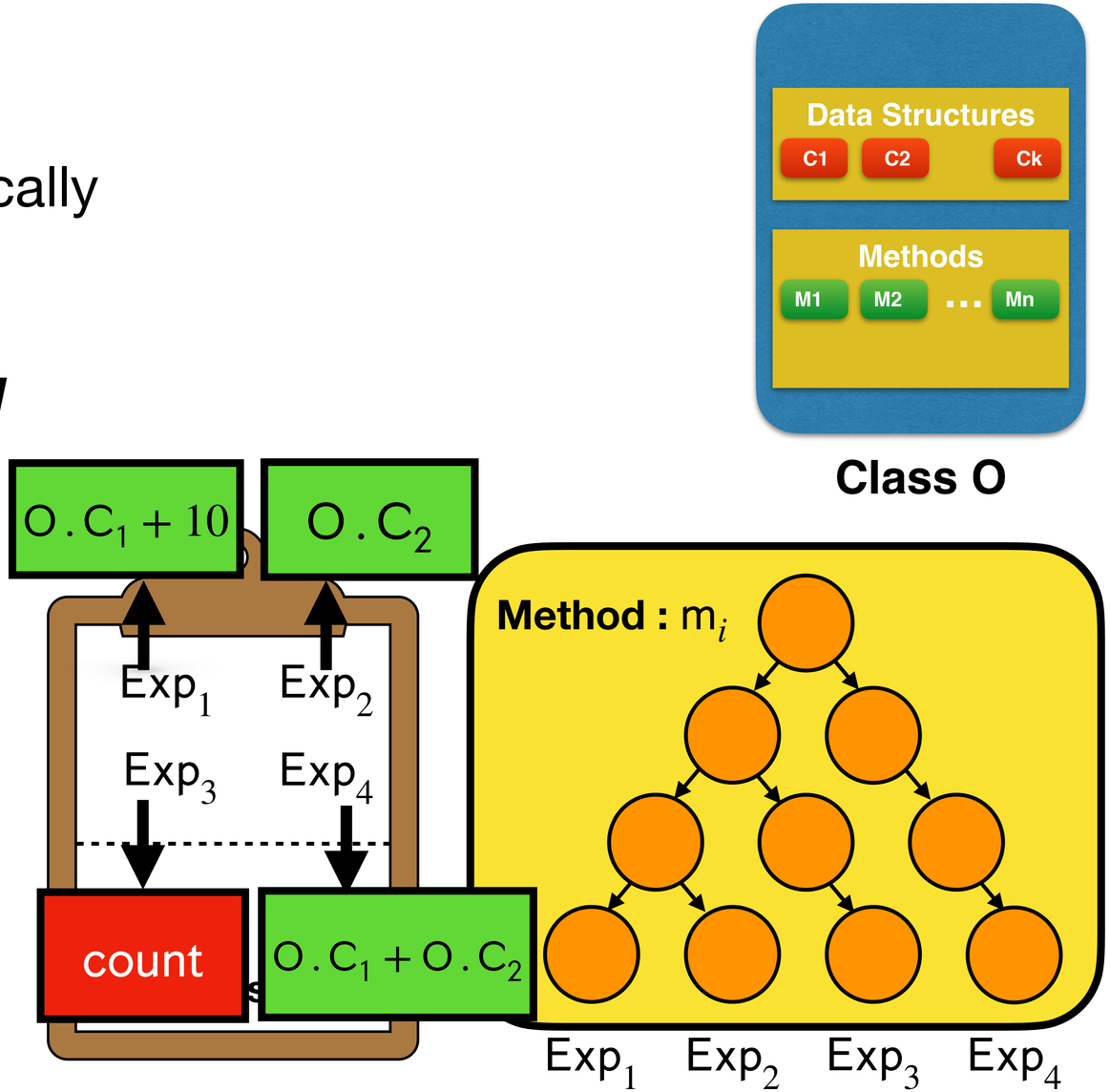
Class O





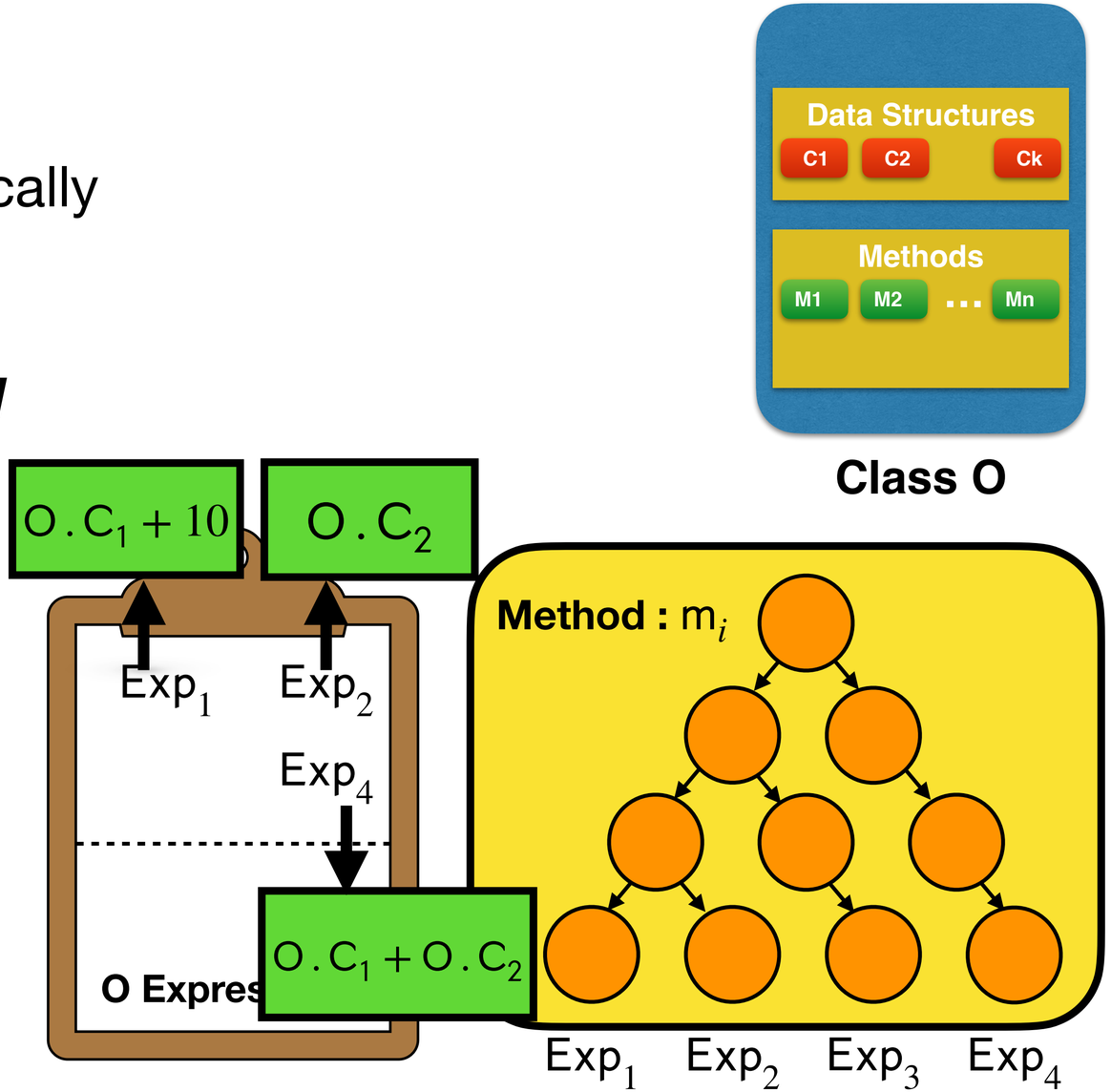
Step 1:Symbolic Execution

- ***All*** public methods in class O are symbolically executed
- Identify all symbolic expressions ***returned***
- Retain useful expressions
  - Contains only O fields and constants



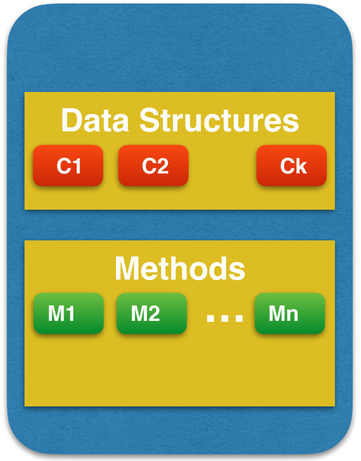
Step 1:Symbolic Execution

- ***All*** public methods in class O are symbolically executed
- Identify all symbolic expressions ***returned***
- Retain useful expressions
  - Contains only O fields and constants

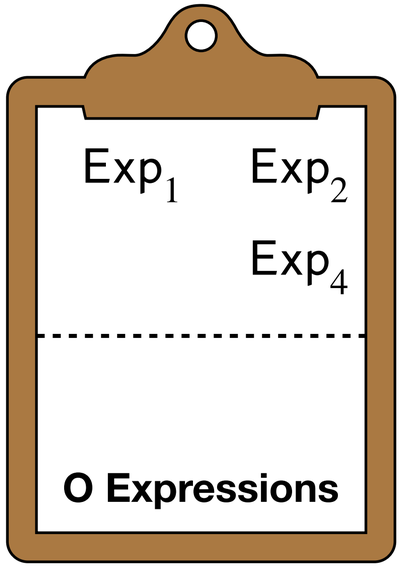


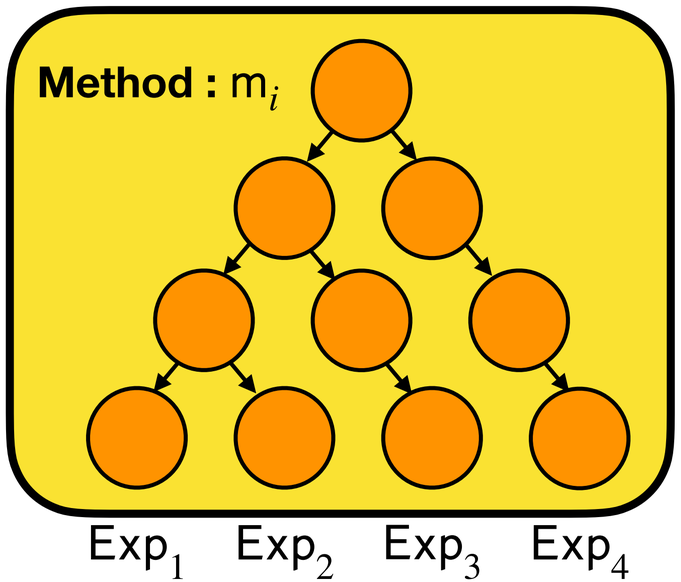
Step 1:Symbolic Execution

- ***All*** public methods in class O are symbolically executed
- Identify all symbolic expressions ***returned***
- Retain useful expressions
  - Contains only O fields and constants



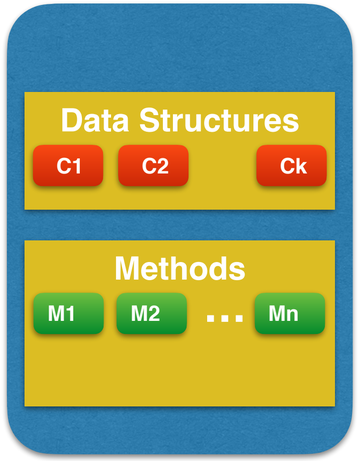
Class O



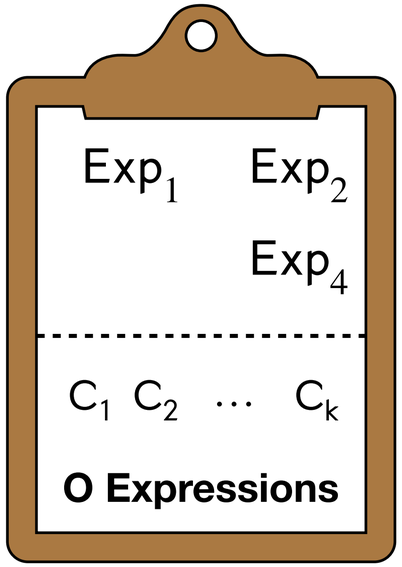


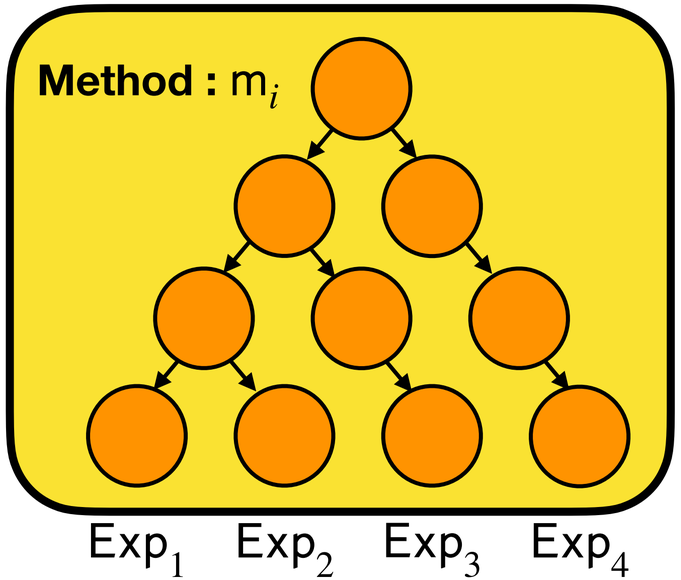
Step 1:Symbolic Execution

- ***All*** public methods in class O are symbolically executed
- Identify all symbolic expressions ***returned***
- Retain useful expressions
  - Contains only O fields and constants
- Identify all field dereferences of class O.



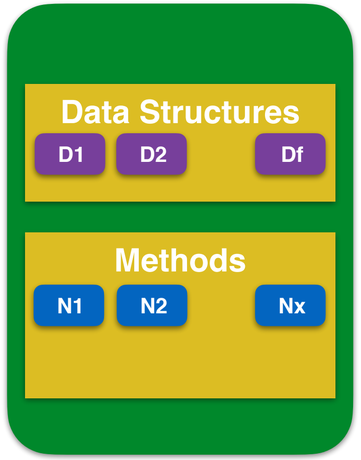
Class O



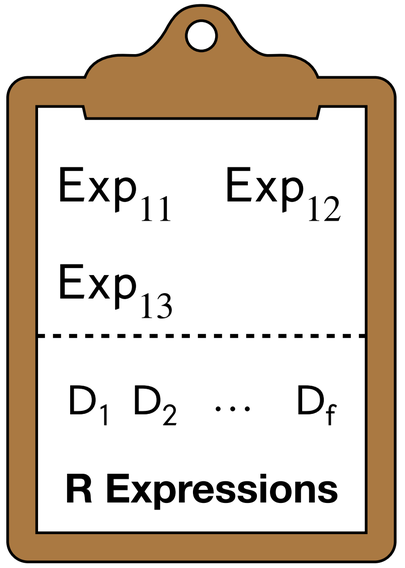


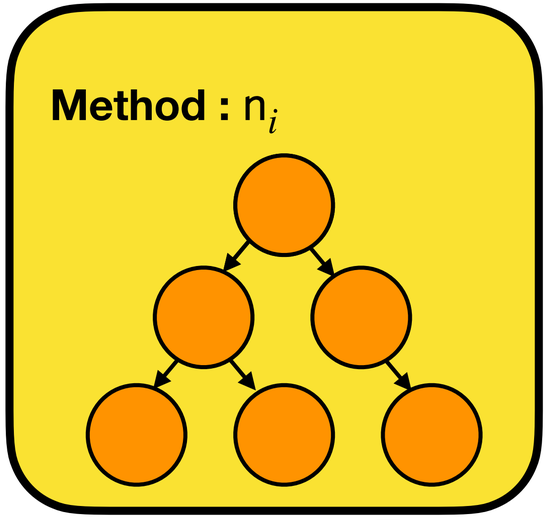
Step 1:Symbolic Execution

- Repeat the same process for class R



Class R

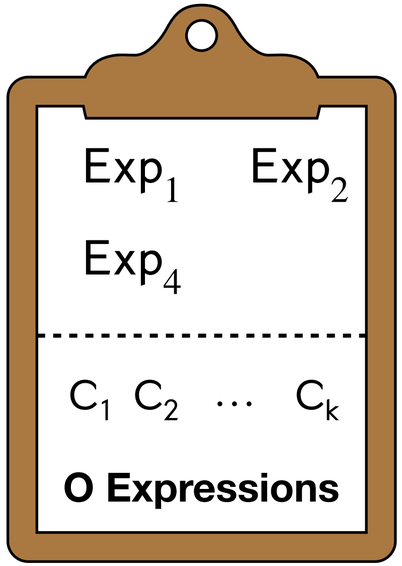


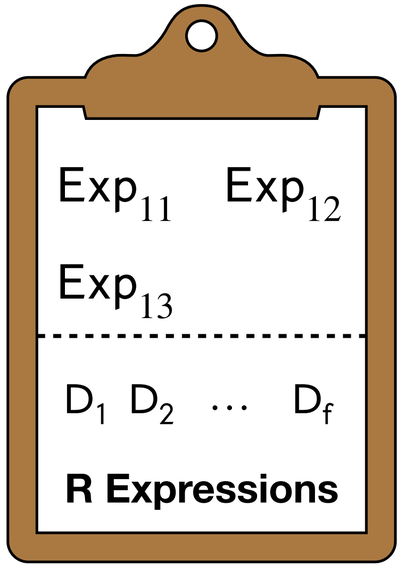


Exp_{11} Exp_{12} Exp_{13}

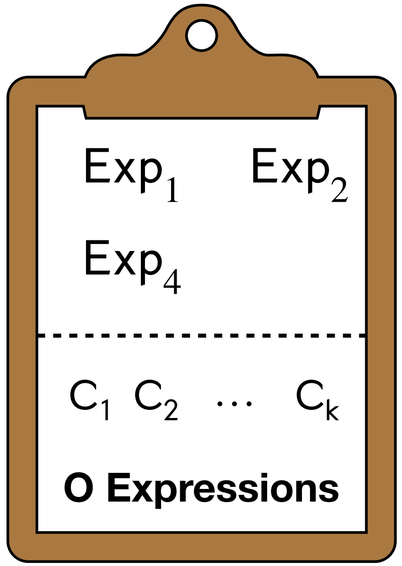
Step 2: Candidate Equivalence Generation

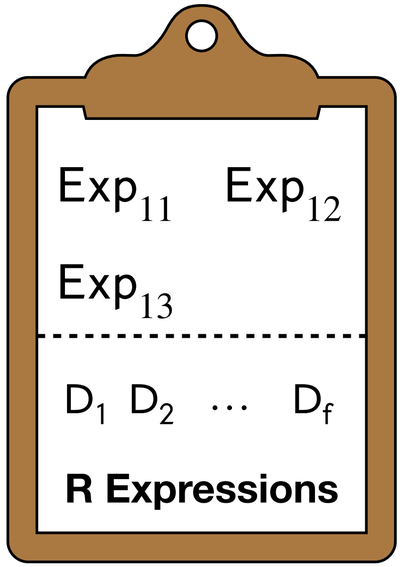
Step 2: Candidate Equivalence Generation





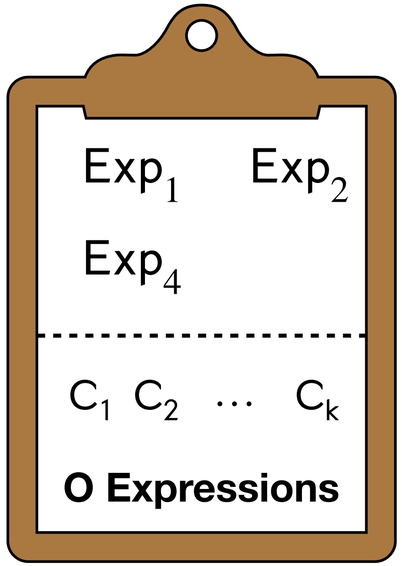
Step 2: Candidate Equivalence Generation

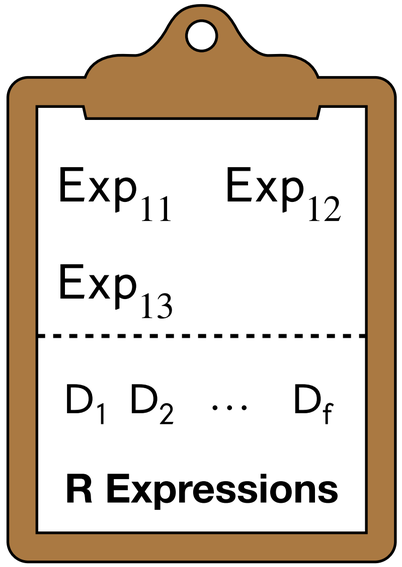




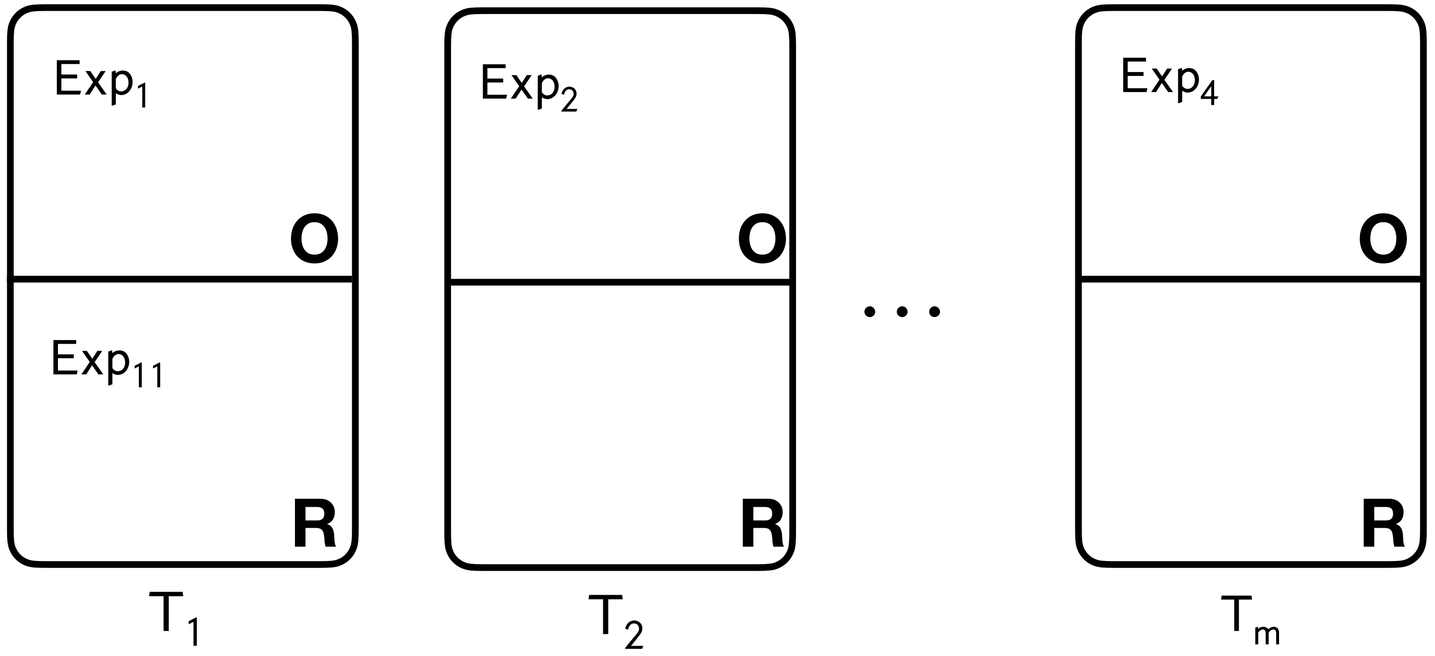
- **Sort expressions based on types**

Step 2: Candidate Equivalence Generation

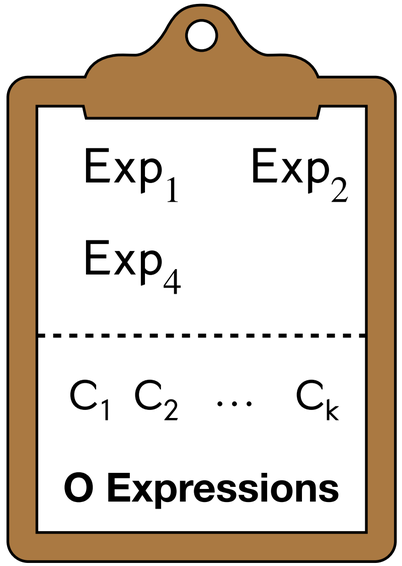


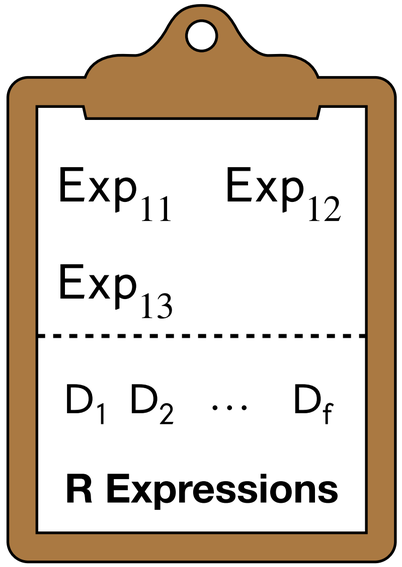


- **Sort expressions based on types**

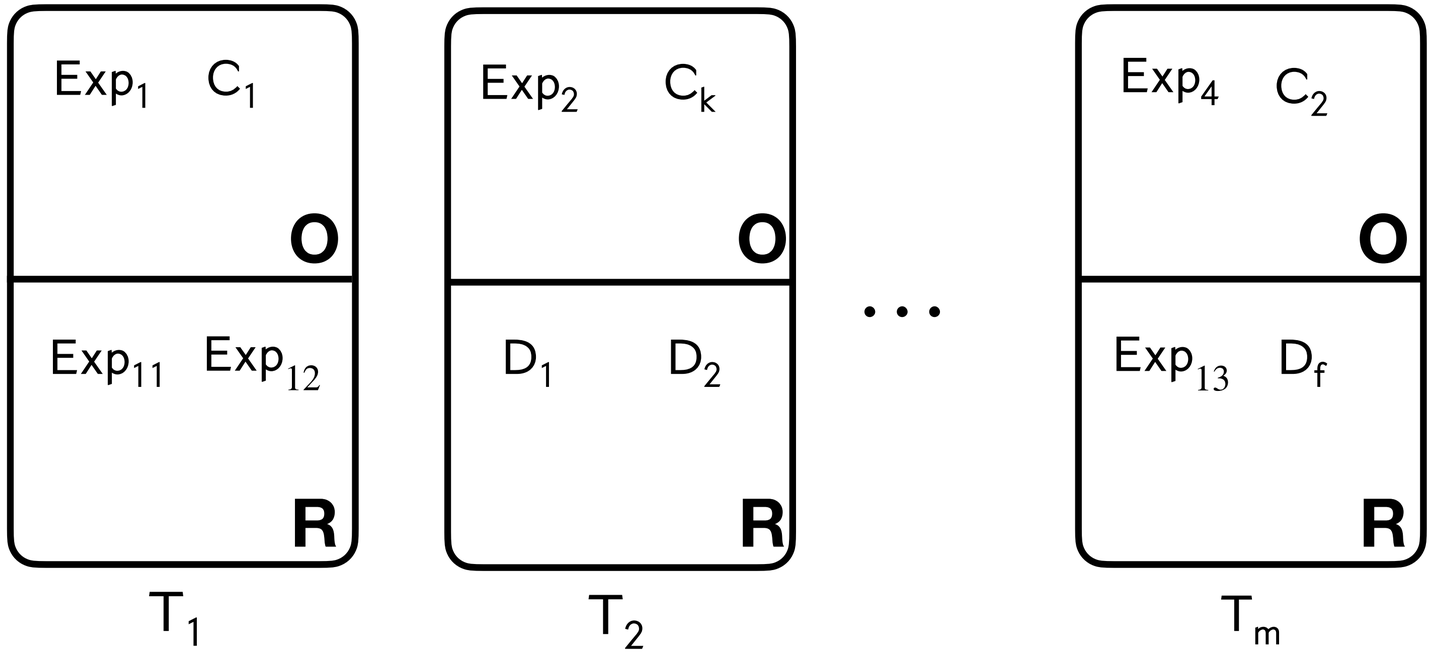


Step 2: Candidate Equivalence Generation

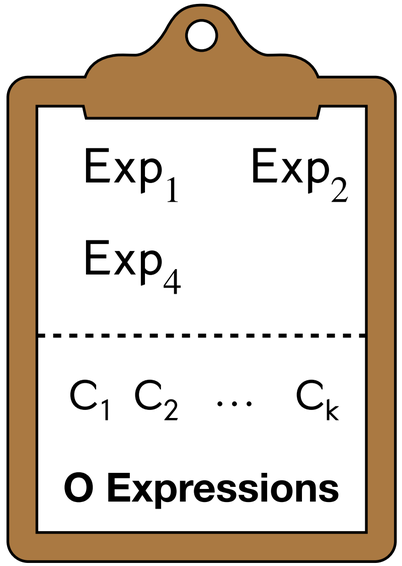


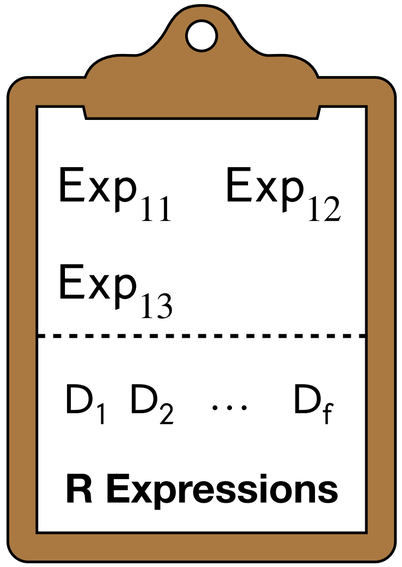


- **Sort expressions based on types**

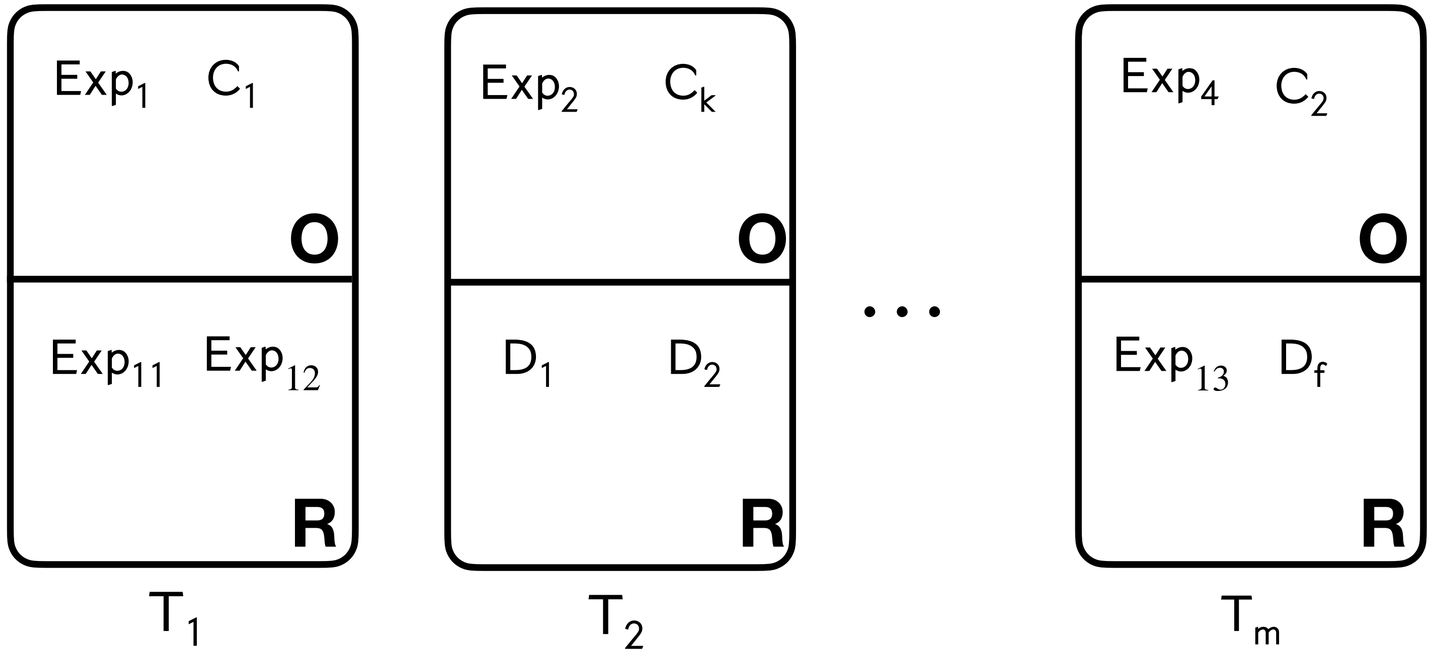


Step 2: Candidate Equivalence Generation

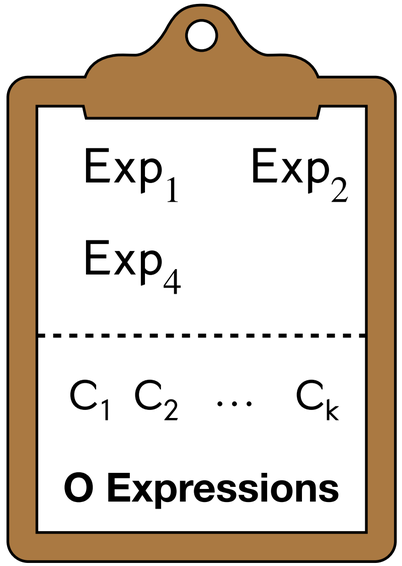


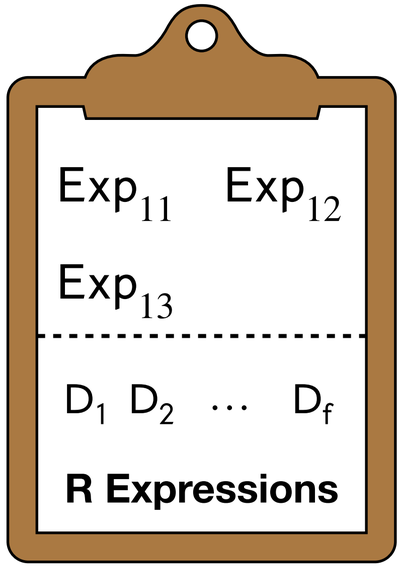


- **Sort expressions based on types**
- **Equate expressions and build predicates**

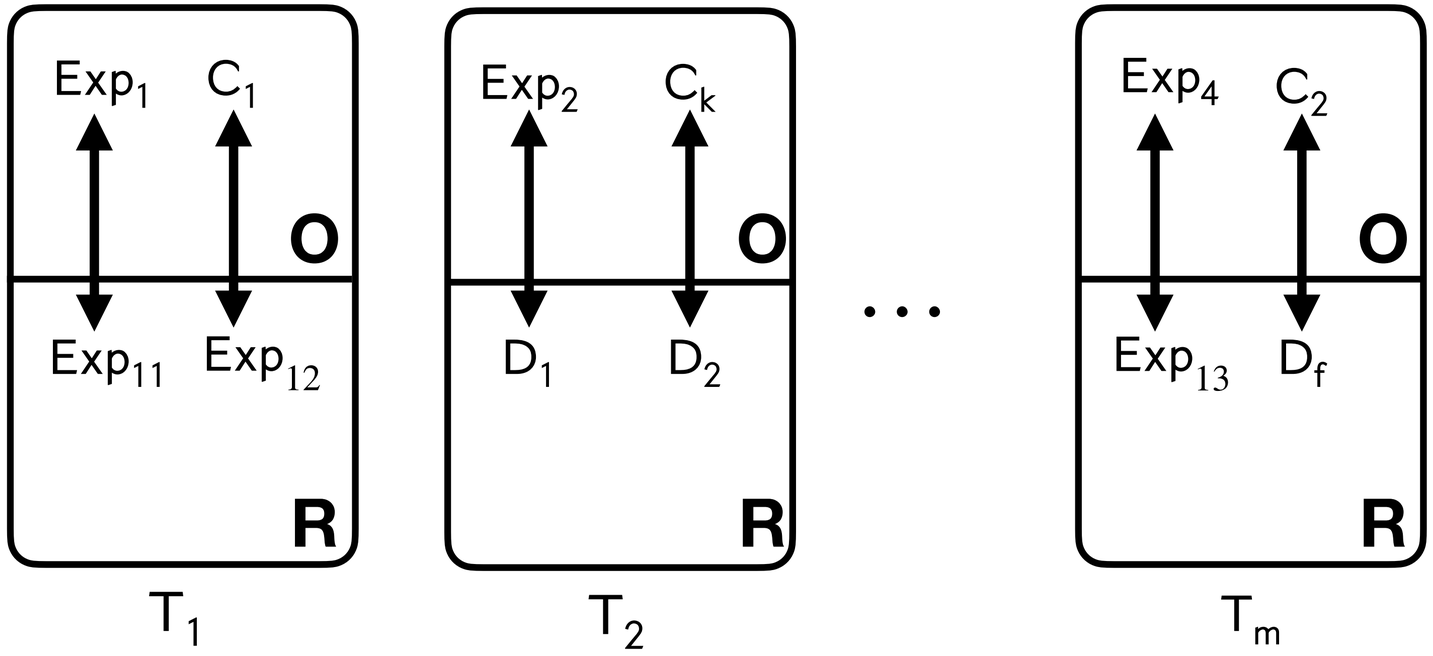


Step 2: Candidate Equivalence Generation





- **Sort expressions based on types**
- **Equate expressions and build predicates**



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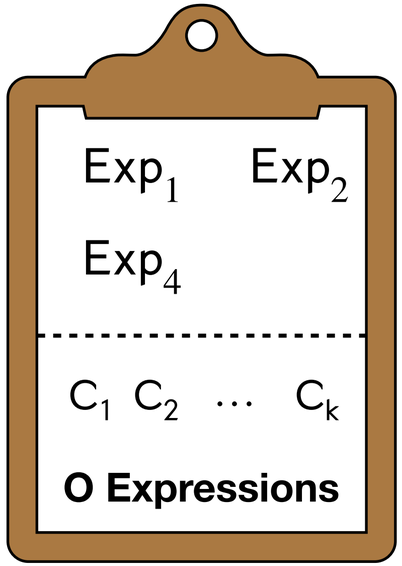

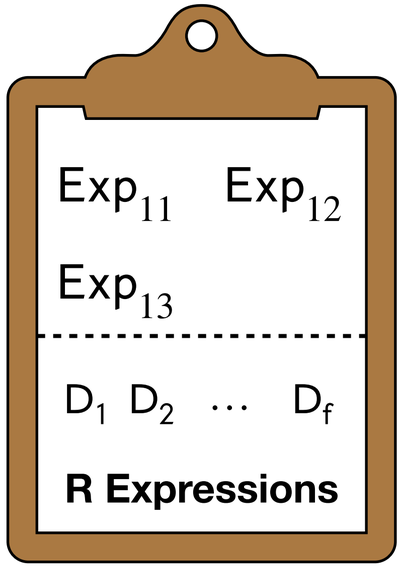

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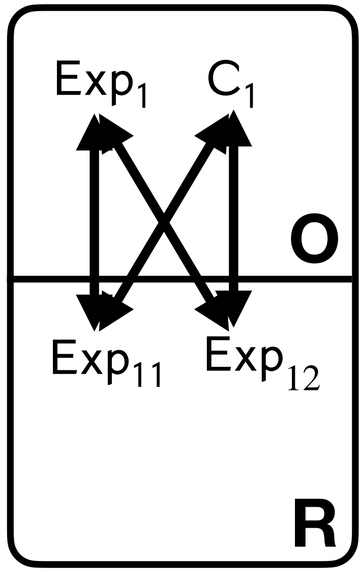

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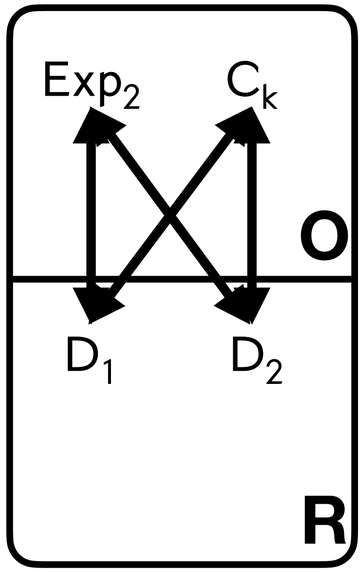

T_2

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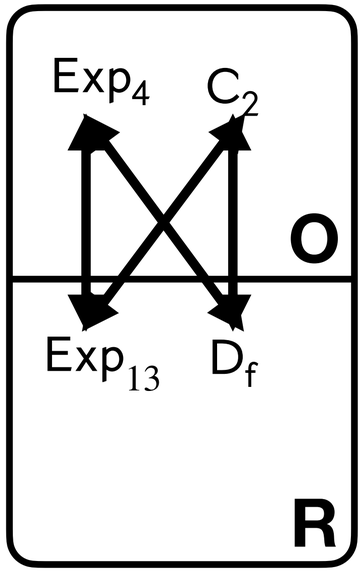
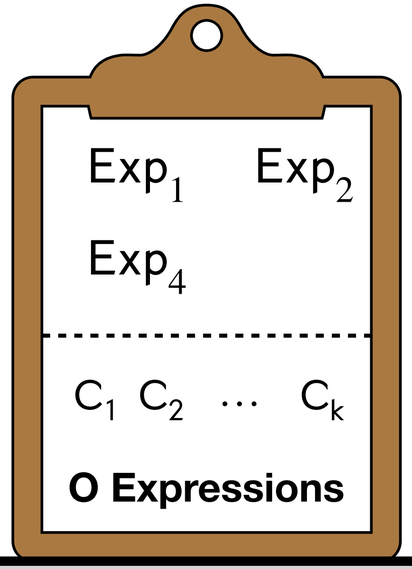


T_m

Step 2: Candidate Equivalence Generation



- **Sort expressions based on types**
- **Equate expressions and build predicates**

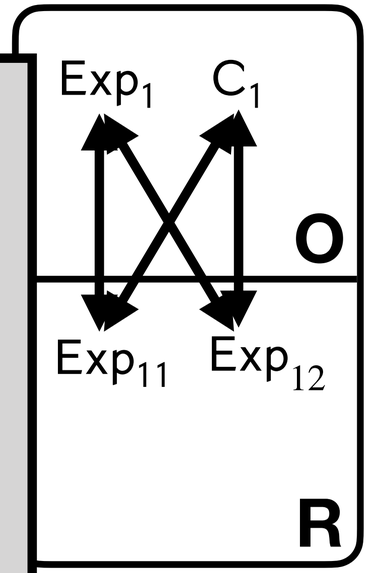
$Exp_1 = Exp_{11} \wedge Exp_2 = D_1 \wedge Exp_4 = Exp_{13}$

$Exp_1 = Exp_{12} \wedge Exp_2 = D_1 \wedge Exp_4 = Exp_{13}$

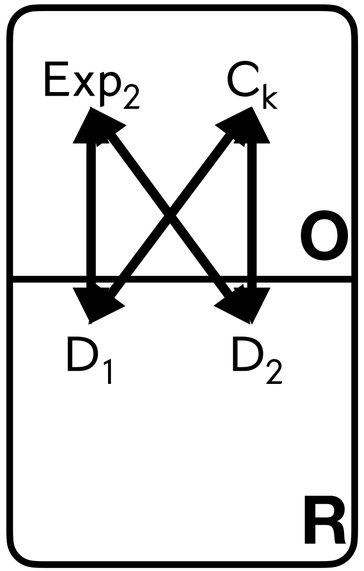
$C_1 = Exp_{11} \wedge Exp_2 = D_1 \wedge Exp_4 = Exp_{13}$

• • •

true

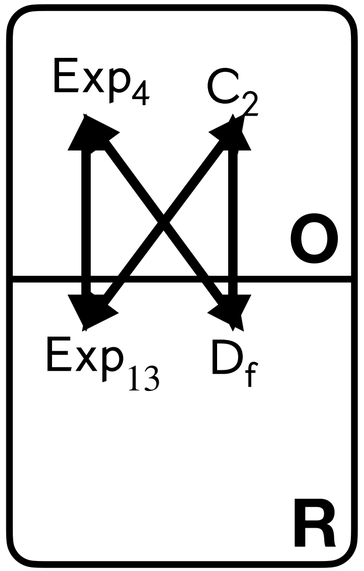


T_1



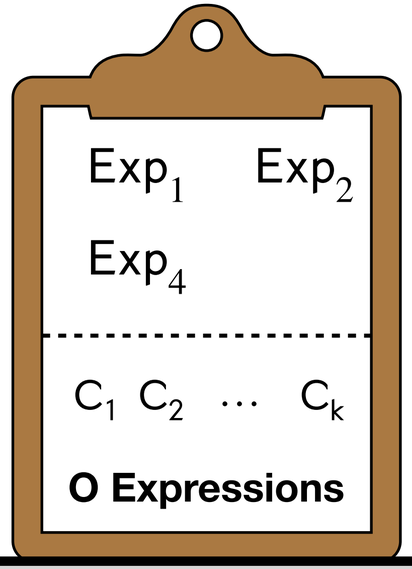
T_2

• • •



T_m

Step 2: Candidate Equivalence Generation



- **Sort expressions based on types**
- **Equate expressions and build predicates**
- **Class O return expressions must be mapped**

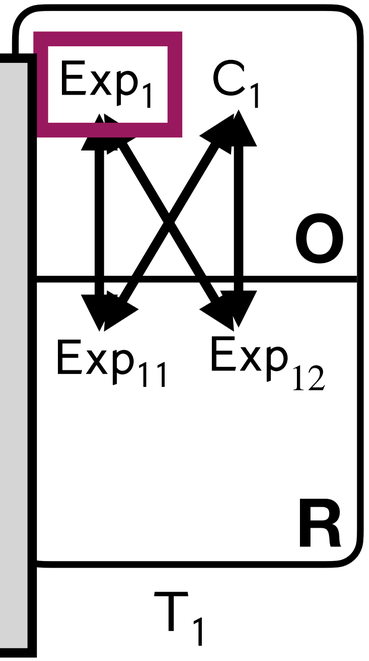
$Exp_1 = Exp_{11} \wedge Exp_2 = D_1 \wedge Exp_4 = Exp_{13}$

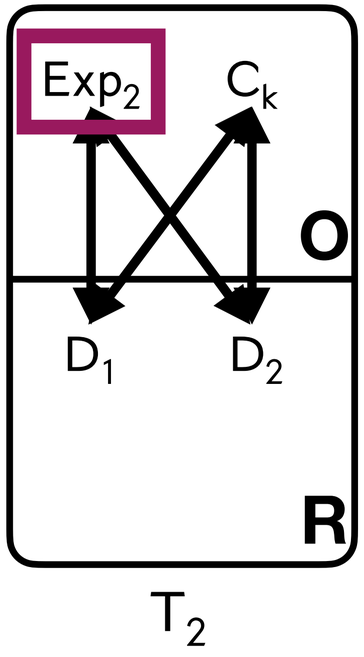
$Exp_1 = Exp_{12} \wedge Exp_2 = D_1 \wedge Exp_4 = Exp_{13}$

$C_1 = Exp_{11} \wedge Exp_2 = D_1 \wedge Exp_4 = Exp_{13}$

• • •

true





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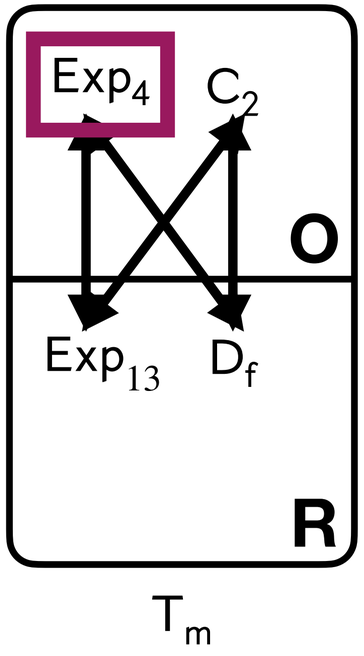
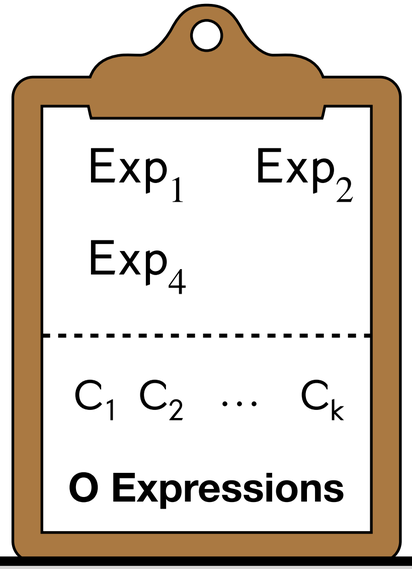


Step 2: Candidate Equivalence Generation



- **Sort expressions based on types**
- **Equate expressions and build predicates**
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$Exp_1 = Exp_{11} \wedge Exp_2 = D_1 \wedge Exp_4 = Exp_{13}$

$Exp_1 = Exp_{12} \wedge Exp_2 = D_1 \wedge Exp_4 = Exp_{13}$

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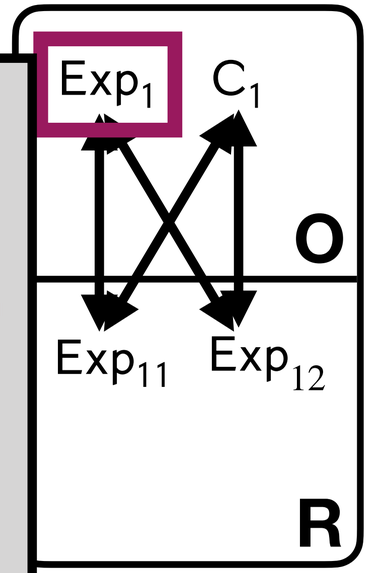
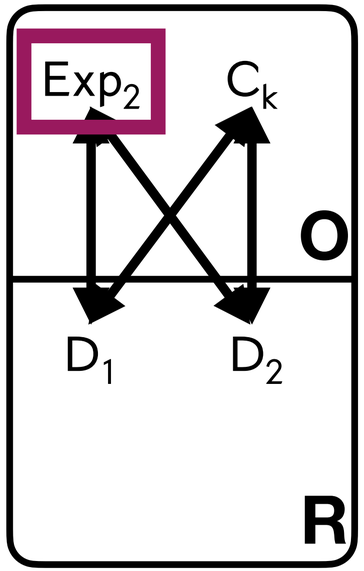
…

~~true~~



T_1



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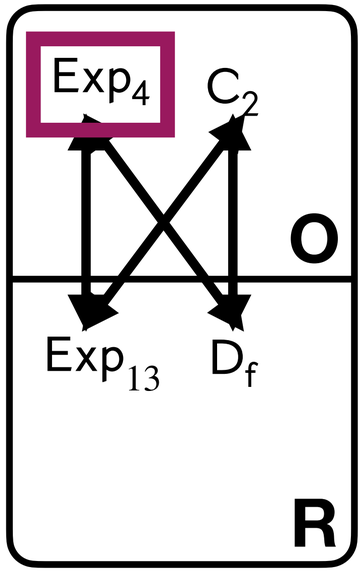


T_m

Step 2: Candidate Equivalence Generation

- **Sort expressions based on types**
- **Equate expressions and build predicates**
- **Class O return expressions must be mapped**
- **Build inter-class equivalence predicates**

$$Exp_1 = Exp_{11} \wedge Exp_2 = D_1 \wedge Exp_4 = Exp_{13}$$

$$Exp_1 = Exp_{12} \wedge Exp_2 = D_1 \wedge Exp_4 = Exp_{13}$$

$$\bullet \bullet \bullet$$

$$Exp_1 = Exp_{12} \wedge Exp_2 = D_2 \wedge Exp_4 = Exp_{13}$$

Step 2: Candidate Equivalence Generation

- **Sort expressions based on types**
- **Equate expressions and build predicates**
- **Class O return expressions must be mapped**
- **Build inter-class equivalence predicates**

$$Exp_1 = Exp_{11} \wedge Exp_2 = D_1 \wedge Exp_4 = Exp_{13}$$

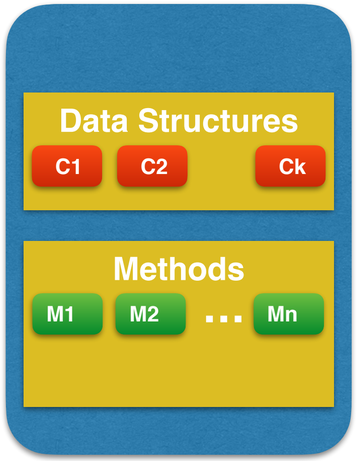
$$Exp_1 = Exp_{12} \wedge Exp_2 = D_1 \wedge Exp_4 = Exp_{13}$$

$$\cdots$$

$$Exp_1 = Exp_{12} \wedge Exp_2 = D_2 \wedge Exp_4 = Exp_{13}$$

Step 2: Candidate Equivalence Generation

- Sort expressions based on types
- Equate expressions and build predicates
- Class O return expressions must be mapped
- Build inter-class equivalence predicates
- Eliminate invalid equivalence predicates



Class O

Step 2: Candidate Equivalence Generation

- Sort expressions based on types
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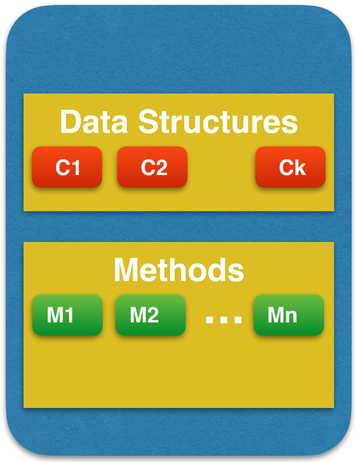

Class O

Step 2: Candidate Equivalence Generation

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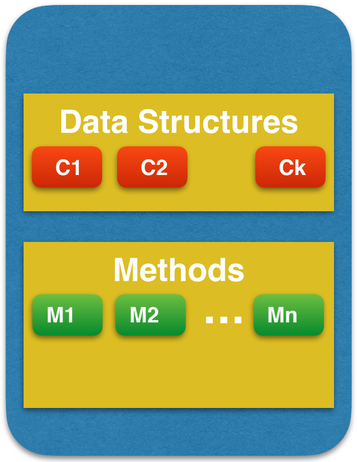

Class O

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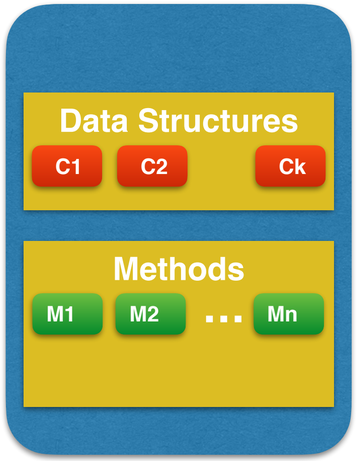

Class O

Step 2: Candidate Equivalence Generation

- Sort expressions based on types
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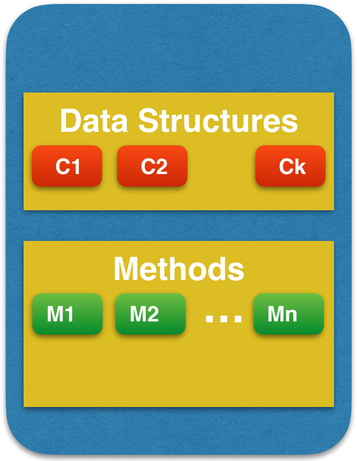
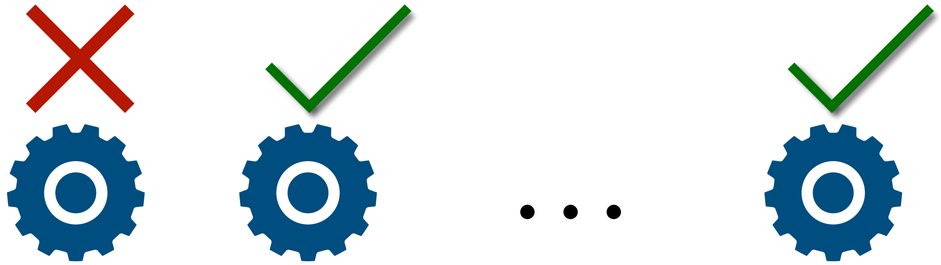


Class O



Iteration 1: Solving the Adapter Class Sketch

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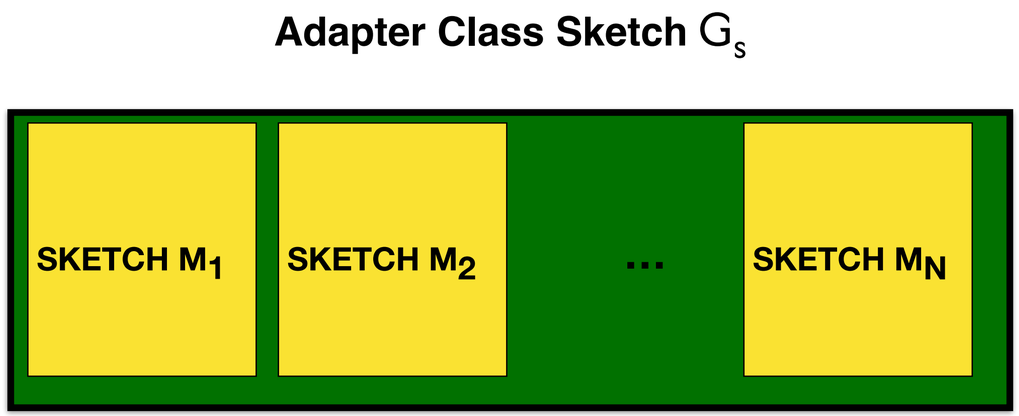

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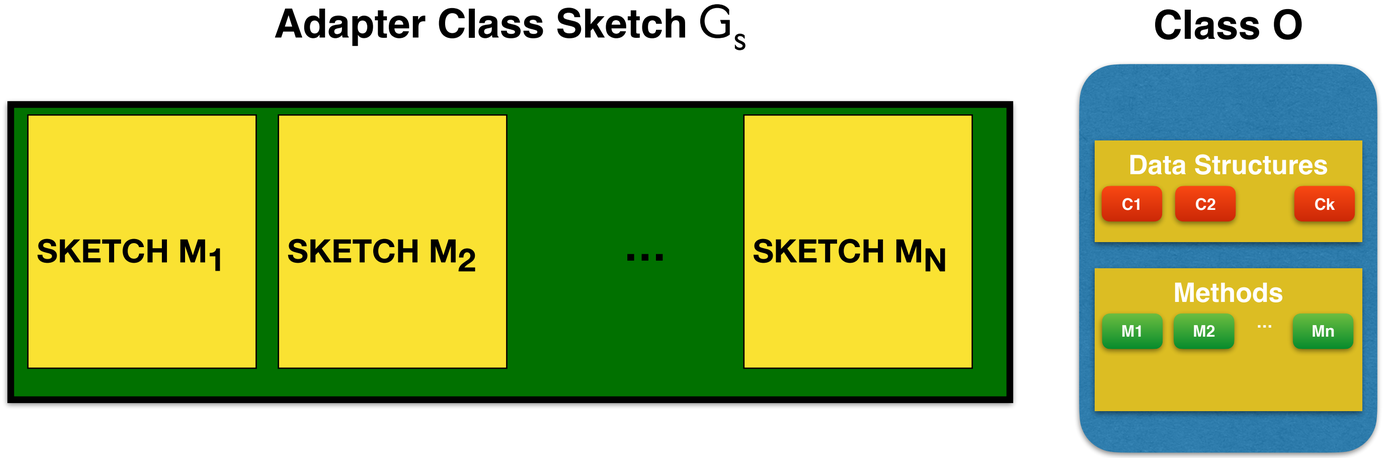
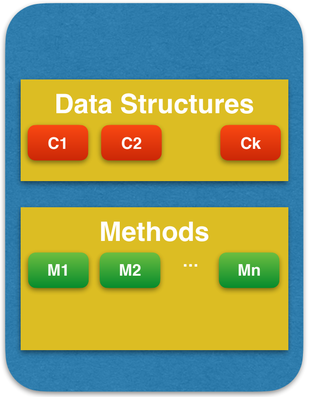


Iteration 1: Solving the Adapter Class Sketch

Interclass Equivalence Predicates

Adapter Class Sketch G_s

Class O



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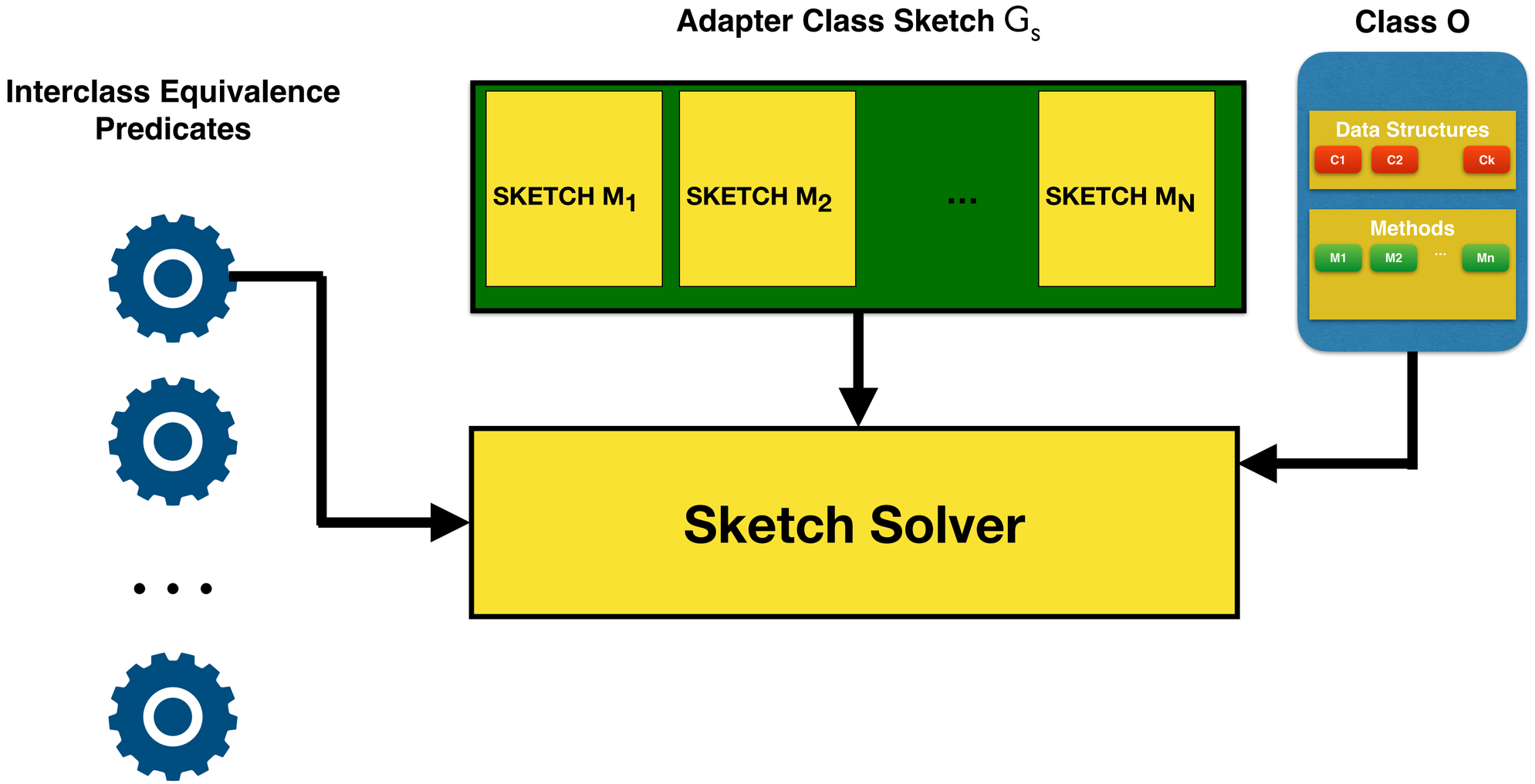

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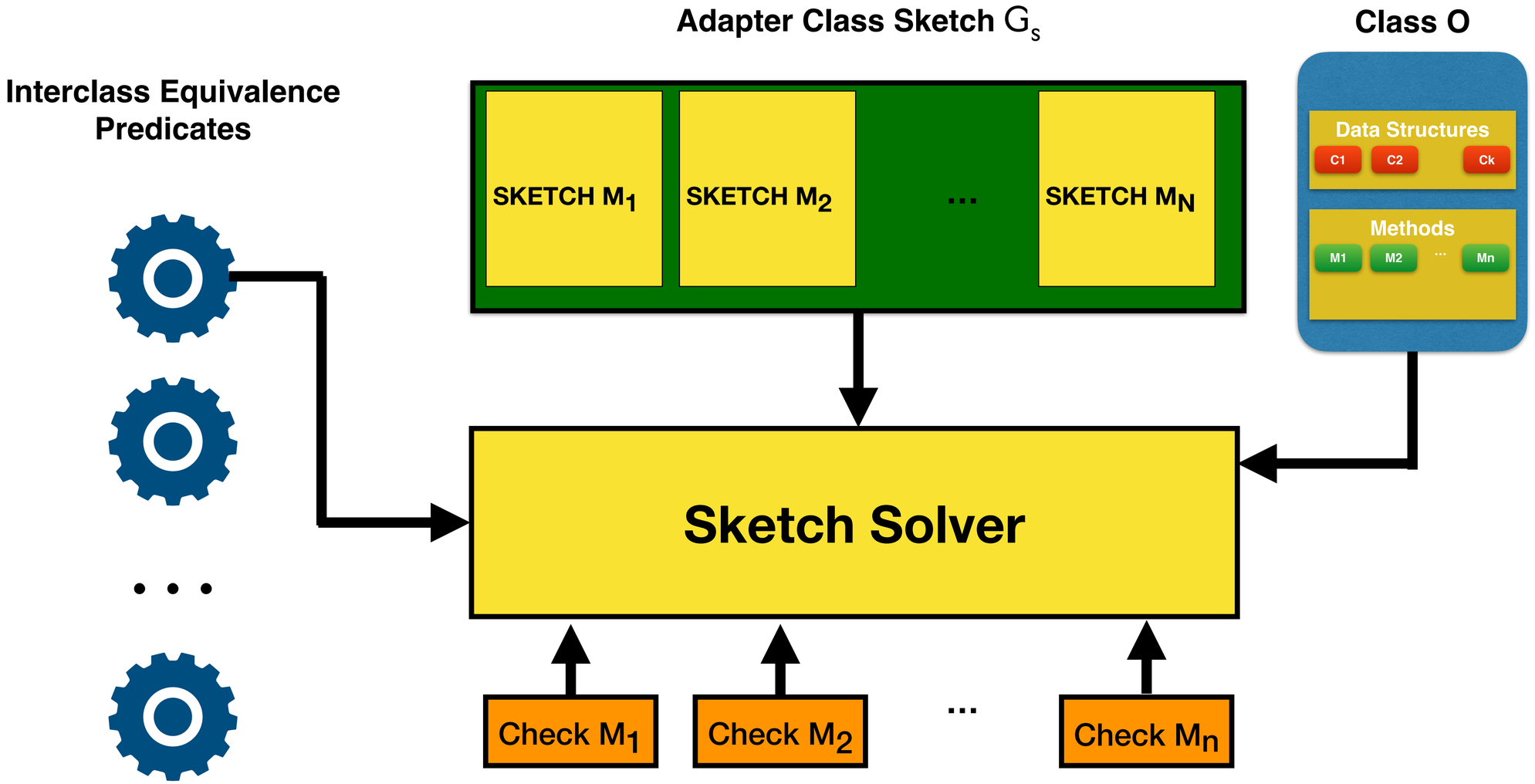

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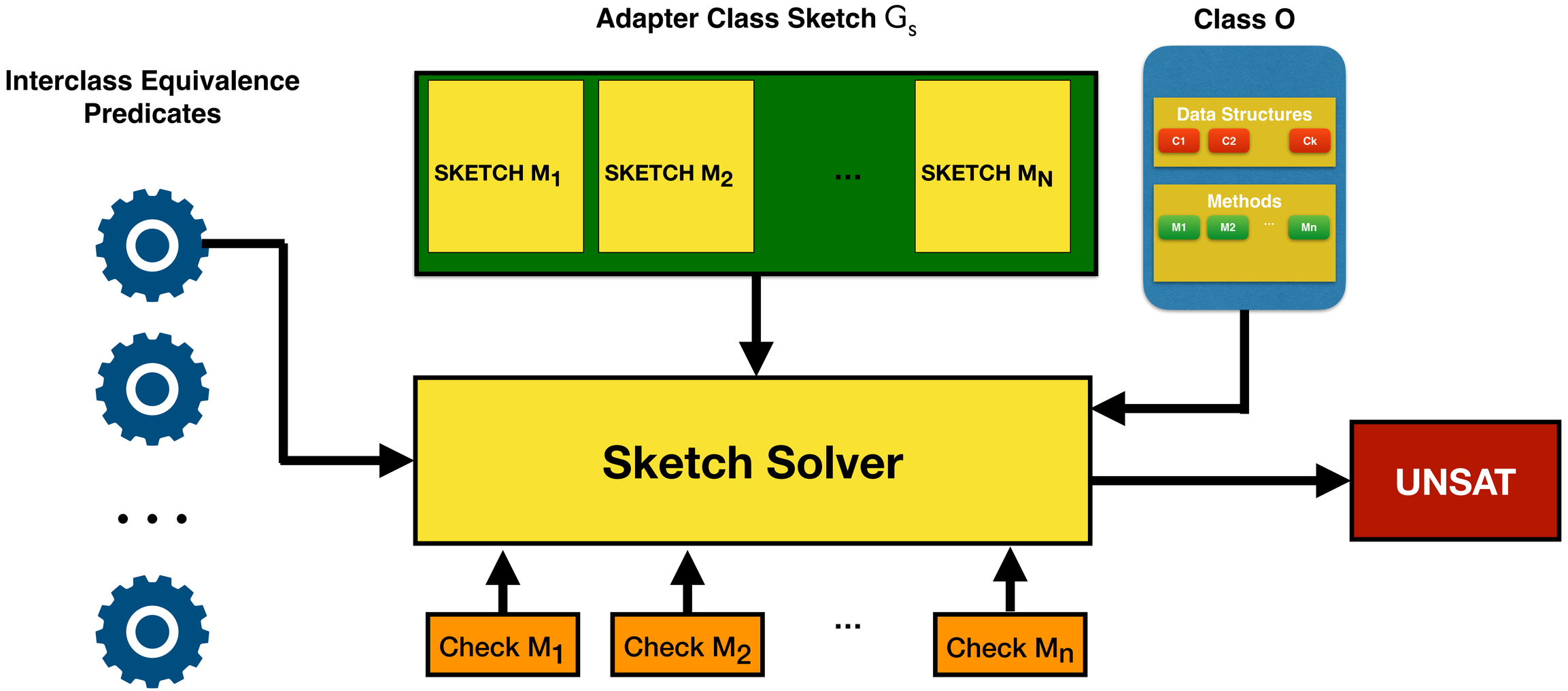

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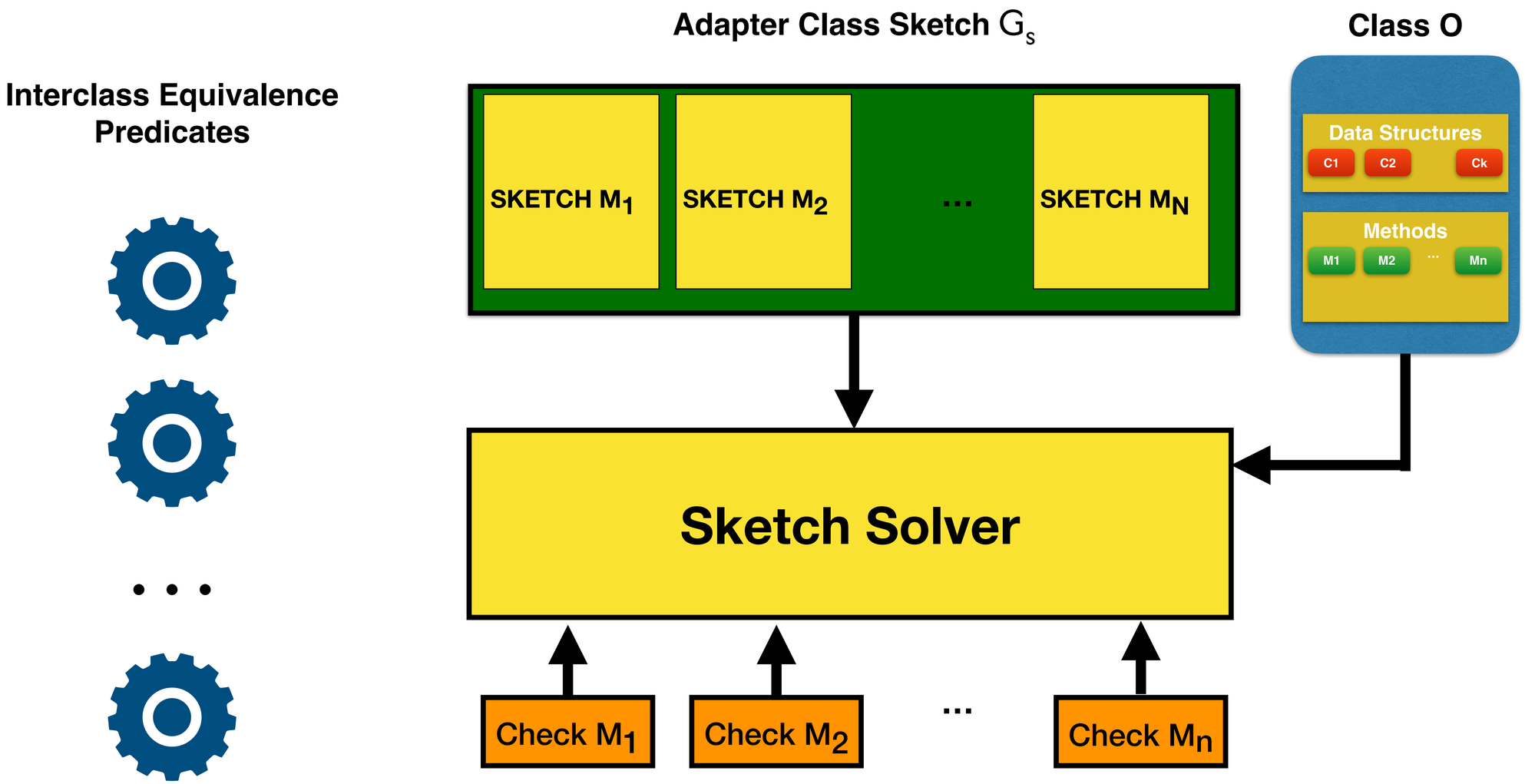
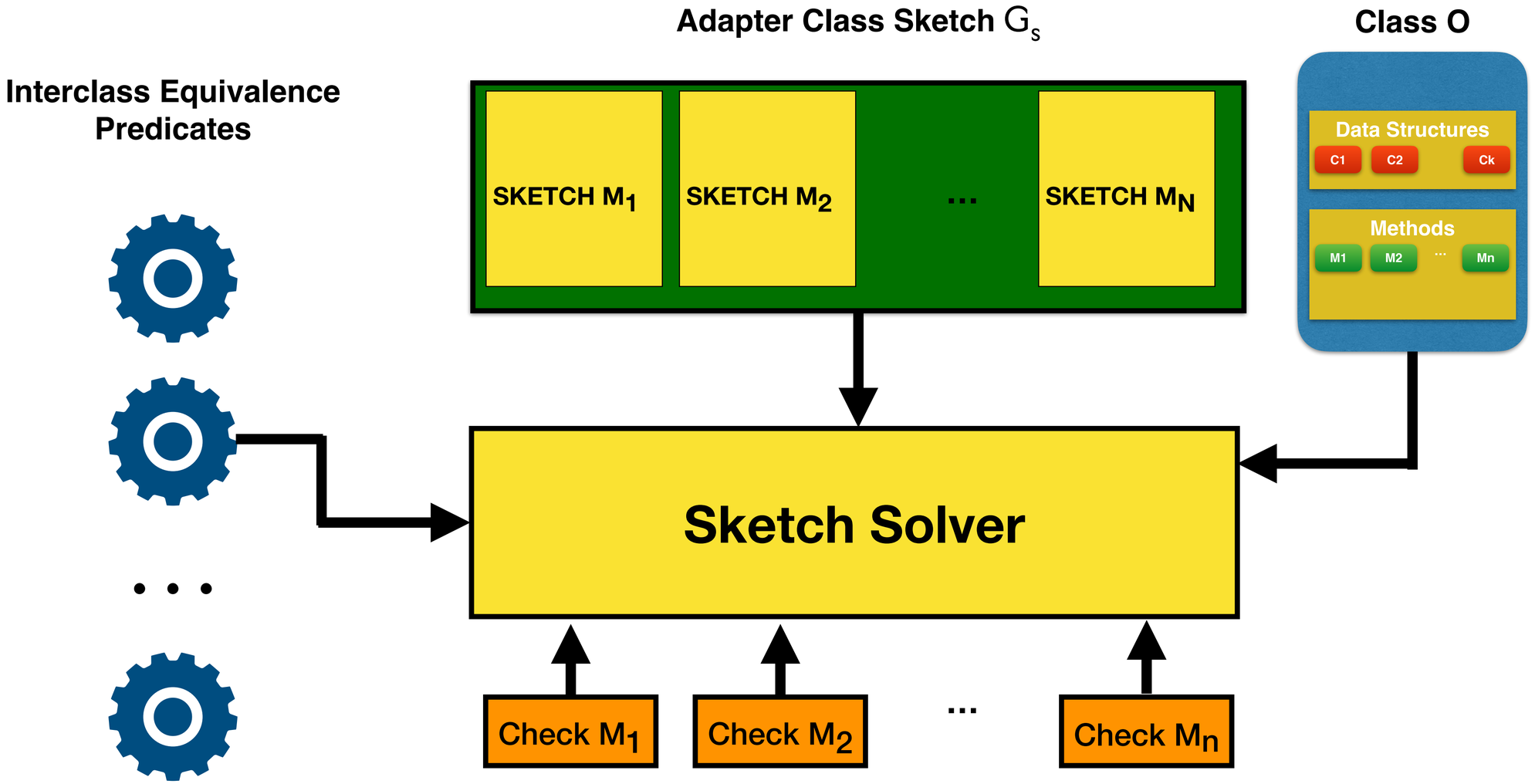
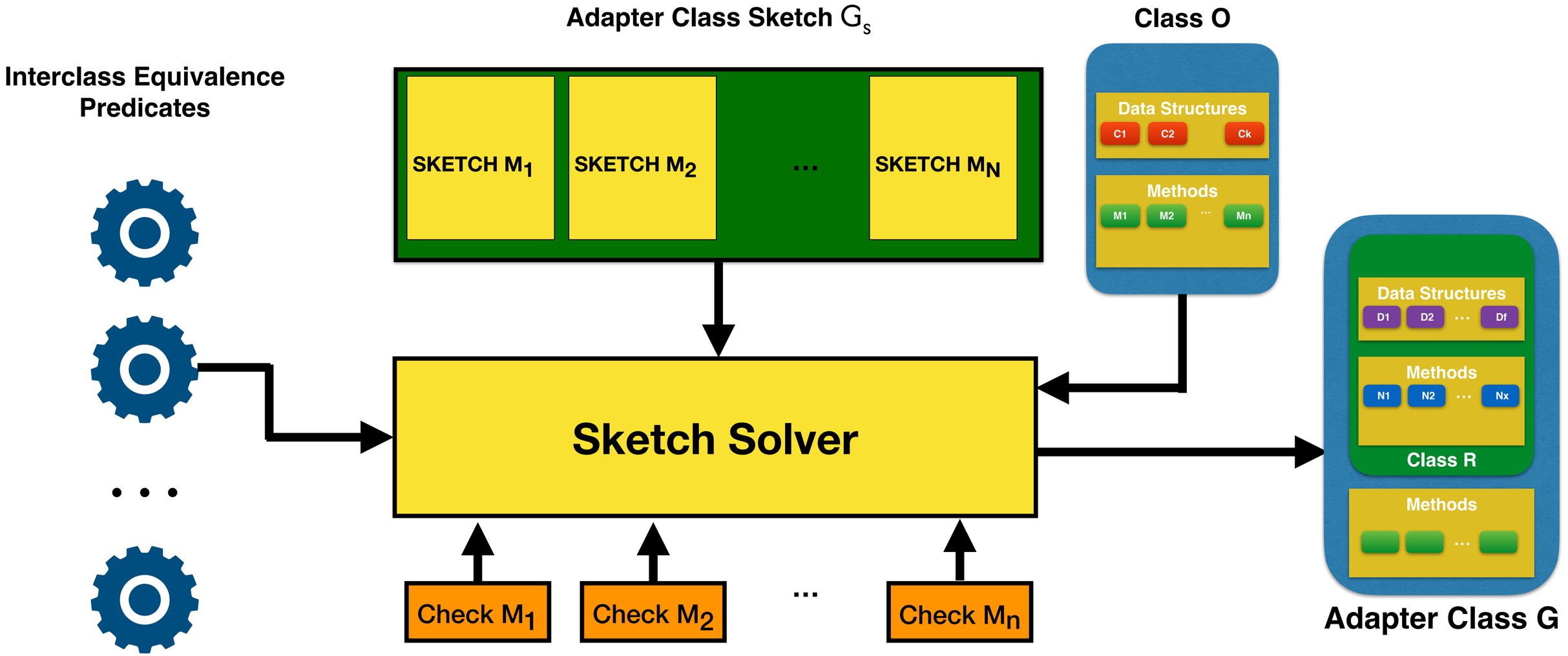


Iteration 2: Solving the Adapter Class Sketch



Iteration 2: Solving the Adapter Class Sketch



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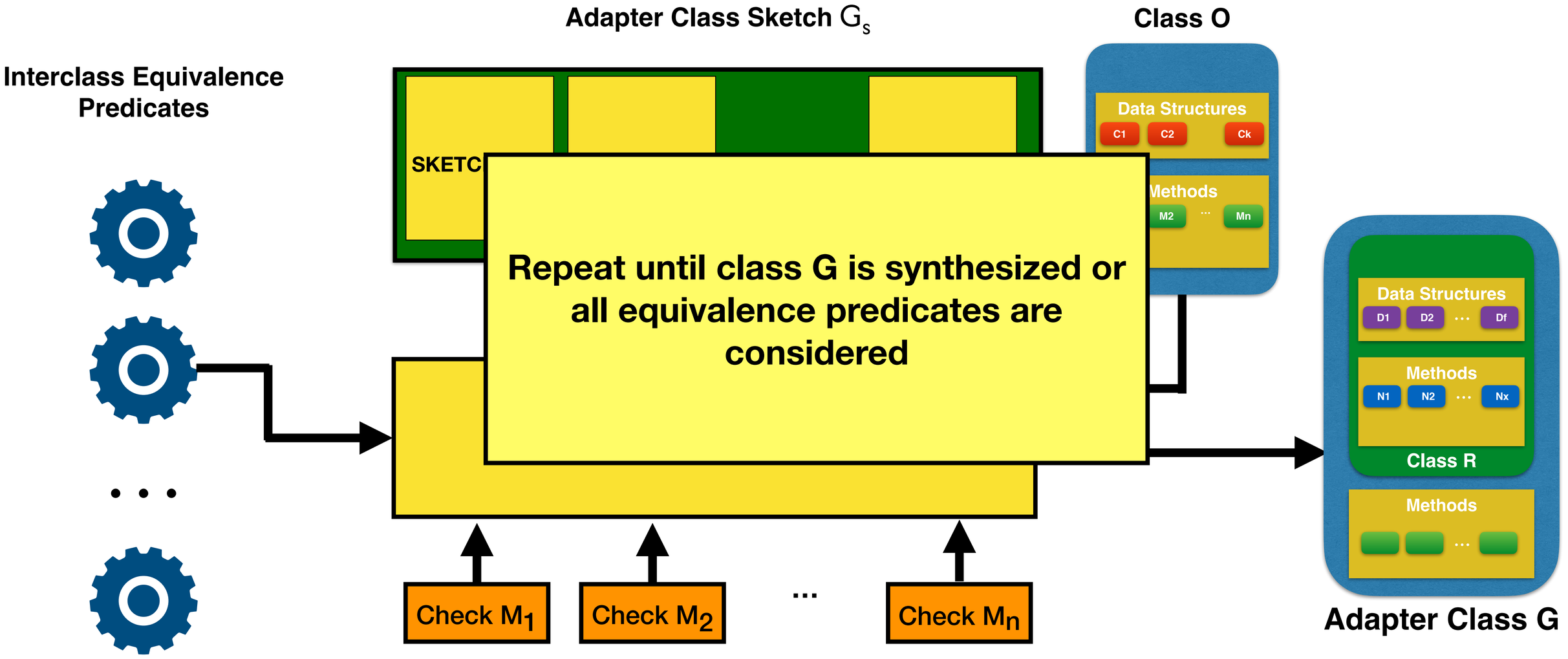

Implementation

- Built on JPF, Mistral and JavaSketch frameworks
- Exceptions are handled using optional try-catch blocks
- Maximum length for arrays and field dereferences: 5
  - Manually verified correctness beyond the limit
- Generic types are instantiated before synthesis
- Constructors are treated as special methods; no assume clause on receivers

Evaluation

- Evaluated on OpenSource Java Classes
- Replacing a class with a similar class
  - Considered 10 classes and 20 class replacement experiments
  - **Inter-class equivalence predicates generated**, Maximum: 8, Average: 2.6
  - **Method invocation sequence** identified as replacement, Maximum: 6, Average: 1.7
  - Allowed partial class synthesis
    - Synthesized **193/375** adapter methods

Evaluation

- Replacing an older version of the class with newer version
  - Considered 6 classes from GitHub > 450 stars
  - Replacement found for 4 classes.
  - 2 cases failed due to bug fixes
  - Fields added/removed/updated, changes to method signature, changes to implementation and cosmetic changes

Broader Implication

- Software is widely available, free and built by others
- Many implementations of the same functionality are available
- Key Question: How can I make sure my software always incorporates best implementation?
- MASK takes a step towards answering this question
- We envision MASK and it’s successors to enable softwares to better themselves

Conclusion

- MASK: Automatic context-agnostic class replacement
  - Synthesize a drop-in adapter class
  - Equivalence of original class and the adapter class is verified
  - Leverages symbolic execution, constraint solving and sketch based synthesis
- Evaluated on open source Java classes
- Can synthesize non-trivial replacements