

CAE

Subclasses with CAE:

```
{class posn
  x y
  {mdist {+ {get this x} {get this y}}}}
  {addDist {+ {dsend arg mdist 0}
              {dsend this mdist 0}}}}
{class posn3D
  x y z
  {mdist {+ {get this z}
            {ssend this posn mdist arg}}}}
  {addDist {ssend this posn addDist arg}}}}
{send {new posn3D 1 2 3} addDist {new posn 3 4}}
```

Programmer manually

- duplicates fields
- implements method inheritance

ICAE

ICAE adds ***implementation inheritance***:

```
{class posn extends object
  x y
  {mdist {+ {get this x} {get this y}}}}
  {addDist {+ {send arg mdist 0}
              {send this mdist 0}}}}

{class posn3D extends posn
  z
  {mdist {+ {get this z}
            {super mdist arg}}}}

{send {new posn3D 1 2 3} addDist {new posn 3 4}}
```

We can compile ICAE programs to CAE

ICAE Grammar

```
<prog> ::= <decl>* <ICAE>
<decl> ::= {class <cid> <fid>* <meth>*}
<meth> ::= {<mid> <ICAE>}
<ICAE> ::= <num>
          | <str>
          | {+ <ICAE> <ICAE>}
          | {- <ICAE> <ICAE>}
          | {if0 <ICAE> <ICAE> <ICAE>}
          | arg
          | this
          | {new <cid> <ICAE>*}
          | {get <ICAE> <fid>}
          | {send <ICAE> <mid> <ICAE>}
          | {super <mid> <ICAE>}
```

NEW

NEW

ICAE Datatypes

```
(define-type ICAE
  [inum (n : number)]
  [istr (s : string)]
  [iadd (lhs : ICAE)
        (rhs : ICAE)]
  [isub (lhs : ICAE)
        (rhs : ICAE)]
  [iif0 (test-expr : ICAE)
        (then-expr : ICAE)
        (else-expr : ICAE)]
  [iarg]
  [ithis]
  [inew (class : symbol)
        (args : (listof ICAE))]
  [iget (obj-expr : ICAE)
        (field-name : symbol)]
  [isend (obj-expr : ICAE)
         (method-name : symbol)
         (arg-expr : ICAE)]
  [isuper (method-name : symbol)
          (arg-expr : ICAE)])
```

ICAE Datatypes

```
(define-type IDecl
  [iclass (name : symbol)
          (super : symbol)
          (fields : (listof IField))
          (methods : (listof IMethod))])
```

```
(define-type IField
  [ifield (name : symbol)])
```

```
(define-type IMethod
  [imethod (name : symbol)
           (body-expr : ICAE)])
```

ICAE Interpreter

```
(define (iinterp idecls iexpr)
  (local [(define expr
            (compile-expr iexpr (iclass 'bad 'bad empty empty)))
          (define cdecls-not-flat
            (map compile-methods idecls))
          (define cdecls
            (map (lambda (cdecl)
                  (flatten-class cdecl idecls cdecls-not-flat))
                 cdecls-not-flat))]
    (interp expr cdecls (numV 0) (numV 0))))
```

ICAE Compiler: Expressions

```
(define compile-expr : (ICAE IDecl -> CAE)
  (lambda (icae this-class)
    (local [(define (recur expr)
              (compile-expr expr this-class))]
      (type-case IC AE icae
        [inum (n) (num n)]
        [istr (s) (str s)]
        [iadd (r l) (add (recur l) (recur r))]
        [isub (r l) (sub (recur l) (recur r))]
        [iif0 (t th el)
              (if0 (recur t) (recur th) (recur el))]
        [iarg () (arg)]
        [ithis () (this)]
        [inew (class-name field-exprs)
              (new class-name (map recur field-exprs))]
        [iget (expr field-name)
              (get (recur expr) field-name)]
        ...))))))
```

ICAIE Compiler: Expressions

```
(define compile-expr : (ICAIE IDecl -> CAE)
  (lambda (icae this-class)
    (local [(define (recur expr)
              (compile-expr expr this-class))]
      (type-case ICAIE icae
        ...
        [isend (expr method-name arg-expr)
              (dsend (recur expr)
                    method-name
                    (recur arg-expr))]
        [isuper (method-name arg-expr)
                (type-case IDecl this-class
                  [iclass (name super-name fields method)
                        (ssend (this)
                              super-name method-name
                              (recur arg-expr))] ] ] ] ] ]))
```


ICAE Compiler: Methods

```
(define (compile-methods idecl)
  (type-case IDecl idecl
    [iclass (name super-name fields methods)
      (class name
        (map (lambda (f)
              (type-case IField f
                [ifield (name) (field name)]))
            fields)
          (map (lambda (m)
                (type-case IMethod m
                  [imethod (name body-expr)
                    (method name
                          (compile-expr body-expr
                                         idecl))]))
              methods))] ]))
```

ICAE Compiler: Flatten Class

```
(define (flatten-class cdecl idecls cdecls)
  (type-case CDecl cdecl
    [class (name fields methods)
      (type-case IDecl (find-iclass name idecls)
        [iclass (name super-name ifields imethods)
          (type-case CDecl (if (equal? super-name 'object)
                                (class 'object empty empty)
                                (flatten-class
                                 (find-class super-name cdecls)
                                 idecls
                                 cdecls)))
          [class (super-name super-fields super-methods)
            (class name
              (add-fields super-fields fields)
              (add/replace-methods super-methods
                                   methods))]]))]))))
```

ICAE Compiler: Flatten Fields

```
(define (add-fields super-fields fields)  
  (append super-fields fields))
```

ICAE Compiler: Flatten Methods

```
(define (add/replace-methods methods new-methods)
  (cond
    [(empty? new-methods) methods]
    [else (add/replace-methods
            (add/replace-method methods (first new-methods))
            (rest new-methods))]))
```

```
(define (add/replace-method methods new-method)
  (cond
    [(empty? methods) (list new-method)]
    [else
     (if (equal? (method-name (first methods))
                 (method-name new-method))
         (cons new-method (rest methods))
         (cons (first methods)
                (add/replace-method (rest methods)
                                    new-method)))]))
```

Typechecking Programs with Classes

Is this program well-formed?

```
{class posn extends object
  x : num  y : num
  {mdist : num -> num
    {+ {send {get this x} mdist 0}
      {send {get this y} mdist 0}}}}
```

10

No — the **x** and **y** fields are not objects

Typechecking Programs with Classes

Is this program well-formed?

```
{class posn extends object
  x : num  y : num
  {mdist : num -> num
    {+ {get this x} {get this z}}}}
```

10

No — `posn` has no `z` field

Typechecking Programs with Classes

Is this program well-formed?

```
{class posn extends object
  x : num  y : num
  {mdist : num -> num
    {+ {get this x} {send this get-y 0}}}}
```

10

No — `posn` has no `get-y` method

Typechecking Programs with Classes

Is this program well-formed?

```
{class posn extends object
  x : num  y : num
  {mdist : num -> posn
    {+ {get this x} {get this y}}}}
```

10

No — result type for `mdist` does not match body type

Typechecking Programs with Classes

Is this program well-formed?

```
{class posn extends object
  x : num  y : num
  {mdist : num -> num
    {+ {get this x} {get this y}}}}
```

10

Yes

Typechecking Programs with Classes

Is this program well-formed?

```
{class posn extends object
  x : num  y : num
  {mdist : num -> num
    {+ {get this x} {get this y}}}}
{new posn 12}
```

No — wrong number of fields in `new`

Typechecking Programs with Classes

Is this program well-formed?

```
{class posn extends object
  x : num  y : num
  {mdist : num -> num
    {+ {get this x} {get this y}}}}
{new posn 12 {new posn 1 2}}
```

No — wrong field type for first **new**

Typechecking Programs with Classes

Is this program well-formed?

```
{class posn extends object
  x : num  y : num
  {mdist : num -> num
    {+ {get this x} {get this y}}}
  {clone : num -> posn
    {new posn {get this x} {get this y}}}}
{send {new posn 1 2} clone 0}
```

Yes

Typechecking Programs with Classes

Is this program well-formed?

```
{class posn extends object
  x : num  y : num
  {mdist : num -> num
    {+ {get this x} {get this y}}}}
  {clone : num -> posn
    {new posn {get this x} {get this y}}}}
{class posn3D extends posn
  z : num
  {mdist : num -> num
    {+ {get this z} {super mdist arg}}}}
{new posn3D 5 7 3}
```

Yes

Typechecking Programs with Classes

Is this program well-formed?

```
{class posn extends object
  x : num  y : num
  {mdist : num -> num
    {+ {get this x} {get this y}}}}
  {clone : num -> posn
    {new posn {get this x} {get this y}}}}
{class posn3D extends posn
  z : num
  {mdist : num -> posn
    {new posn 10 10}}}}
{new posn3D 5 7 3}
```

No — override of `mdist` changes result type

Typechecking Programs with Classes

Is this program well-formed?

```
{class posn extends object
  x : num  y : num
  {mdist : num -> num
    {+ {get this x} {get this y}}}}
  {clone : num -> posn
    {new posn {get this x} {get this y}}}}
{class posn3D extends posn
  z : num
  {mdist : num -> num
    {+ {get this z} {super mdist arg}}}}
  {clone : num -> posn3D
    {new posn3D
      {get this x}
      {get this y}
      {get this z}}}}
{new posn3D 5 7 3}
```

No — override of `clone` changes result type

Typechecking Programs with Classes

Is this program well-formed?

```
{class posn extends object
  x : num  y : num
  {mdist : num -> num
    {+ {get this x} {get this y}}}}
  {clone : num -> posn
    {new posn {get this x} {get this y}}}}
{class posn3D extends posn
  z : num
  {mdist : num -> num
    {+ {get this z} {super mdist arg}}}}
  {clone : num -> posn
    {new posn3D
      {get this x}
      {get this y}
      {get this z}}}}
{new posn3D 5 7 3}
```

Yes — which means that we need subtypes

Typechecking Programs with Classes

Is this program well-formed?

```
{class posn extends object
  ...}
{class posn3D extends posn
  ...}
{if0 ... {new posn 1 2} {new posn3D 5 7 3}}
```

Yes — and expression type is `posn`

TICAE Grammar

```
<prog> ::= <decl>* <ICAE>
<decl> ::= {class <cid> <field>* <meth>*}
<field> ::= <fid> : <TE>
<meth> ::= {<mid> : <TE> -> <TE> <ICAE>}
<TE> ::= num
      | str
      | <cid>
```

NEW

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TICAE Datatypes

```
(define-type TDecl
  [tclass (name : symbol)
          (super-name : symbol)
          (fields : (listof TField))
          (methods : (listof TMethod))])
```

```
(define-type TField
  [tfield (name : symbol)
          (te : TE)])
```

```
(define-type TMethod
  [tmethod (name : symbol)
           (arg-te : TE)
           (result-te : TE)
           (body-expr : ICAE)])
```

TICAE Datatypes

```
(define-type TE
  [numTE]
  [strTE]
  [objTE (class-name : symbol)])
```

```
(define-type Type
  [numT]
  [strT]
  [objT (class-name : symbol)])
```

TICAE Type Checking

```
(define (typecheck tdecls expr)
  (begin
    (map (lambda (tdecl)
          (type-case TDecl tdecl
            [tclass (name super-name fields methods)
              (map (lambda (m)
                    (begin
                      (typecheck-method m tdecl tdecls)
                      (check-override m tdecl tdecls)))
                  methods))])
          tdecls)
    (typecheck-expr expr tdecls (numT)
      (tclass 'bad 'bad empty empty))))
```

TICAE Type Checking: Methods

```
(define (typecheck-method method this-tdecl tdecls)
  (type-case TMethod method
    [tmethod (name arg-te result-te body-expr)
      (if (is-subtype?
            (typecheck-expr body-expr tdecls
                            (parse-type arg-te) this-tdecl)
            (parse-type result-te)
            tdecls)
          (values)
          (type-error body-expr
                      (to-string (parse-type result-te)))))]))
```

TICAE Type Checking: Method Overrides

```
(define (check-override method this-tdecl tdecls)
  (local [(define super-name
            (tclass-super-name this-tdecl))
          (define super-method
            (try
              (find-method-in-tree (tmethod-name method)
                                   (find-tclass super-name tdecls)
                                   tdecls)
              (lambda () method)))]
    (if (and (equal? (tmethod-arg-te method)
                     (tmethod-arg-te super-method))
            (equal? (tmethod-result-te method)
                     (tmethod-result-te super-method)))
        (values)
        (error 'typecheck (string-append
                          "bad override of "
                          (to-string method-name))))))
```

TICAE Type Checker

```
(define typecheck-expr : (ICAE (listof TDecl) Type TDecl -> Type)
  (lambda (expr tdecls arg-type this-class)
    (local [(define (recur expr)
              (typecheck-expr expr tdecls arg-type this-class))]
      (type-case ICAE expr
        ...
        [inum (n) (numT)]
        [istr (s) (strT)]
        [iadd (l r)
              (type-case Type (recur l)
                [numT ()
                  (type-case Type (recur r)
                    [numT () (numT)]
                    [else (type-error r "num")])]
                [else (type-error l "num")])]
        [isub (l r) ...]
        [iarg () arg-type]
        ...))))))
```


TICAE Type Checker

```
(define typecheck-expr : (ICAE (listof TDecl) Type TDecl -> Type)
  (lambda (expr tdecls arg-type this-class)
    (local [(define (recur expr)
              (typecheck-expr expr tdecls arg-type this-class))]
      (type-case ICAE expr
        ...
        [iif0 (test-expr then-expr else-expr)
              (local [(define test-type (recur test-expr))
                      (define then-type (recur then-expr))
                      (define else-type (recur else-expr))]
                (type-case Type (recur test-expr)
                  [numT ()
                    (cond
                     [(is-subtype? then-type else-type tdecls)
                      else-type]
                     [(is-subtype? else-type then-type tdecls)
                      then-type]
                     [else
                      (type-error else-expr
                                   (to-string then-type))]])]
                  [else (type-error test-expr "num")]))])
        ...))))))
```

TICAE Type Checker

```
(define typecheck-expr : (ICAE (listof TDecl) Type TDecl -> Type)
  (lambda (expr tdecls arg-type this-class)
    (local [(define (recur expr)
              (typecheck-expr expr tdecls arg-type this-class))]
      (type-case ICAE expr
        ...
        [ithis ()
         (type-case TDecl this-class
           [tclass (name super-name fields methods)
            (objT name)]]]
        ...))))))
```

TICAE Type Checker

```
(define typecheck-expr : (ICAE (listof TDecl) Type TDecl -> Type)
  (lambda (expr tdecls arg-type this-class)
    (local [(define (recur expr)
              (typecheck-expr expr tdecls arg-type this-class))]
      (type-case ICAE expr
        ...
        [inew (class-name exprs)
              (local [(define arg-types (map recur exprs))]
                (if (andmap2 (lambda (t1 t2)
                              (is-subtype? t1 t2 tdecls))
                              arg-types
                              (get-all-field-types class-name tdecls))
                    (objT class-name)
                    (type-error expr "field type mismatch")))]
        ...))))))
```

TICAE Type Checker

```
(define typecheck-expr : (ICAE (listof TDecl) Type TDecl -> Type)
  (lambda (expr tdecls arg-type this-class)
    (local [(define (recur expr)
              (typecheck-expr expr tdecls arg-type this-class))]
      (type-case ICAE expr
        ...
        [iget (obj-expr field-name)
         (type-case Type (recur obj-expr)
           [objT (class-name)
            (local [(define field
                      (find-field-in-tree
                       field-name
                       (find-tclass class-name tdecls)
                       tdecls))]
              (type-case TField field
                [tfield (name te)
                 (parse-type te)]))]
            [else (type-error obj-expr "object")]]]
        ...))))))
```

TICAE Type Checker

```
(define typecheck-expr : (ICAE (listof TDecl) Type TDecl -> Type)
  (lambda (expr tdecls arg-type this-class)
    (local [(define (recur expr)
              (typecheck-expr expr tdecls arg-type this-class))]
      (type-case ICAE expr
        ...
        [isend (obj-expr method-name arg-expr)
         (local [(define obj-type (recur obj-expr))
                  (define arg-type (recur arg-expr))]
           (type-case Type obj-type
             [objT (class-name)
              (typecheck-send class-name method-name
                              arg-expr arg-type tdecls)]
             [else
              (type-error obj-expr "object")]))])
        ...))))))
```

TICAE Type Checker

```
(define typecheck-expr : (ICAE (listof TDecl) Type TDecl -> Type)
  (lambda (expr tdecls arg-type this-class)
    (local [(define (recur expr)
              (typecheck-expr expr tdecls arg-type this-class))]
      (type-case ICAE expr
        ...
        [isuper (method-name arg-expr)
                 (local [(define arg-type (recur arg-expr))]
                     (typecheck-send (tclass-super-name this-class)
                                       method-name
                                       arg-expr arg-type tdecls))]
        ...))))))
```

TICAE Type Checker: Sends

```
(define typecheck-send
  (lambda (class-name method-name arg-expr arg-type tdecls)
    (type-case TMethod (find-method-in-tree
                        method-name
                        (find-tclass class-name tdecls)
                        tdecls)
      [tmethod (name arg-te result-te body-expr)
        (if (is-subtype? arg-type (parse-type arg-te) tdecls)
            (parse-type result-te)
            (type-error arg-expr
                        (to-string (parse-type arg-te)))))])))
```

TICAE Type Checker: Subtypes

```
(define (is-subclass? name1 name2 tdecls)
  (cond
    [(equal? name1 name2) true]
    [(equal? name1 'object) false]
    [else
     (type-case TDecl (find-tclass name1 tdecls)
       [tclass (name super-name fields methods)
        (is-subclass? super-name name2 tdecls)]))]))
```

```
(define (is-subtype? t1 t2 tdecls)
  (type-case Type t1
    [objT (name1)
     (type-case Type t2
       [objT (name2)
        (is-subclass? name1 name2 tdecls)]
       [else false])]
    [else (equal? t1 t2)]))
```


TICAE Type Checker: Tree Helpers

```
(define find-in-tree
  (lambda (find-in-list extract)
    (lambda (name tdecl tdecls)
      (local [(define items (extract tdecl))
              (define super-name
                (tclass-super-name tdecl))]
        (if (equal? super-name 'object)
            (find-in-list name items)
            (try (find-in-list name items)
                 (lambda ()
                   ((find-in-tree find-in-list extract)
                    name
                     (find-tclass super-name tdecls)
                     tdecls))))))))))

(define find-field-in-tree
  (find-in-tree find-tfield tclass-fields))

(define find-method-in-tree
  (find-in-tree find-tmethod tclass-methods))
```

TICAE Type Checker: Other Helpers

```
(define (parse-type te)
  (type-case TE te
    [numTE () (numT)]
    [strTE () (strT)]
    [objTE (name) (objT name)]))

(define (get-all-field-types class-name tdecls)
  (if (equal? class-name 'object)
      empty
      (type-case TDecl (find-tclass class-name tdecls)
        [tclass (name super-name fields methods)
         (append
          (map (lambda (f) (parse-type (tfield-te f)))
               fields)
          (get-all-field-types super-name tdecls))])))

(define (andmap2 f l1 l2)
  (cond
    [(and (empty? l1) (empty? l2)) true]
    [(and (cons? l1) (cons? l2))
     (and (f (first l1) (first l2))
           (andmap2 f (rest l1) (rest l2)))]
    [else false]))
```

TICAE Interpreter

```
(define (tinterp tdecls expr)
  (iinterp (map strip-types tdecls)
           expr))

(define (strip-types tdecl)
  (type-case TDecl tdecl
    [tclass (name super-name fields methods)
     (iclass
      name
      super-name
      (map (lambda (f)
             (type-case TField f
               [tfield (name te) (ifield name)]))
           fields)
      (map (lambda (m)
             (type-case TMethod m
               [tmethod (name arg-te result-te body-expr)
                (imethod name body-expr)]))
           methods))]))
```

Implementing Classes

TICAE
types



ICAE
inheritance
super



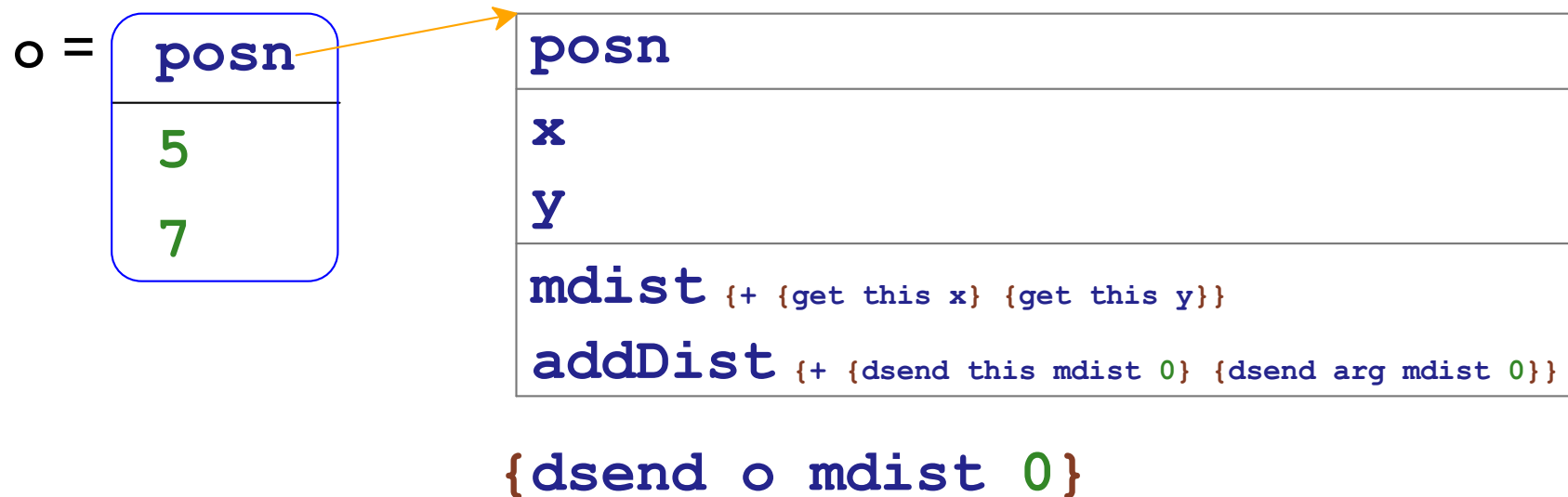
CAE
method dispatch
fields

```
{class posn extends object
  x : num  y : num
  {mdist : num -> num
    {+ {get this x} {get this y}}}}
  {addDist : posn -> num
    {+ {send this mdist 0} {send arg mdist 0}}}}
{class posn3D extends posn
  z : num
  {mdist : num -> num
    {+ {get this z} {super mdist arg}}}}
{send {new posn3D 7 5 3} mdist 0}
```

```
{class posn extends object
  x y
  {mdist {+ {get this x} {get this y}}}}
  {addDist {+ {send this mdist 0} {send arg mdist 0}}}}
{class posn3D extends posn
  z
  {mdist {+ {get this z} {super mdist arg}}}}
{send {new posn3D 7 5 3} mdist 0}
```

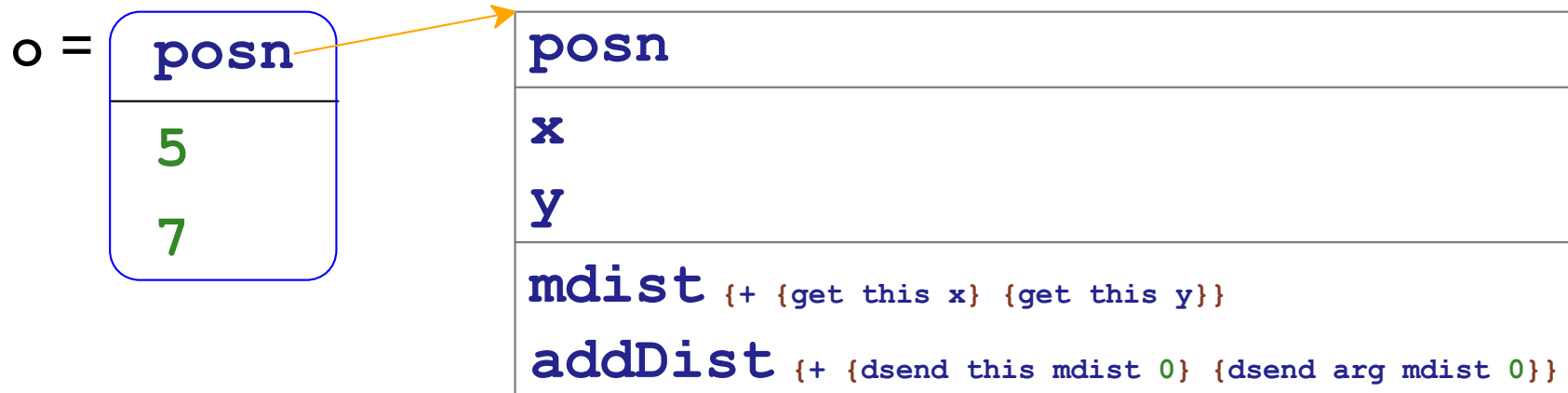
```
{class posn
  x y
  {mdist {+ {get this x} {get this y}}}}
  {addDist {+ {dsend this mdist 0} {dsend arg mdist 0}}}}
{class posn3D
  x y z
  {mdist {+ {get this z} {ssend this posn mdist arg}}}}
  {addDist {+ {dsend this mdist 0} {dsend arg mdist 0}}}}
{dsend {new posn3D 7 5 3} mdist 0}
```

Run-Time Dispatch by Name



dsend follows reference to class table, searches method list

Run-Time Dispatch by Name



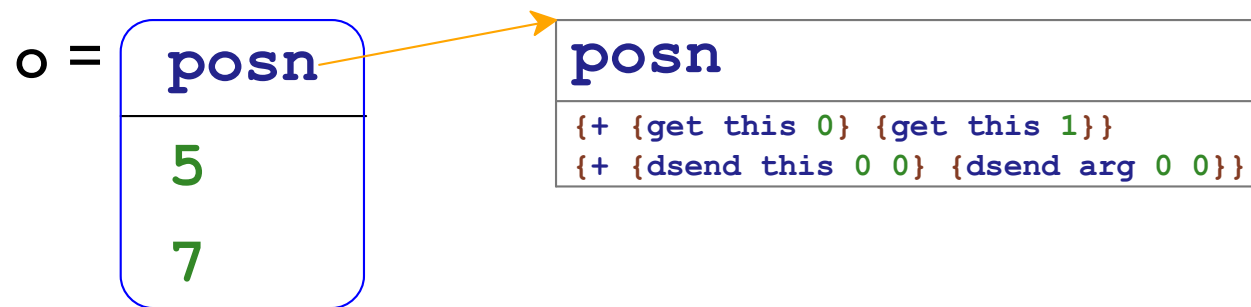
`{dsend o mdist 0}`

```
{class posn extends object
  x : num y : num
  {mdist : num -> num
    {+ {get this x} {get this y}}}
  {addDist : posn -> num
    {+ {send this mdist 0} {send arg mdist 0}}}}
```

\Rightarrow typechecking ensures
search will succeed

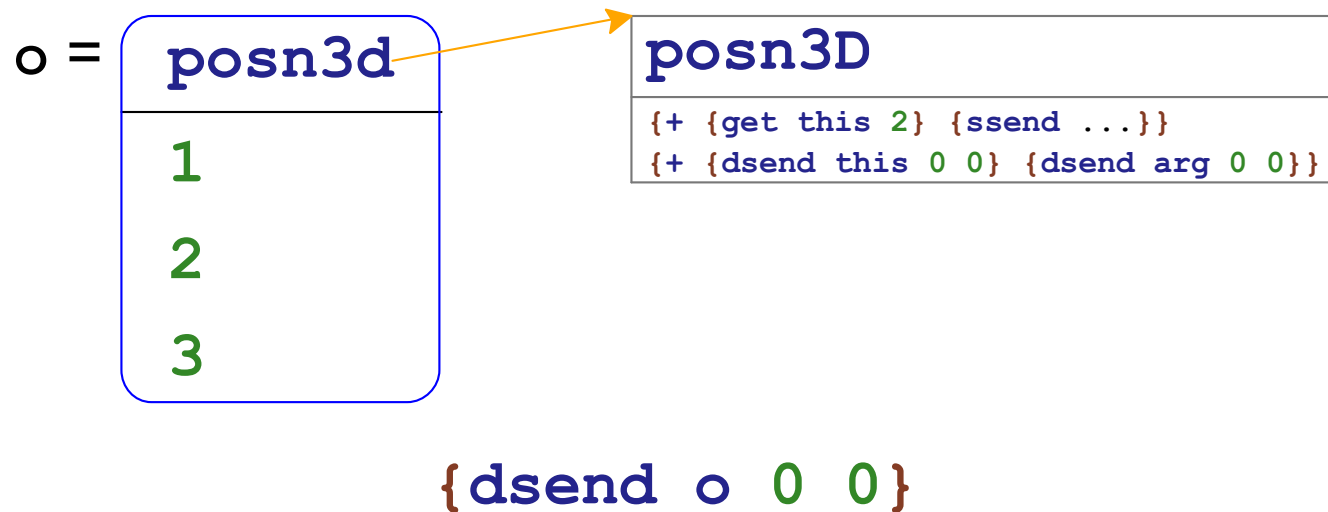
If we order methods in expansion, method will always
be first in list

Run-Time Dispatch by Position

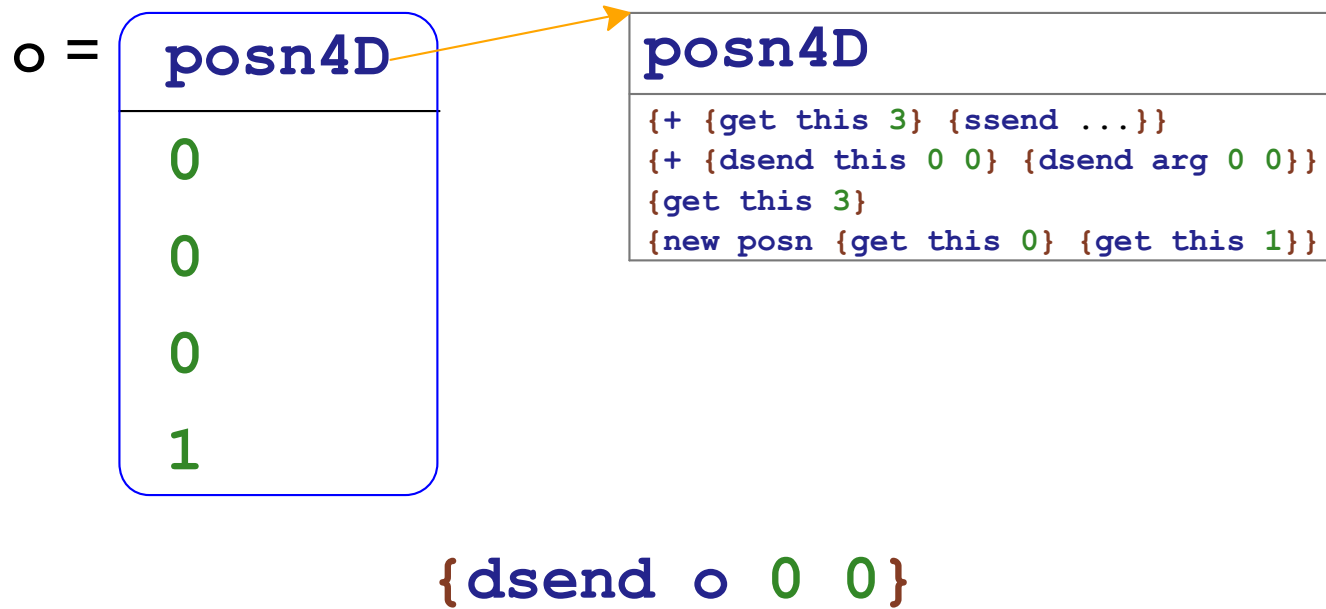


{dsend o 0 0}

Run-Time Dispatch by Position



Run-Time Dispatch by Position



Compiling Classes

TICAE

no change

```
{class posn extends object
  x : num y : num
  {mdist : num -> num
    {+ {get this x} {get this y}}}
  {addDist : posn -> num
    {+ {send this mdist 0} {send arg mdist 0}}}}
{class posn3D extends posn
  z : num
  {mdist : num -> num
    {+ {get this z} {super mdist arg}}}}
{send {new posn3D 7 5 3} mdist 0}
```



CICAЕ

*name class in
each method call*

```
{class posn extends object
  x y
  {mdist {+ {get this x} {get this y}}}
  {addDist {+ {send this posn mdist 0} {send arg posn mdist 0}}}}
{class posn3D extends posn
  z
  {mdist {+ {get posn3d this z} {super mdist arg}}}}
{send {new posn3D 7 5 3} posn3d mdist 0}
```



CCAЕ

*methods and fields
as positions*

```
{class posn 2
  {mdist {+ {get this 0} {get this 1}}}
  {addDist {+ {dsend this 0 0} {dsend arg 0 0}}}}
{class posn3D 3
  {mdist {+ {get this z} {ssend this posn 0 arg}}}
  {addDist {+ {dsend this 0 0} {dsend arg 0 0}}}}
{dsend {new posn3D 7 5 3} 0 0}
```