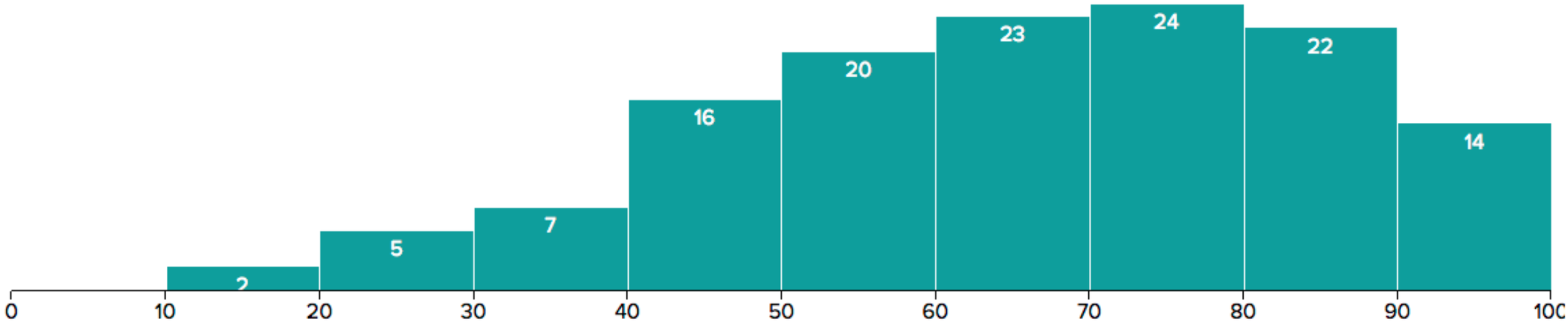

2
5
7
16
20
23
24
22
14
0
10
20
30
40
50
60
70
80
90
100

Objects

Outline

- Central concepts in OO languages
- Objects as activation records (Simula)
- Dynamically-typed object-oriented languages
  - Class-based languages (Smalltalk)
  - Prototype-based languages (JavaScript)

Central concepts in OO languages

1. Dynamic lookup
2. Encapsulation
3. Subtyping
4. Inheritance

What are examples of objects?

What are examples of objects?

- File system

```
#include <unistd.h>

int open(const char *path, int oflag, ...);
ssize_t write(int fildes, const void *buf, size_t nbyte);
```

- DOM Elements

```
var log = document.getElementById(“log”);
log.textContent = “w00t w00t”;
```

- Integer

```
3 + 44
```

etc.

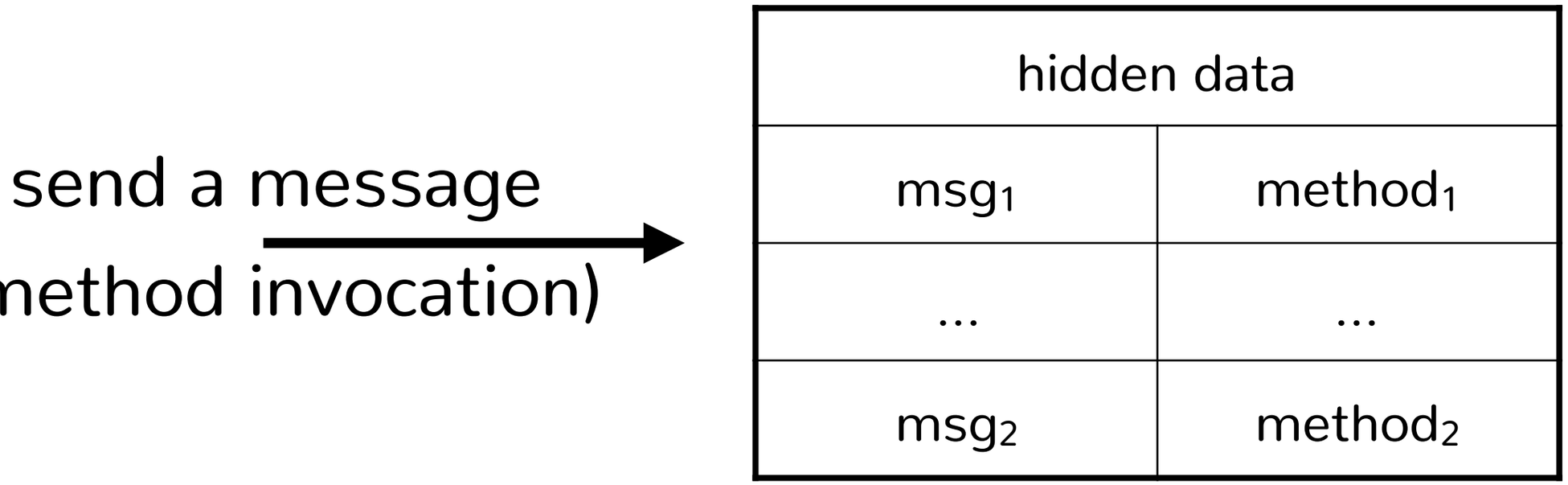
What is an object?

send a message
(method invocation)

hidden data	
msg_1	$method_1$
...	...
msg_2	$method_2$

- How is this different from ADTs?

What is an object?



- How is this different from ADTs?
  - Behavioral not structural

Terminology

Terminology

- **Selector**: name of a message (method name)
  - E.g., `remove`

Terminology

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  - E.g., `remove`
- **Message**: selector + arguments
  - E.g., `remove("log")`

Terminology

- **Selector**: name of a message (method name)
  - E.g., `remove`
- **Message**: selector + arguments
  - E.g., `remove("log")`
- **Method**: code used when responding to message
  - E.g.,

```
Array.prototype.remove = function (val) {
  var i;
  while((i == this.indexOf(val)) !== -1)
    this.splice(i,1);
  return this;
}
```

1. Dynamic lookup

`object.message(args)`

- Invoke operation on object
  - Smalltalk: send message to object
  - C++: call member function on object
- Method is selected dynamically
  - Run-time operation
  - Depends on implementation of the object receiving the message

Is dynamic lookup = overloading?

- A: yes
- B: no

Is dynamic lookup = overloading?

- A: yes
- B: no

Dynamic lookup ≠ overloading

- In overloading we can use the same symbol to refer to different implementations
  - E.g., `1 + 1` and `1.0 + 1.0` use different implementations:

```
instance Num Int where
(+) = intPlus
...

instance Num Float where
(+) = floatPlus
...
```

  - How is dynamic lookup different from this?

Dynamic lookup ≠ overloading

- Consider:

```
for(var i = 0; i < arrA.length; i++) {
  ... arrA[i] + arrB[i] ...
}
```

- Here: send message `+arrB[i]` to object `arrA[i]`
- Which + we use is determined at run-time! Why?

Dynamic lookup ≠ overloading

Dynamic lookup ≠ overloading

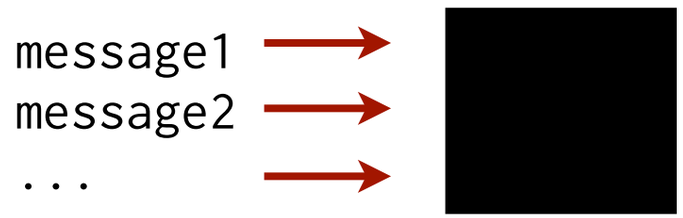
- Overloading
  - Meaning of `operation(args)` is always the same
  - Code to be executed is resolved at compile-time

Dynamic lookup ≠ overloading

- Overloading
  - Meaning of `operation(args)` is always the same
  - Code to be executed is resolved at compile-time
- Dynamic lookup
  - Meaning of `object.message(args)` depends on both `object` and `message`
  - Code to be executed is resolved at run-time

2. Abstraction / Encapsulation

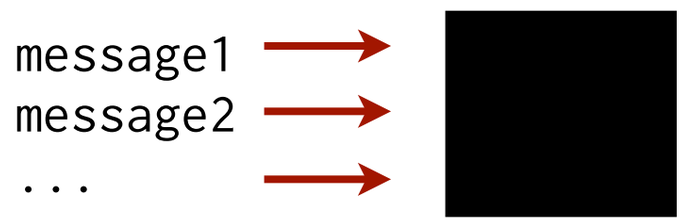
- Restricting access to a program component according to its specified interface



2. Abstraction / Encapsulation

- Restricting access to a program component according to its specified interface

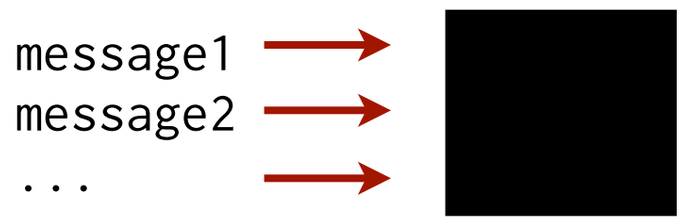
- Encapsulation separates views of
  - User of a component (has “abstract” view)



2. Abstraction / Encapsulation

- Restricting access to a program component according to its specified interface

- Encapsulation separates views of
  - User of a component (has “abstract” view)
    - Operates by applying fixed set of operations provided by builder of abstraction



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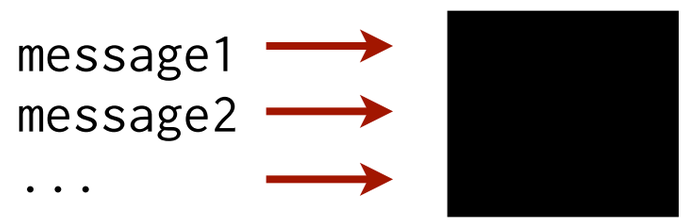


  - Builder of component (has detailed view)

2. Abstraction / Encapsulation

- Restricting access to a program component according to its specified interface

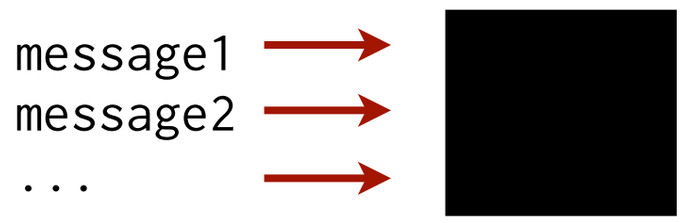
- Encapsulation separates views of

  - User of a component (has "abstract" view)

    - Operates by applying fixed set of operations provided by builder of abstraction

  - Builder of component (has detailed view)

    - Operates on representation



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- Restricting access to a program component according to its specified interface

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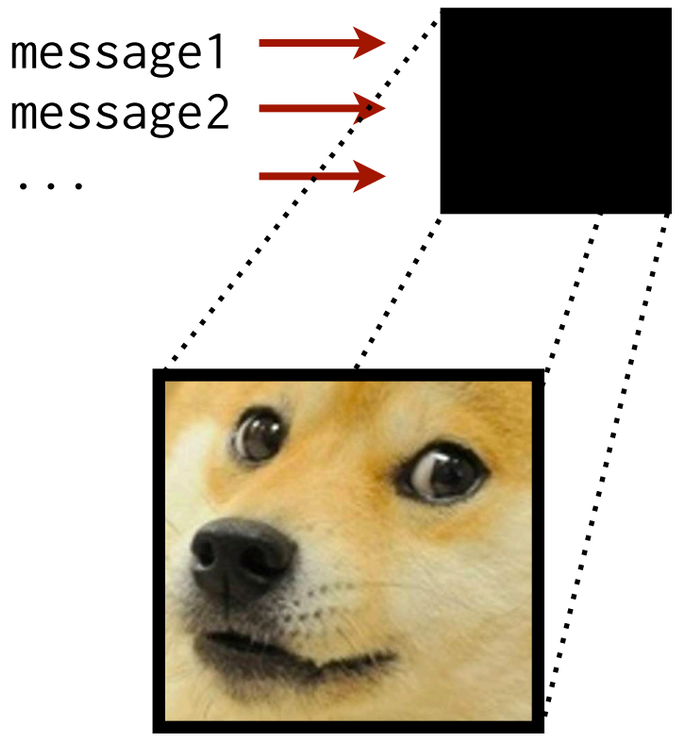
  - Builder of component (has detailed view)

    - Operates on representation



3. Subtyping

3. Subtyping

- **Interface:** external view of object
  - Messages understood by object (i.e., its type)
  - E.g.,

```
interface(Point)      == [“x”, “y”, “move”]
interface(ColorPoint) == [“x”, “y”, “move”, “color”]
```

3. Subtyping

- **Interface:** external view of object
  - Messages understood by object (i.e., its type)
  - E.g.,
    `interface(Point)` `== ["x", "y", "move"]`
    `interface(ColorPoint) == ["x", "y", "move", "color"]`
- Subtyping is a relation (<:) between interfaces
  - If interface of `A` objects contains the whole interface of `B` object: `A` **objects can be used where** `B` **objects are expected**
  - We say `A` is a subtype of a `B`: `A <: B`
  - E.g., `ColoredPoint <: Point`

4. Inheritance

- It’s the same thing as subtyping?
  - A: yes
  - B: no

4. Inheritance

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4. Inheritance

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- **Implementation:** internal representation of object
  - Code for methods and supporting mechanism

4. Inheritance

- **Implementation:** internal representation of object
  - Code for methods and supporting mechanism
- Inheritance: language feature that allows code reuse
  - New objects may be defined by reusing implementation of other objects
  - E.g., `ColoredPoint` implementation of `move` can reuse code used to implement `move` for `Point` objects

Subtyping implies inheritance?

- A: yes
- B: no

Subtyping implies inheritance?

- A: yes
- B: no

Subtyping ≠ inheritance

```
Point:
 x
 y
 move
```

```
ColoredPoint:
 x
 y
 move
 color
```

Subtyping ≠ inheritance

Point:		ColoredPoint:
x		x
y	:>	y
move		move
		color

Subtyping ≠ inheritance

Point:		ColoredPoint:
x		x
y	:>	y
move		move
		color

```
Point.prototype.move =
  function(dx, dy) {
    this.x += dx;
    this.y += dy;
  }
```

Subtyping ≠ inheritance

Point:		ColoredPoint:
x		x
y	:>	y
move		move
		color

```
Point.prototype.move =
  function(dx, dy) {
    this.x += dx;
    this.y += dy;
  }
```

```
ColoredPoint.prototype.move =
 Point.prototype.move;
```

Subtyping ≠ inheritance

Point:		ColoredPoint:
x		x
y	:>	y
move		move
		color

```
Point.prototype.move =
  function(dx, dy) {
    this.x += dx;
    this.y += dy;
  }
```

```
ColoredPoint.prototype.move =
 function(dx, dy) {
   this.x += dx+Math.random();
   this.y += dy+Math.random();
}
```

Subtyping ≠ inheritance

Point:		ColoredPoint:
x		x
y	:>	y
move		move
		color

```
Point.prototype.move =
  function(dx, dy) {
    this.x += dx;
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  }
```

```
edPoint.prototype.move =
unction(dx, dy) {
    this.x += dx+Math.random();
    this.y += dy+Math.random();
}
```

NO INHERITANCE!

Inheritance implies subtyping?

- A: yes
- B: no

Inheritance implies subtyping?

- A: yes
- B: no

Inheritance implies subtyping?

- A: yes
- B: no

What'a an example?

Inheritance implies subtyping?

- A: yes
- B: no

What'a an example?

C++:private inheritance, JS: just reuse methods

Why do we care about these?

- Dynamic lookup
  - In function-oriented programs, functions that operate on different kinds of data: need to select correct operations
- Abstraction, subtyping, inheritance
  - Organize system according to component interfaces
  - Extend system concepts/components
  - Reuse implementation through inheritance

Outline

- Central concepts in object-oriented languages
- Objects as activation records (Simula)
- Dynamically-typed object-oriented languages
  - Class-based languages (Smalltalk)
  - Prototype-based languages (JavaScript)

Objects as activation records

- Idea: after a function call is executed, leave the activation record on the stack, return pointer to it
  - E.g., Constructing objects in a JavaScript-like language

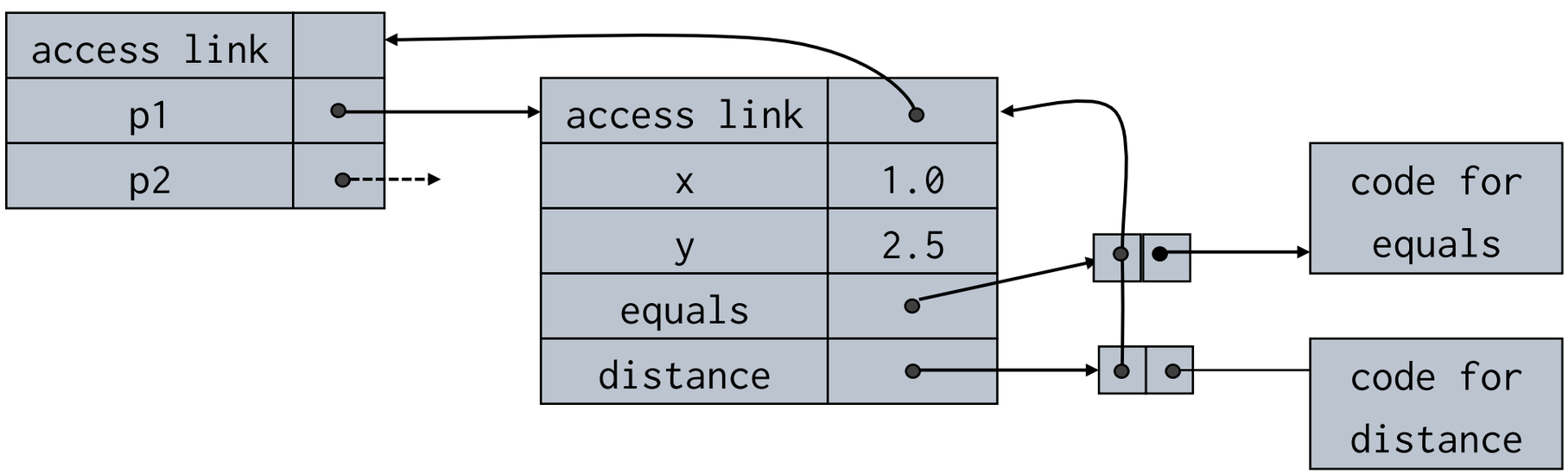
```
class Point(x, y) {
   let equals = function (p) {
      return Math.abs(x - p.x) +
             Math.abs(y - p.y) < 0.00001;
   }
   let distance = function (p) {
      var dx = x - p.x, dy = y - p.y;
      return Math.sqrt(dx*dx) + Math.sqrt(dy*dy);
   }
}
```

Objects as activation records

- Add syntax for calling class & accessing object methods

```
let p1 = new Point (1.0, 2.5);
let p2 = new Point (2.0, 2.5);
p1.equals(p2);
```

  - After executing first line:

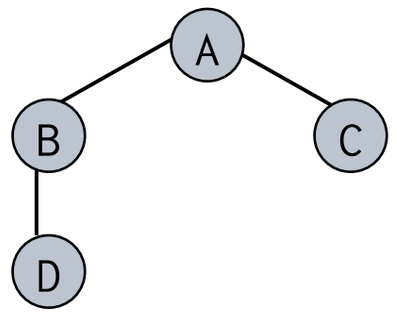


Simula

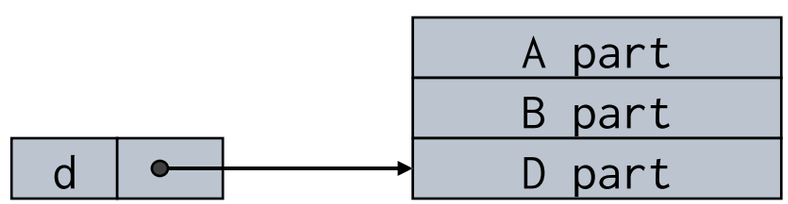
- First object-oriented language
  - Inspired many later designs, including Smalltalk and C+++
- Objects in Simula
  - **Class:** function returning a pointer to its activation record
  - **Object:** instance of class, i.e., activation record produced by call to class
  - **Object access:** access any local variable/function using dot-notation: `object.var`
  - **Memory management:** garbage collect activation records

Derived classes in Simula

- A class declaration can be prefixed by a class name
  - E.g., `class A`
    `A class B`
    `A class C`
    `B class D`



- An object of a "prefixed class" is the concatenation of objects of each class in prefix
  - Inheritance & subtyping
  - E.g., `d = new D(...)`

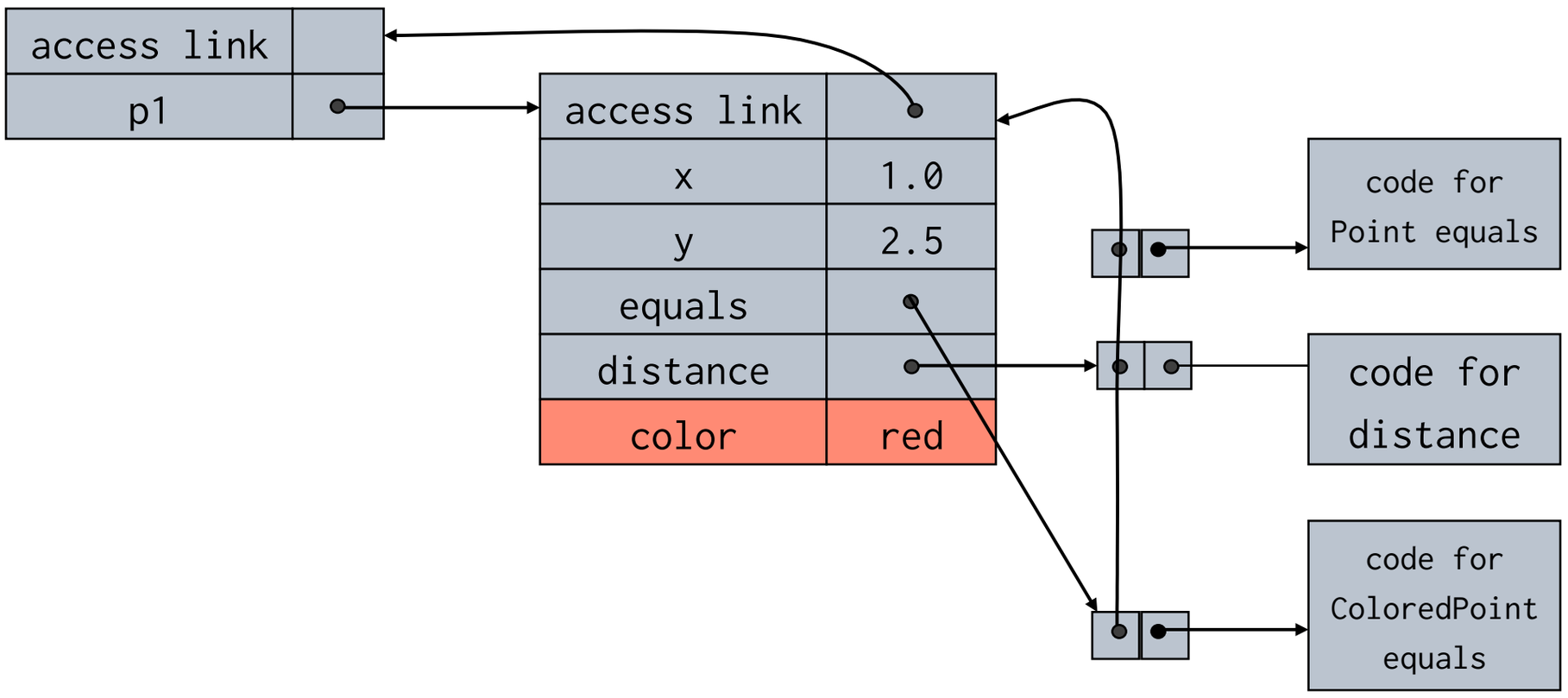


- We say `D` is a *subclass* of `B` and `B` is a *superclass* of `D`

Prefix classes

```
Point class ColoredPoint(color) {
  let equals = function (p) {
     return (Math.abs(x - p.x) +
            Math.abs(y - p.y) < 0.00001)
            && color == p.color;
  }
}
```

```
var p1 = new ColoredPoint(1.0,2.5,”red”);
```



Simula summary

- Main OO features
  - Classes: function that returns pointer to its activation record
  - Objects: activation record produced by call to class
  - Subtyping & inheritance: class hierarchy & prefixing
- Missing features
  - Encapsulation: all data and functions accessible
  - No notion of self/super (discussed in next few slides)

Outline

- Central concepts in object-oriented languages
- Objects as activation records (Simula)
- Dynamically-typed object-oriented languages
  - Class-based languages (Smalltalk)
  - Prototype-based languages (JavaScript)

Smalltalk

- Object-oriented language
  - Everything is an object, even classes
  - All operations are messages to objects
  - Popularized objects
- The weird parts
  - Intended for “non-programmer”
  - Syntax presented by language-specific editor

FIGURE 11.19 GRAIL

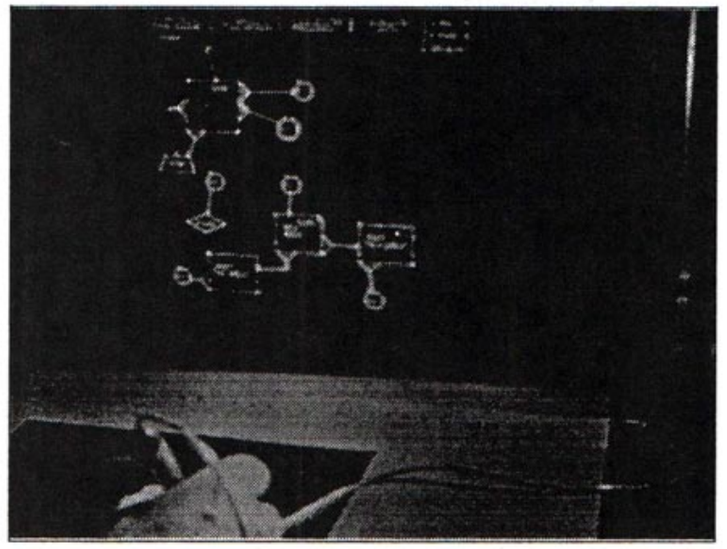


FIGURE 11.20 Seymour Papert and LOGO Turtle

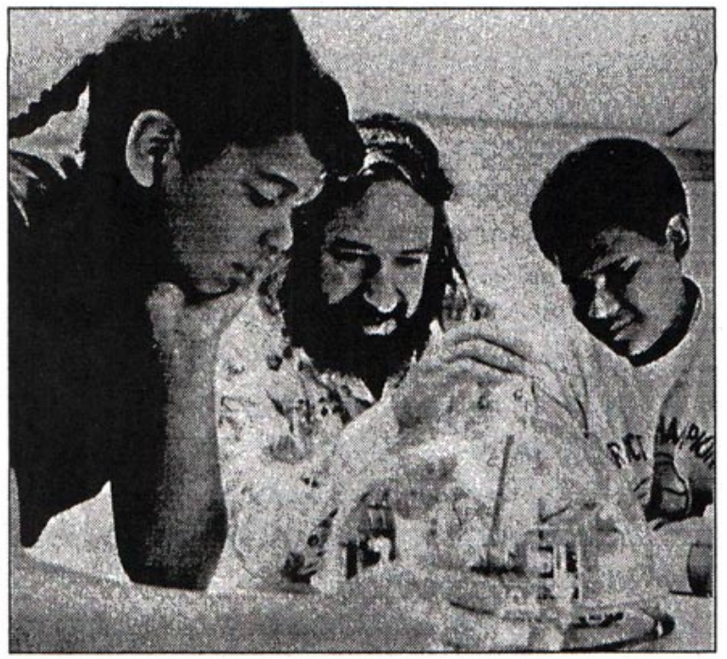
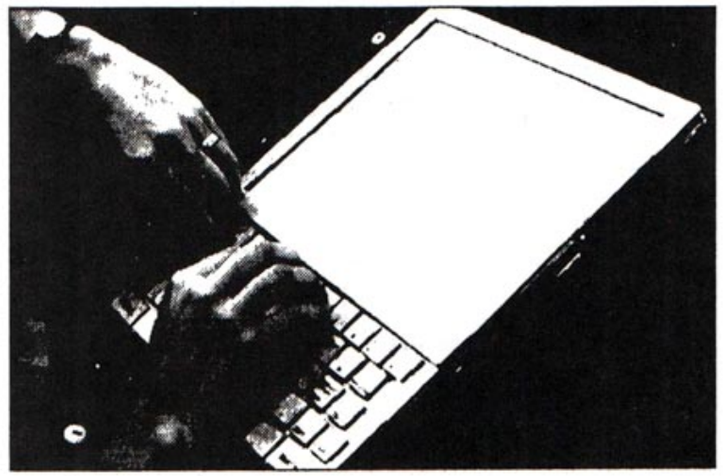


FIGURE 11.21 The Dynabook model



Smalltalk terminology

- **Class**: Defines behavior of its objects
- **Object**: Instance of some class
- **Selector**: name of a message
- **Message**: selector + arguments
- **Method**: code used when responding to message
- **Instance variable**: Data stored in object
- **Subclass**: Class defined by giving incremental modifications to some superclass

Smalltalk semantics

- Everything is an object
- Object communicate by sending/receiving messages
- Objects have their own state
- Every object is an instance of a class
- A class provides behavior for its instances

Example: Points

- Written in language-specific editor, in tabular form:

class name	`Point`
super class	`Object`
class variables	`pi`
instance variables	`x  y`
class messages and methods	
⟨`message & methods`⟩	
instance messages and methods	
⟨`message & methods`⟩	

Example: Points

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Instance messages and methods

- Getters and setters
  - Smalltalk does not have public variables
  - Get x-coordinate: `pt x`
  - Set new coordinates: `pt x:5 y:3`
- "Normal" methods
  - Move point: `pt moveDx:4 Dy: 5`
  - Draw point: `pt draw`

Instance messages and methods

- Getters and setters
  - Smalltalk does not have public variables
  - Get x-coordinate: `pt x`
  - Set new coordinates: `pt x:5 y:3`
- "Normal" methods
  - Move point: `pt moveDx:4 Dy: 5`
  - Draw point: `pt draw`

mixfix selectors

Instance messages and methods

```
x || ^ x
y || ^ y
x:xcoord y:ycoord ||
  x <- xcoord
  y <- ycoord
moveDx:dx Dy:dy ||
  x <- x + dx
  y <- y + dy
draw ||
   ...
```

Instance messages and methods

```
x || ^ x
y || ^ y
x:xcoord y:ycoord ||
   x <- xcoord
   y <- ycoord
moveDx:dx Dy:dy ||
   x <- x + dx
   y <- y + dy
draw ||
    ...
```

New local scope

Instance messages and methods

```
x || ^x
y || ^y
x:xcoord y:ycoord ||
   x <- xcoord
   y <- ycoord
moveDx:dx Dy:dy ||
   x <- x + dx
   y <- y + dy
draw ||
    ...
```

Instance variables

Instance messages and methods

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x || ^ x
y || ^ y
x:xcoord y:ycoord ||
   x <- xcoord
   y <- ycoord
moveDx:dx Dy:dy ||
   x <- x + dx
   y <- y + dy:dy
draw ||
    ...
```

Mutable assignment

Instance messages and methods

```
x || ^x
y || ^y
x:xcoord y:ycoord ||
  x <- xcoord
  y <- ycoord
moveDx:dx Dy:dy ||
  x <- x + dx
  y <- y + dy:dy
draw ||
   ...
```

Return

Example: Points

class name	`Point`
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class messages and methods	
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Example: Points

class name	`Point`
super class	`Object`
class variables	`pi`
instance variables	x y
class messages and methods	
`⟨message & methods⟩`	
instance messages and methods	
`⟨message & methods⟩`	

Class messages and methods

- Class are objects too!
  - `self` is overloaded: always points to actual object

```
newOrigin ||
 ^ self new x: 0 y: 0

newX:xvalue Y:yvalue ||
  ^ self new x: xvalue y: yvalue

initialize ||
  pi <- 3.14159
```

Class messages and methods

- Class are objects too!
  - `self` is overloaded: always points to actual object

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newOrigin ||
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new message on self (Point class)

Class messages and methods

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  - `self` is overloaded: always points to actual object

```
newOrigin ||
  ^ self new x: 0 y: 0

newX:xvalue Y:yvalue ||
   ^ self new x: xvalue y: yvalue

initialize ||
   pi <- 3.14159
```

new message on self (Point class)

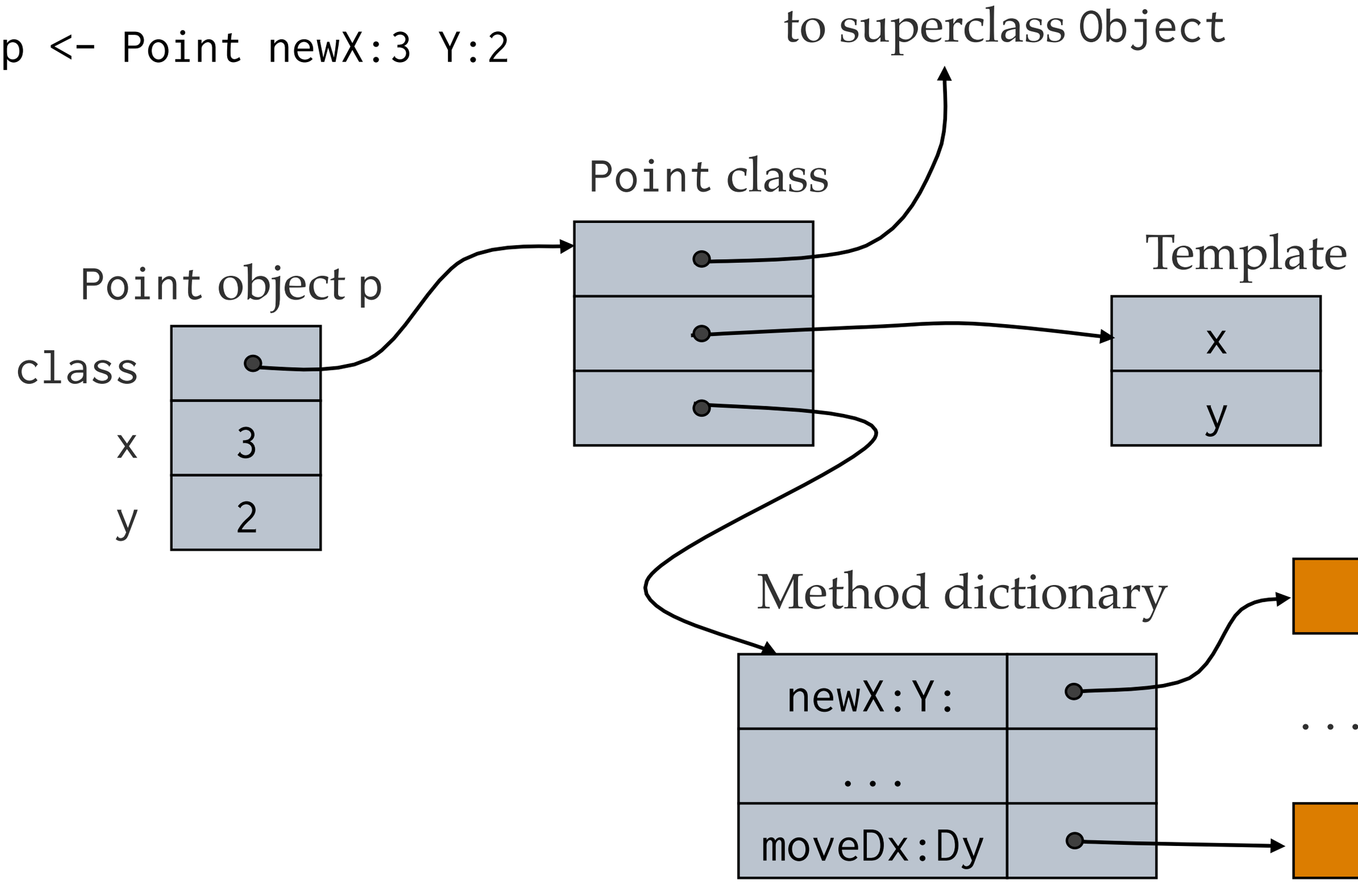
x:0 y: 0 message on new Point obj

How are objects represented?

- Objects have space for instance variable
- Objects have pointer to class
- Classes have pointers to
  - Super class (e.g., Object)
  - Template: names of instance variables
  - Method dictionary: maps selectors to code

Example representation of `Point`

```
p <- Point newX:3 Y:2
```



Example: Points

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Example: Points

class name	`Point`
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instance messages and methods	
⟨`message & methods`⟩	

Inheritance

- Define `ColoredPoint` form `Point`:

class name	`ColoredPoint`
super class	`Point`
class variables	
instance variables	`color`
class messages and methods	
`newX:xv Y:yv C:cv`	`| ...`
instance messages and methods	
`color`	`| ^ color`
`draw`	`| ...`

Inheritance

- Define `ColoredPoint` form `Point`:

class name	`ColoredPoint`
super class	`Point`
class variables	
instance variables	`color`
class messages and methods	
`newX:xv Y:yv C:cv`	`| ...`
instance messages and methods	
`color`	`| ^ color`
`draw`	`| ...`

new instance variable

Inheritance

- Define `ColoredPoint` form `Point`:

class name	`ColoredPoint`
super class	`Point`
class variables	
instance variables	`color`
class messages and methods	
`newX:xv Y:yv C:cv`	`| | ...`
instance messages and methods	
`color`	`| | ^ color`
`draw`	`| | ...`

new instance variable

new method

Inheritance

- Define `ColoredPoint` form `Point`:

class name	`ColoredPoint`
super class	`Point`
class variables	
instance variables	`color`
class messages and methods	
`newX:xv Y:yv C:cv`	`| | ...`
instance messages and methods	
`color`	`| | ^ color`
`draw`	`| | ...`

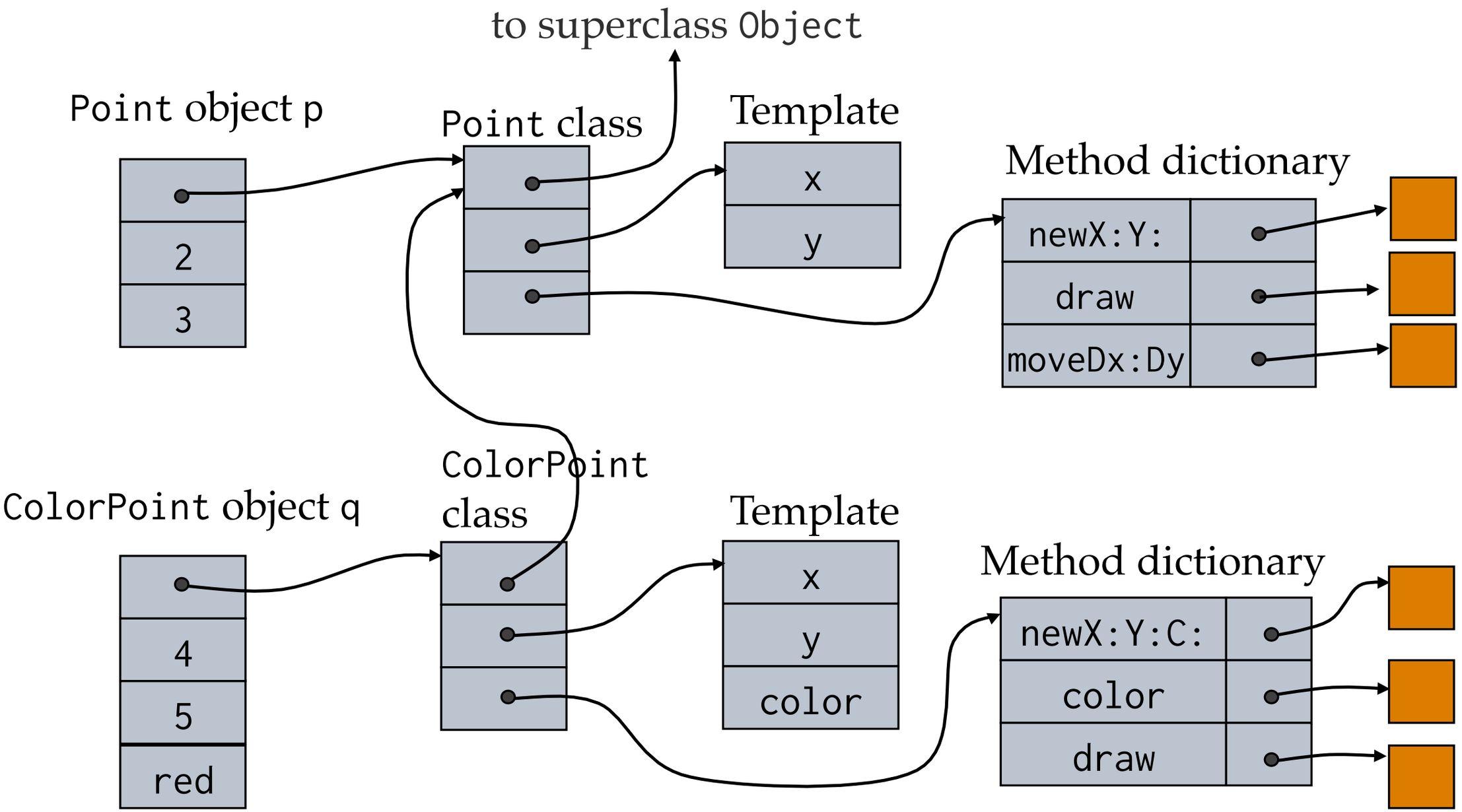
new instance variable

new method

override `draw` method

Run-time representation

```
p <- Point newX:3 Y:2
q <- ColorPoint newX:4 Y:5 C:red
```



What's the point?

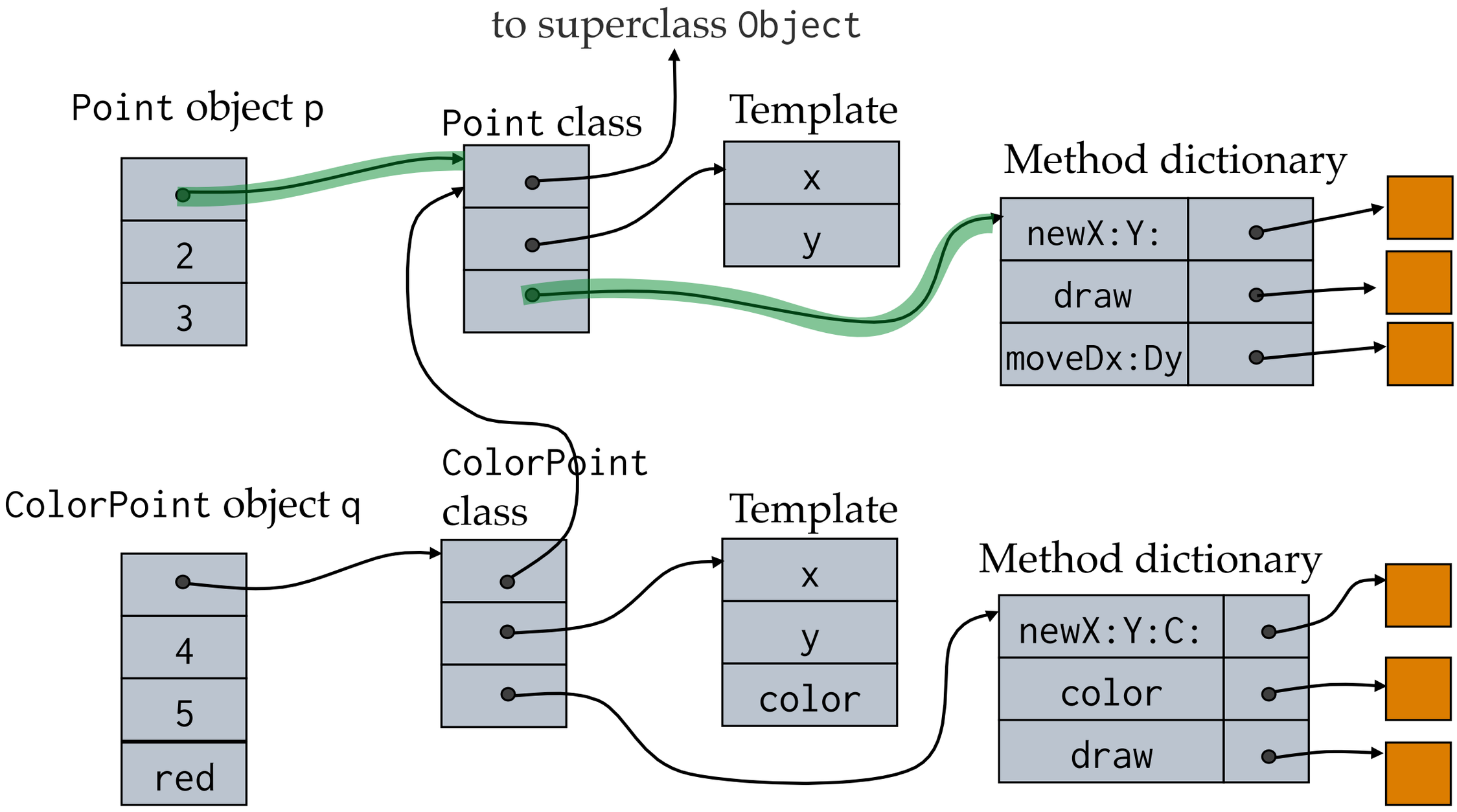
- Tells us exactly how to look up methods!
  - E.g., for Points: `p moveDx:5 Dy:5`
  - E.g., for ColorPoints: `q moveDx:5 Dy:5`

What's the point?

- Tells us exactly how to look up methods!
  - E.g., for Points: `p moveDx:5 Dy:5`
  - E.g., for ColorPoints: `q moveDx:5 Dy:5`

Dynamic lookup

- Dynamic lookup for `p moveDx:5 Dy:5`



What's the point?

- Tells us exactly how to look up methods!
  - E.g., for Points: `p moveDx:5 Dy:5`
  - E.g., for ColorPoints: `q moveDx:5 Dy:5`

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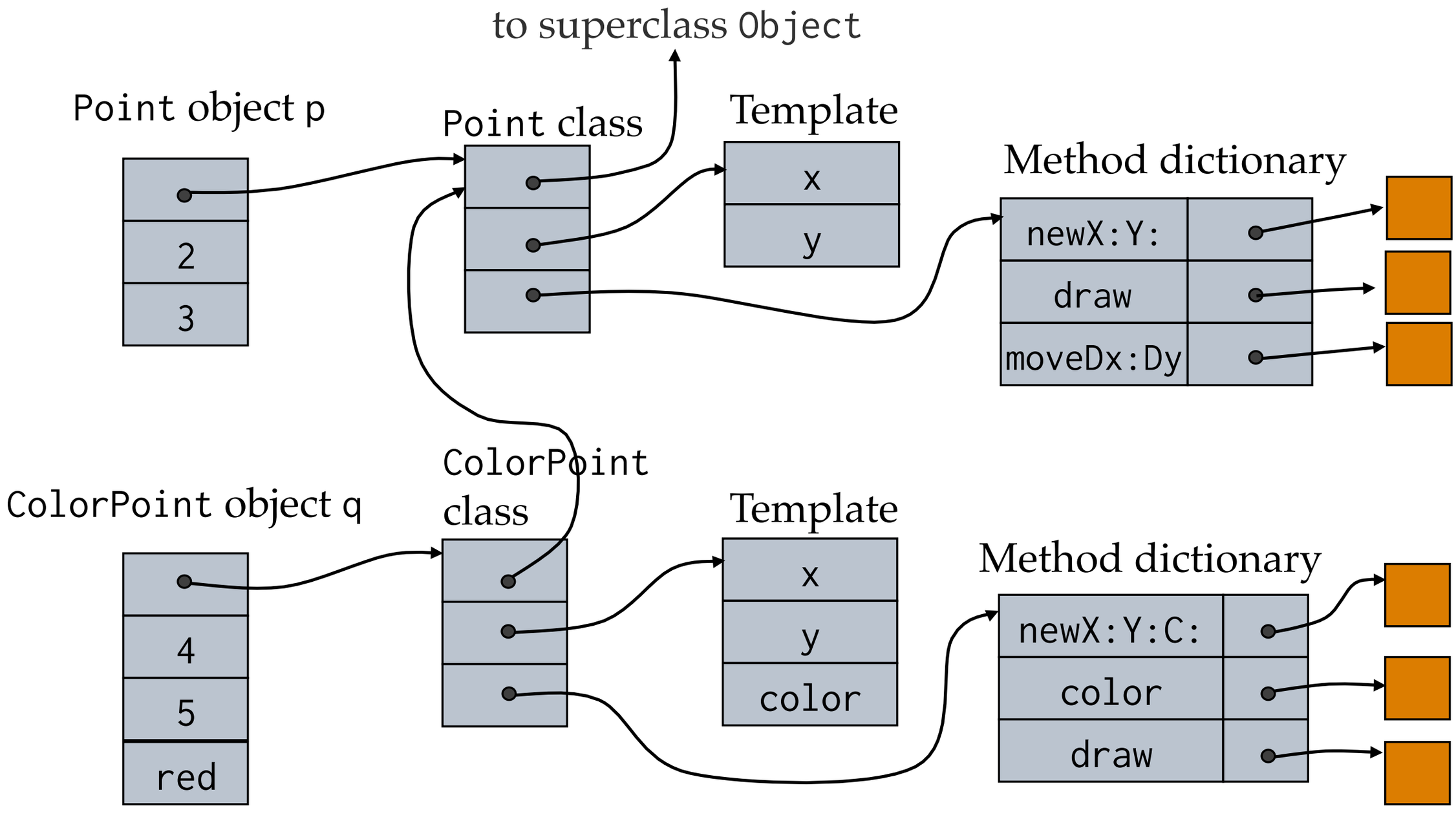

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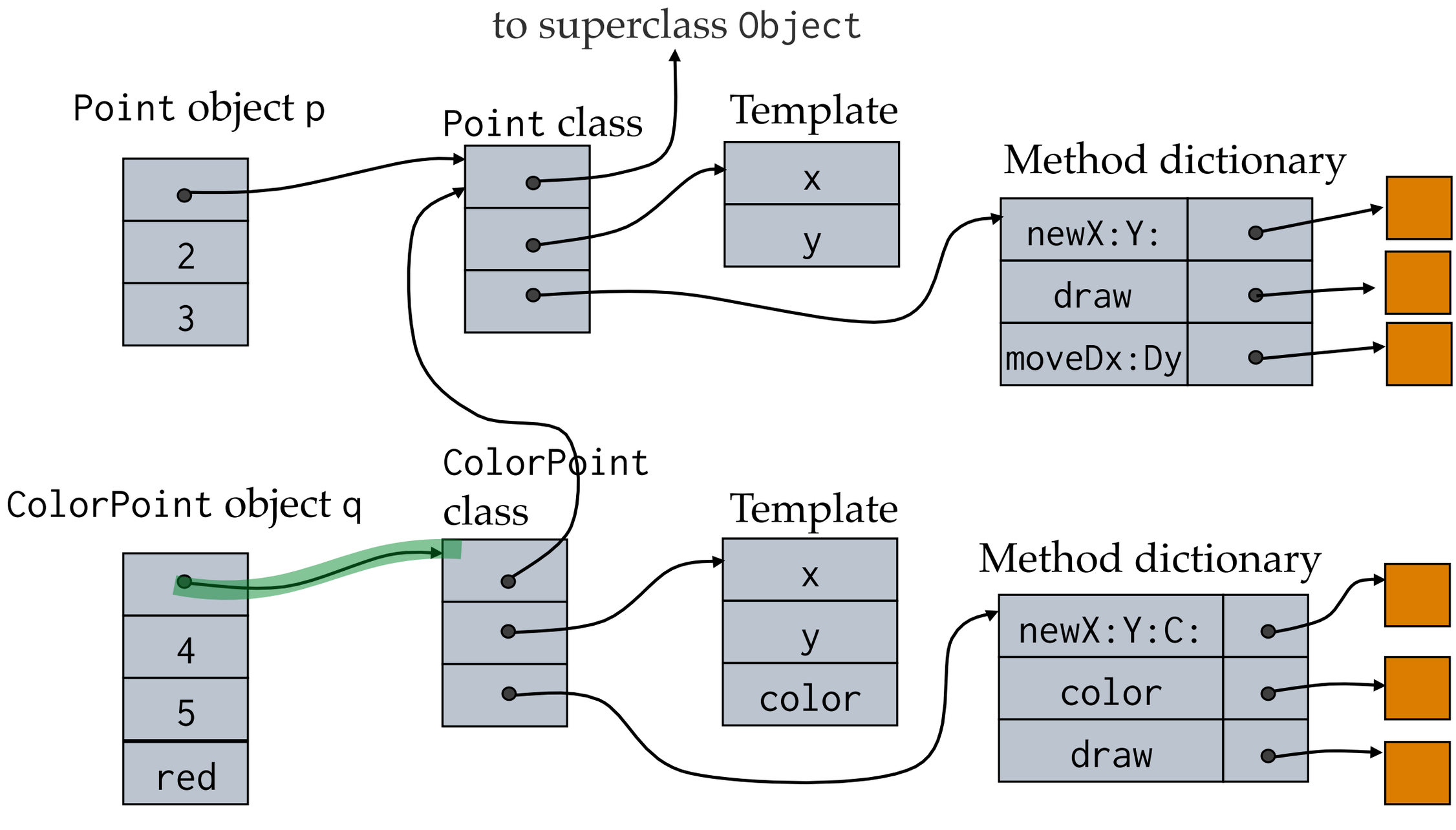

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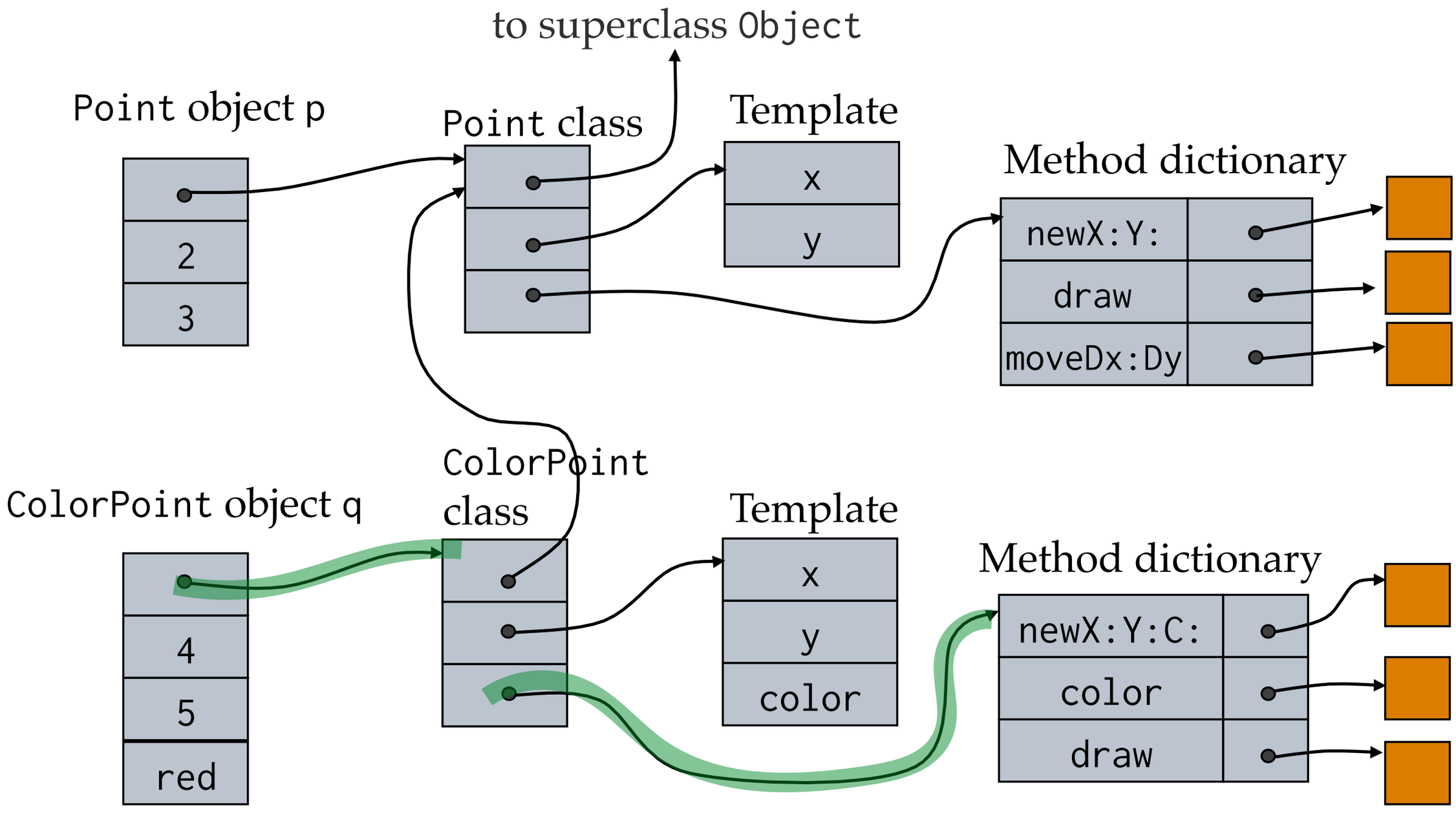

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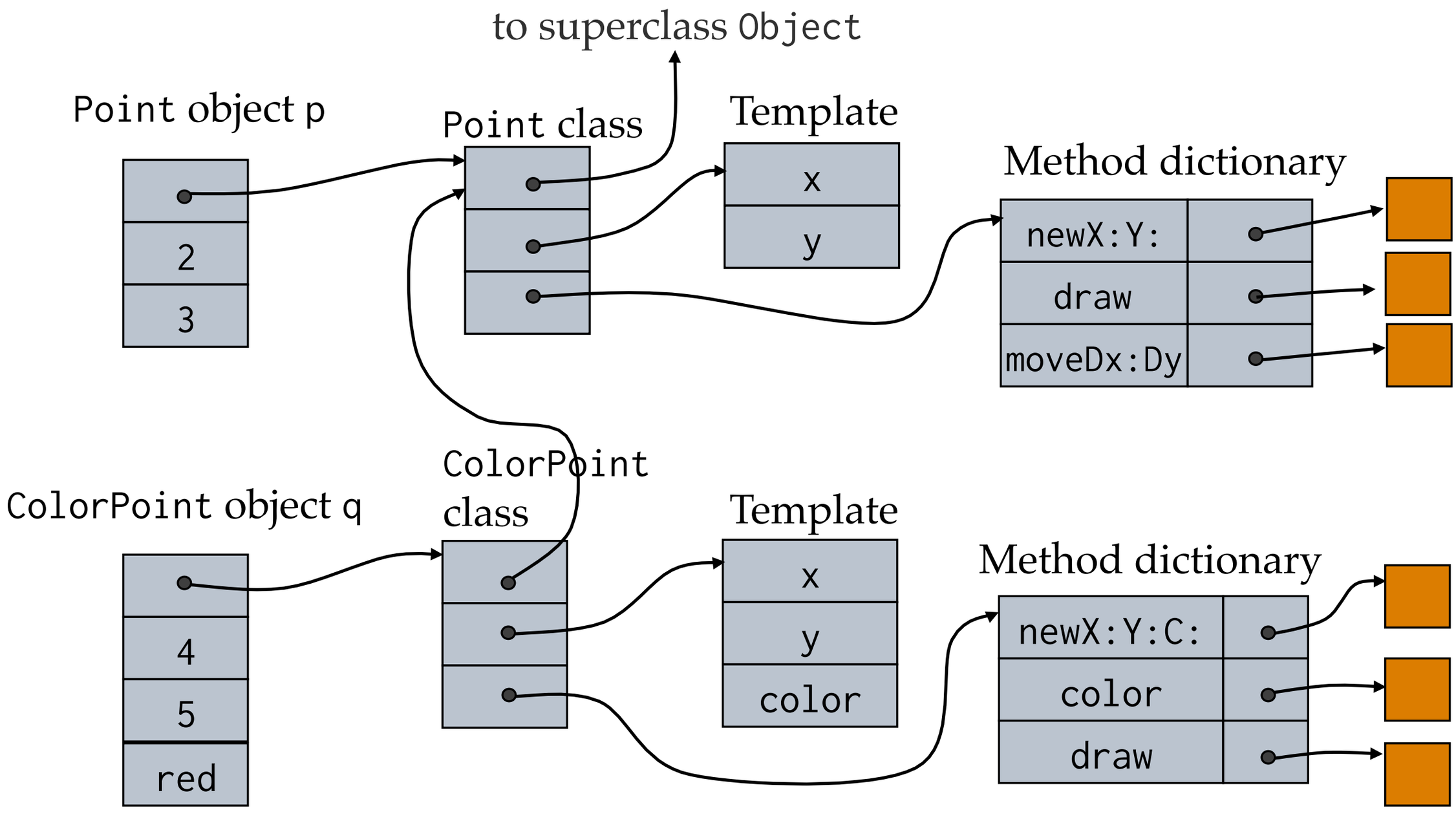

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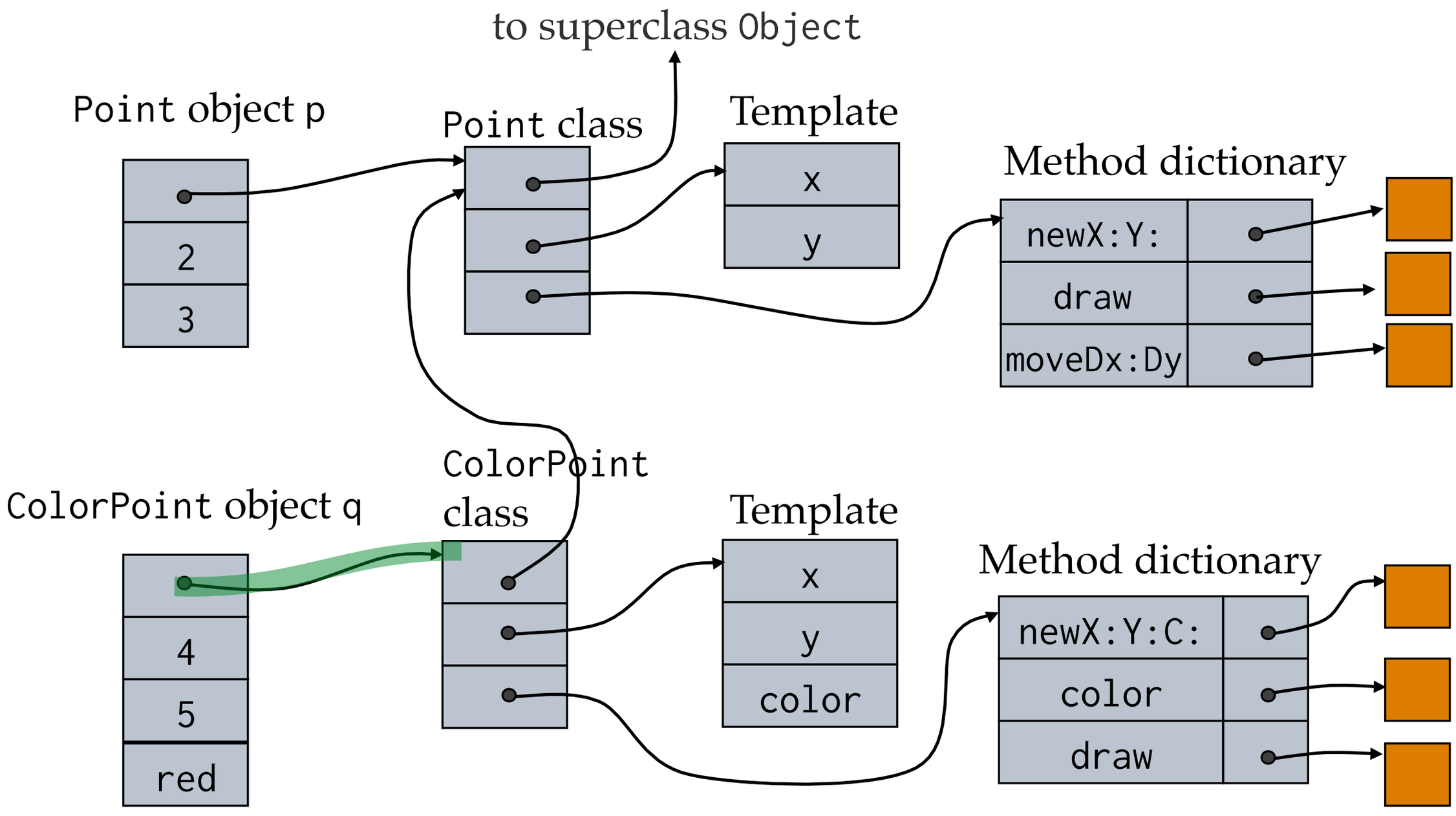

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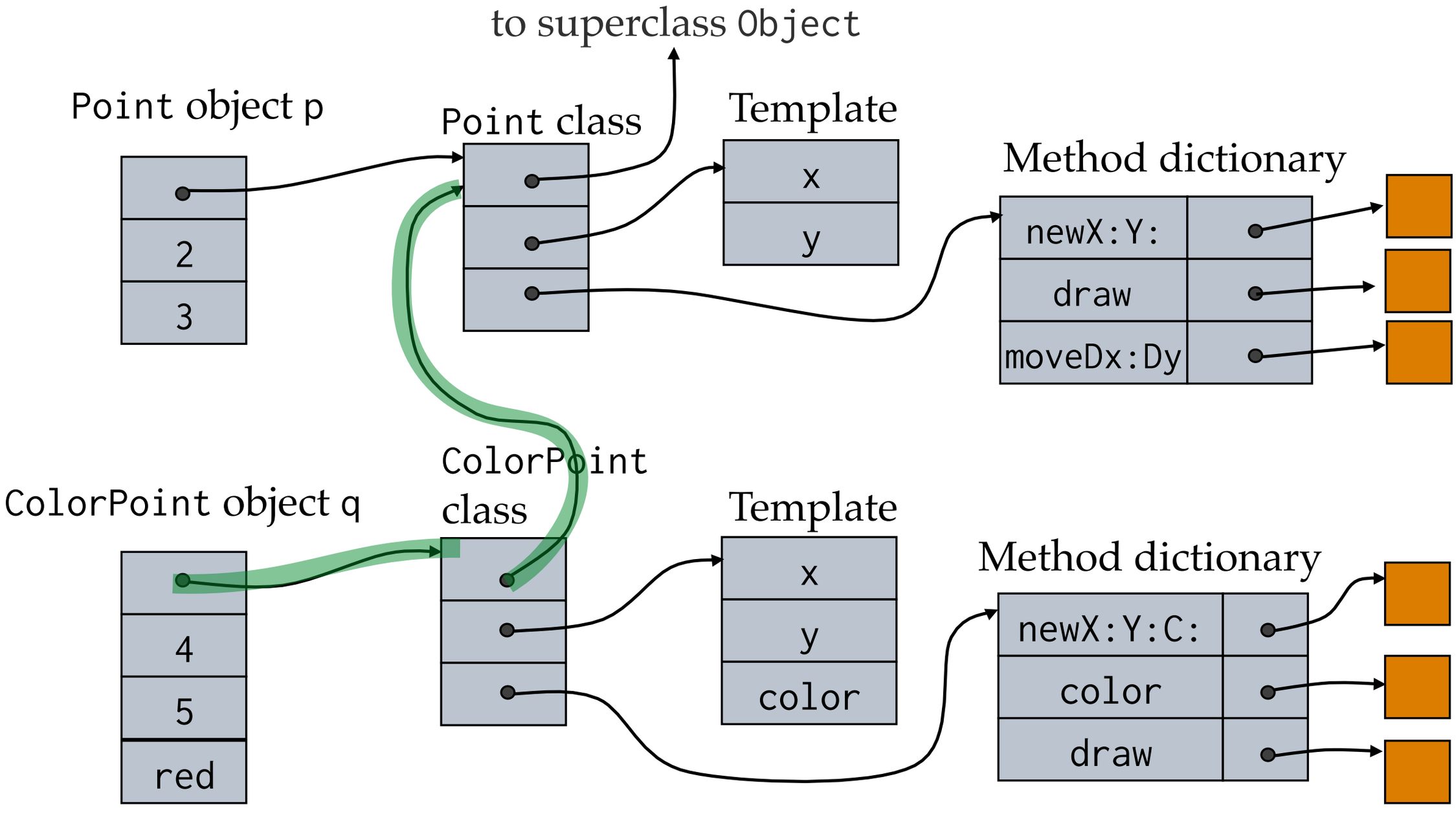

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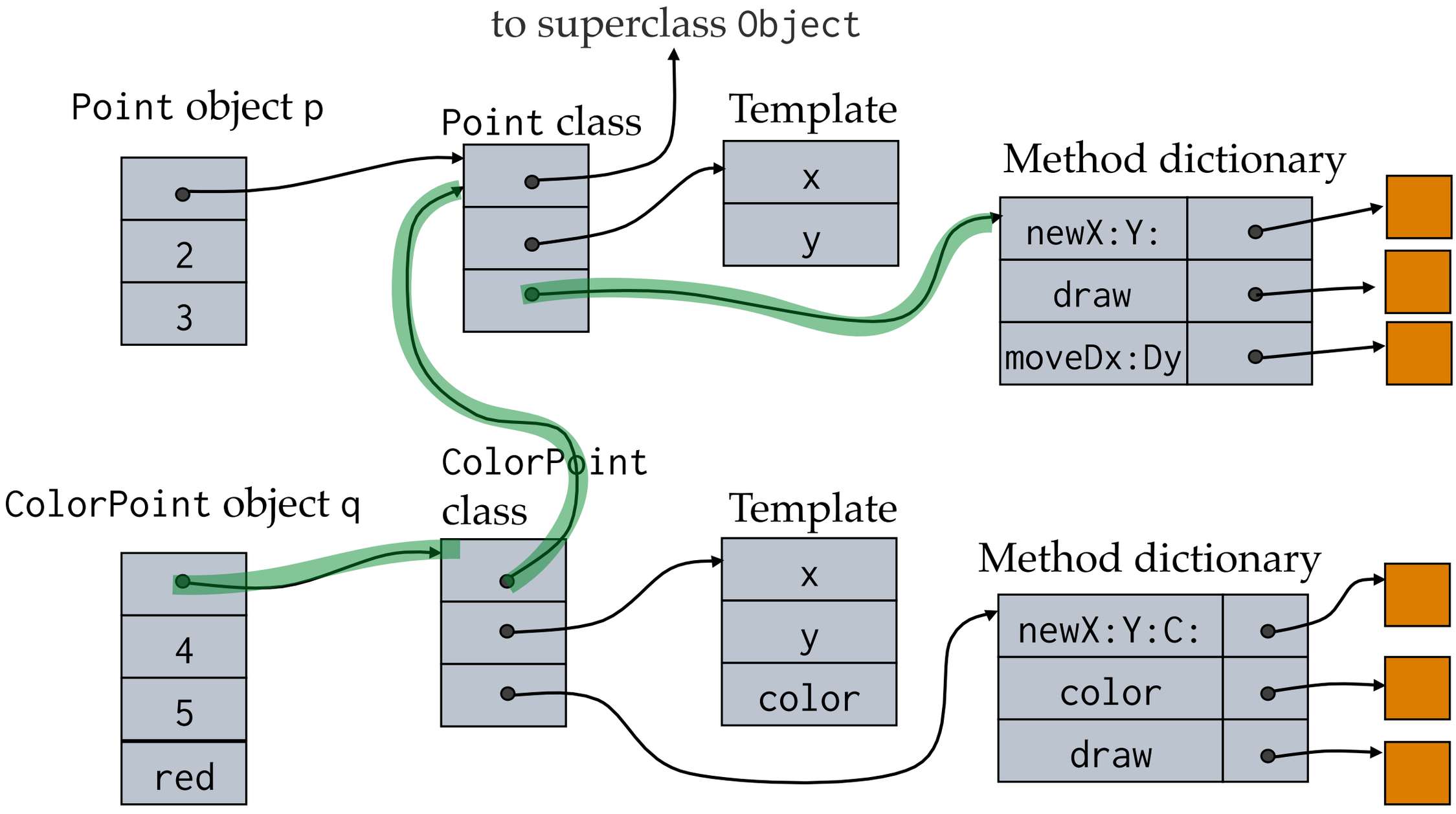

Smalltalk summary

- Classes: create objects that share methods
- Encapsulation: public methods, hidden instance vars
- Subtyping: implicit (based on handled messages)
- Inheritance: subclasses, `self`, `super`

Outline

- Central concepts in object-oriented languages
- Objects as activation records (Simula)
- Dynamically-typed object-oriented languages
  - Class-based languages (Smalltalk)
  - Prototype-based languages (JavaScript)

JavaScript: the Self parts

Self

- Prototype-based pure object-oriented language
- Designed at Xerox PARC & Stanford
- Dynamically typed, everything is an object
- Operations on objects
  - send message, add new slot, replace old slot, remove slot
- No compelling application until JavaScript

JavaScript: the Self parts

- Object is a collection of properties (named values)
  - Data properties are like “instance variables”
    - Retrieved by effectively sending **get message** to object
    - Assigned by effectively sending **set message** to object
  - Methods: properties containing JavaScript code
    - Have access to object of this method called `this`
  - Prototype (i.e., parent)
    - Points to existing object to inherit properties

Creating objects

- When invoking function with `new` keyword, runtime creates a new object and sets the receiver (`this`) to it before calling function

```
function Point(x, y) {
  this.x = x;
  this.y = y;
  return this;
 }

var p1 = new Point(4, 17);
var p2 = new Point(4, 3);
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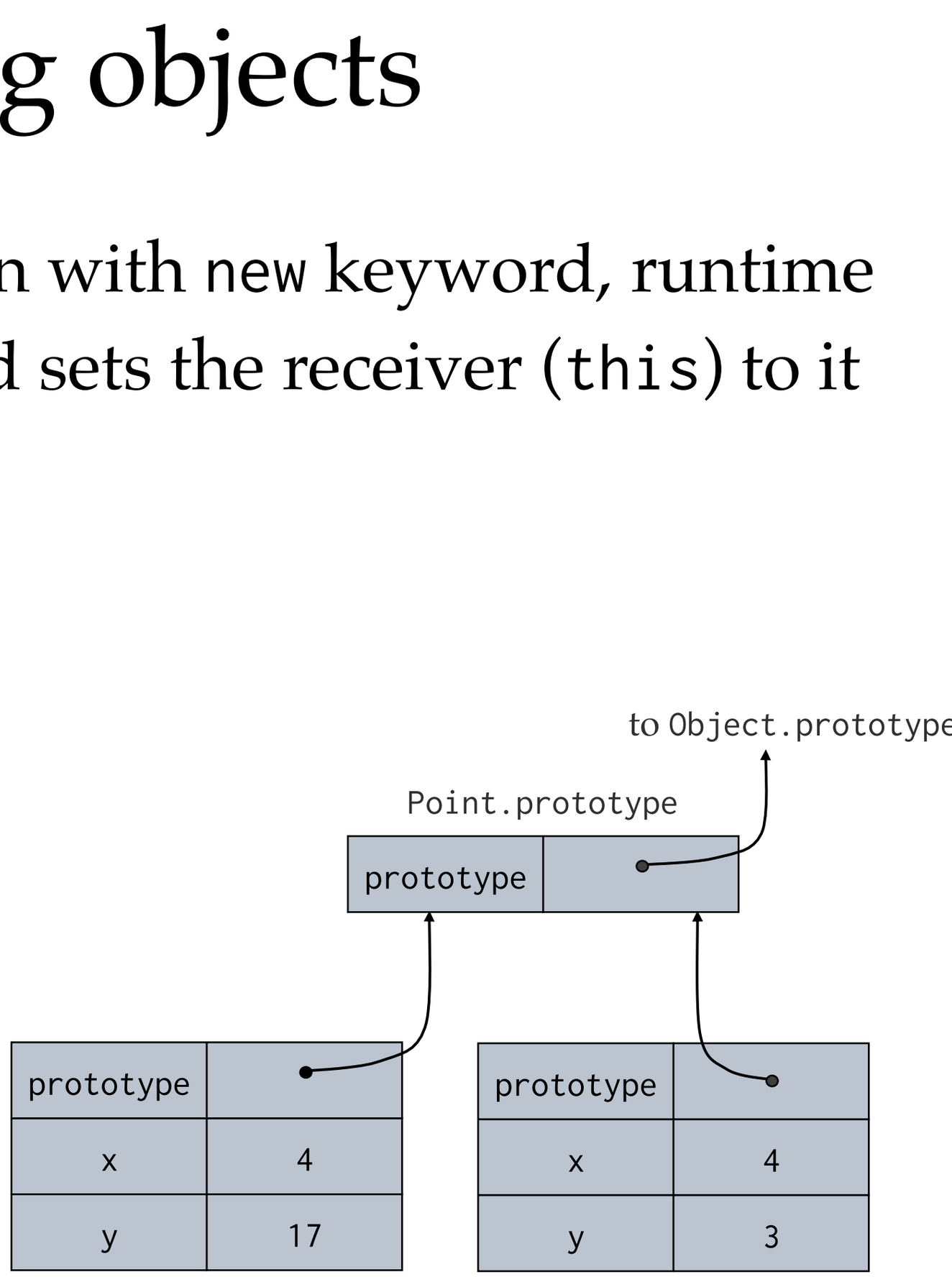

Methods

- What if we want to compare objects?

```
function Point(x, y) {
  this.x = x;
  this.y = y;
  this.equals = function (p) {
    ...
  };
  return this;
 }

var p1 = new Point(4, 17);
var p2 = new Point(4, 3);
p1.equals(p2);
```

Methods

```
Point.prototype.equals = function(p) {
  return Math.abs(this.x - p.x) +
         Math.abs(this.y - p.y) < 0.00001;
}

Point.prototype.distance = function(p) {
  var dx = this.x - p.x, dy = this.y - p.y;
  return Math.sqrt(dx*dx) + Math.sqrt(dy*dy);
}

var p1 = new Point(4, 17);
var p2 = new Point(4, 3);
p1.equals(p2);
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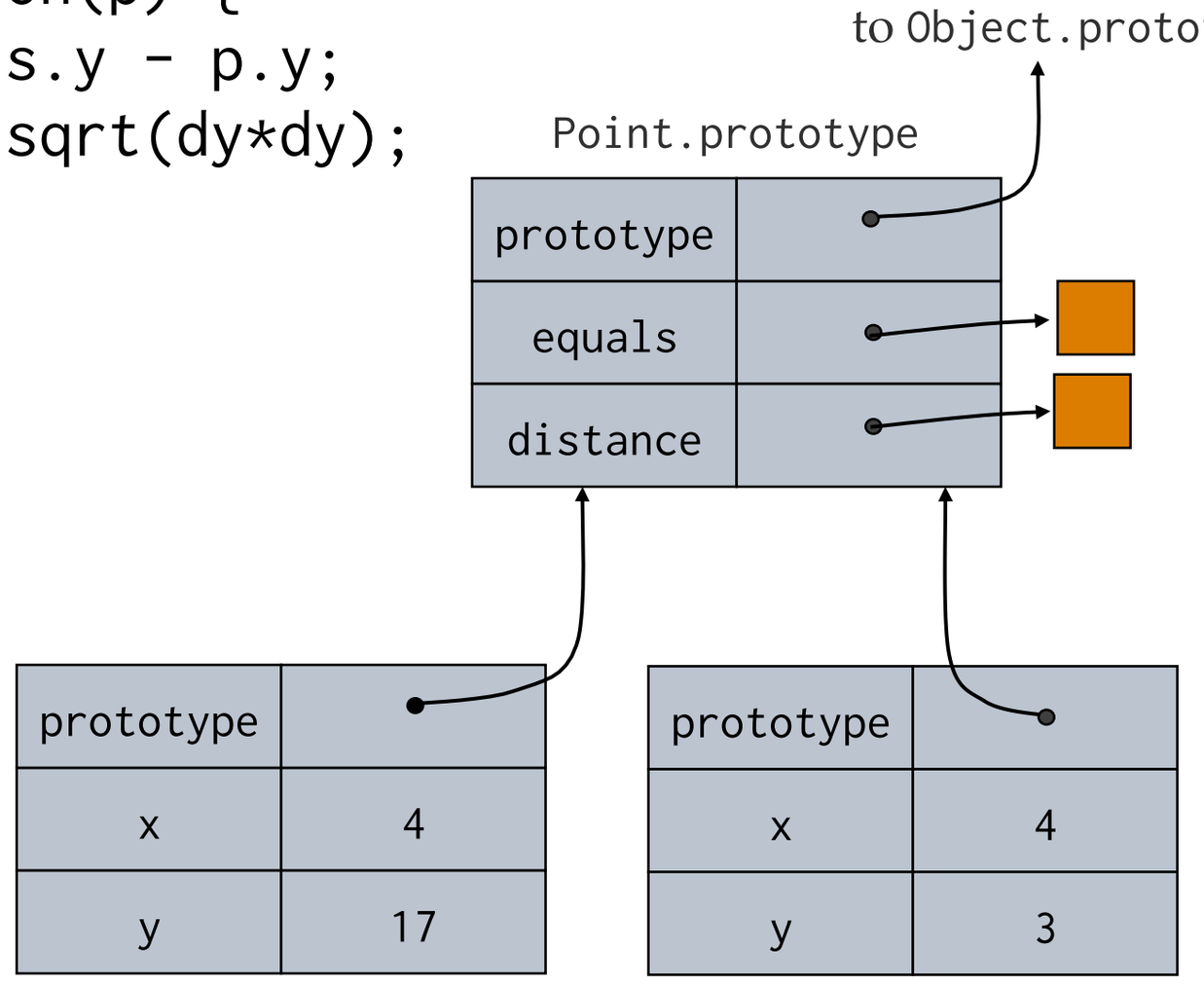

How does method invocation work?

- Invoking method = sending message to object
  - Implementation: call function with receiver set to the object
  - E.g. `p1.equals(p2)` is equivalent to:
    `Point.prototype.equals.call(p1, p2)`
  - How do you find function to call?
- Dynamic lookup!
  - Chase prototypes until
    method is found

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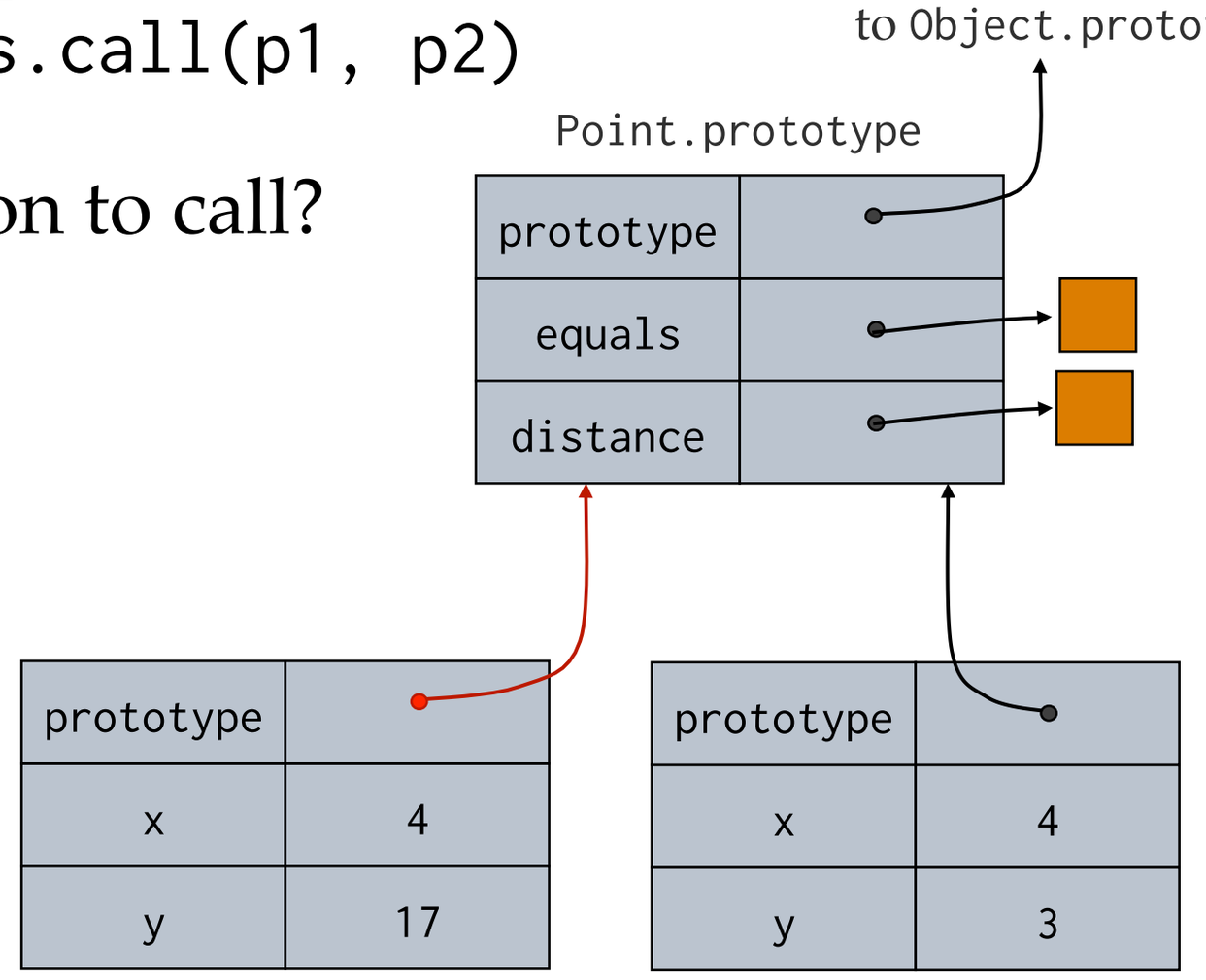

Dynamic lookup

Dynamic lookup

- What happens when a message is sent to an object and there is no corresponding method?
  - E.g., `p1.toHashValue();`

Dynamic lookup

- What happens when a message is sent to an object and there is no corresponding method?
  - E.g., `p1.toHashValue();`
- JavaScript has `Proxy` API that will let you intercept any messages (get, set, delete, hasOwn, etc.)

Proxies

- Define handlers and wrap object:

```
const handlers = {
        set: (target, property, value) => {
            ...
        },
        ...
};
let trappedObj = new Proxy(obj, handlers);
```

- How does this affect dynamic lookup?
- What is the cost of such a language feature?

Encapsulation & subtyping

- Encapsulation
  - Public methods
  - No private/protected data
  - Can use WeakMaps to do encapsulation, ugly
- Subtyping
  - Interface: the messages an object implements methods for
  - Solely need to define the right properties to have <: relation

Inheritance

Let's make `ColoredPoint` inherit form `Point`:

```
ColoredPoint.prototype = Point.prototype;
```

- Is this correct? A: yes B: no

Inheritance

Let's make `ColoredPoint` inherit form `Point`:

- Approach:

```
ColoredPoint.prototype = Object.create(Point.prototype);
```

- `Object.create` creates new object with specified prototype

Inheritance

```
function ColoredPoint(x, y, color) {
   Point.call(this, x, y);
   this.color = color;
}
ColoredPoint.prototype = Object.create(Point.prototype);
ColoredPoint.prototype.equals = function(p) {
  return (Math.abs(x - p.x) +
          Math.abs(y - p.y) < 0.00001)
          && color === p.color;
}
```

Inheritance

Could we have done it reverse order? A: yes, B: no

```
ColoredPoint.prototype.equals = function(p) {
  return (Math.abs(x - p.x) +
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          && color === p.color;
}
ColoredPoint.prototype = Object.create(Point.prototype);
```

Inheritance

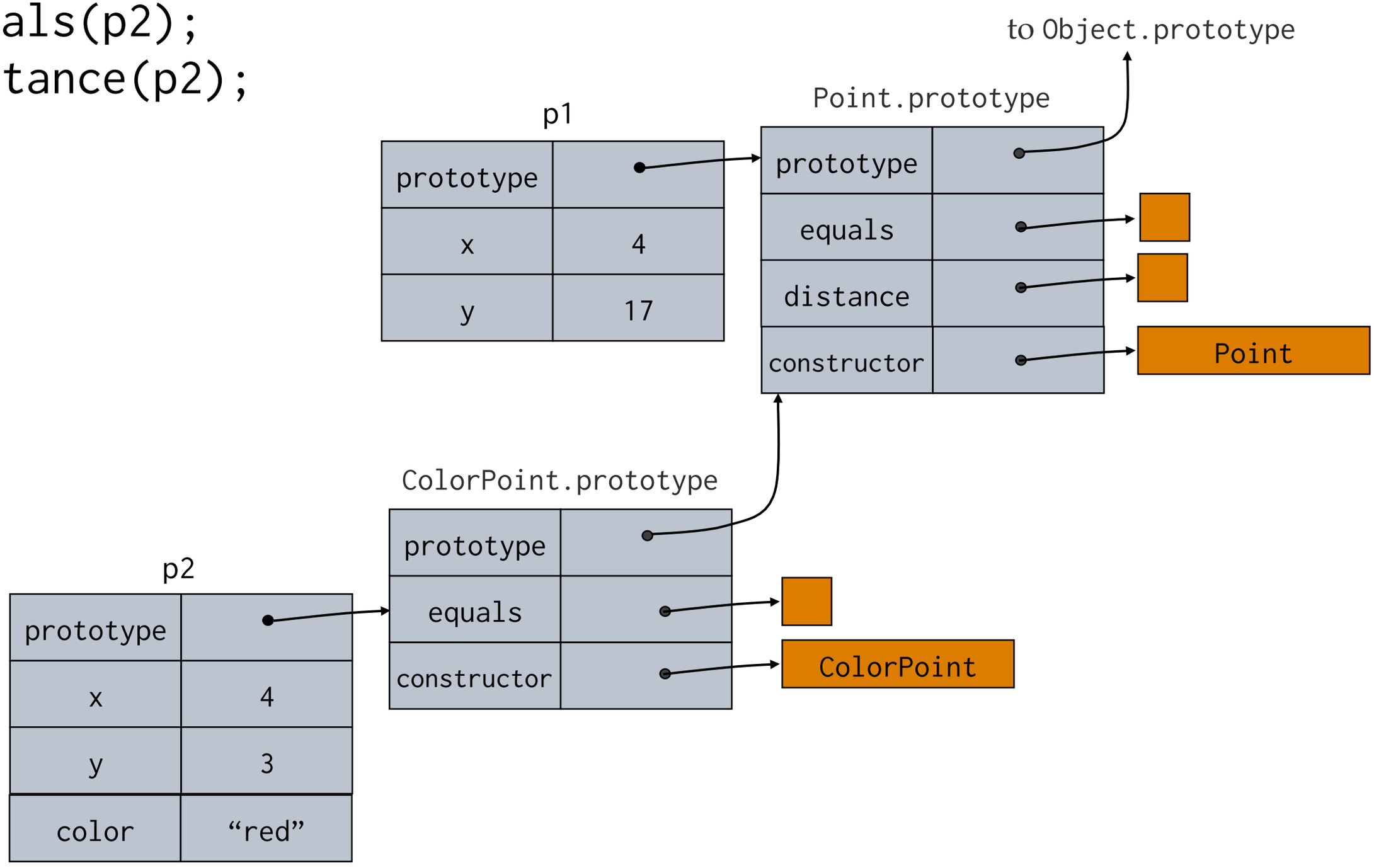
```
var p1 = new Point (4,17);
var p2 = new ColorPoint (4,3,”red”);
p1.equals(p2);
p1.distance(p2);
```

p1

p2

Inheritance

```
var p1 = new Point (4,17);
var p2 = new ColorPoint (4,3,”red”);
p1.equals(p2);
p1.distance(p2);
```



JavaScript summary

- Objects: created by calling functions as constructors
- Encapsulation: public methods, hidden instance vars
- Subtyping: implicit (based on handled messages)
- Inheritance: prototype hierarchy
- Classes: desugars to prototypal implementation

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