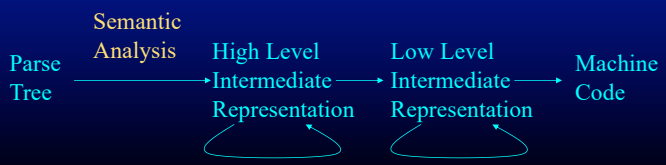
6.1100

Intermediate Formats

for object oriented languages

Program Representation Goals

- Enable Program Analysis and Transformation
  - Semantic Checks, Correctness Checks, Optimizations
- Structure Translation to Machine Code
  - Sequence of Steps



High Level IR

- Preserves Object Structure
- Preserves Structured Flow of Control
- Primary Goal: Analyze Program

Low Level IR

- Moves Data Model to Flat Address Space
- Eliminates Structured Control Flow
- Suitable for Low Level Compilation Tasks
  - Register Allocation
  - Instruction Selection

Examples of Object Representation and Program Execution (This happens when program runs)

Example Vector Class

```
class vector {
  int v[ ];
  …
  void add(int x) {
      int i;
      i = 0;
      while (i < v.length) { v[i] = v[i]+x; i = i+1; }
  }
}
```

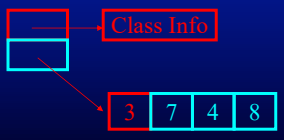
Representing Arrays

- Items Stored Contiguously In Memory
- Length Stored In First Word

- Color Code
  - Red - generated by compiler automatically
  - Blue, Yellow, Lavender - program data or code
  - Magenta - executing code or data

Representing Vector Objects

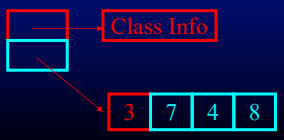
- First Word Points to Class Information
  - Method Table, Garbage Collector Data
- Next Words Have Object Fields
  - For vectors, Next Word is Reference to Array



Invoking Vector Add Method

vect.add(1);

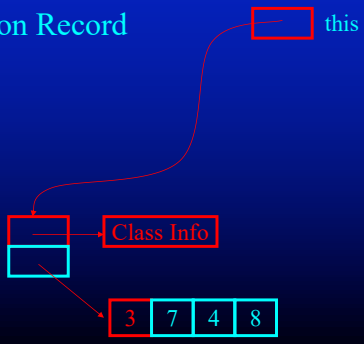
- Create Activation Record



Invoking Vector Add Method

vect.add(1);

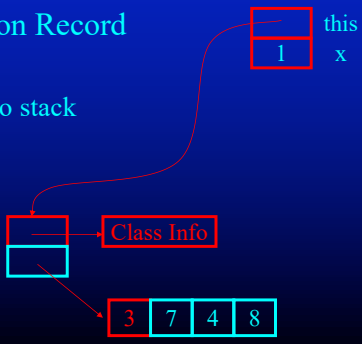
- Create Activation Record
  - this onto stack



Invoking Vector Add Method

vect.add(1);

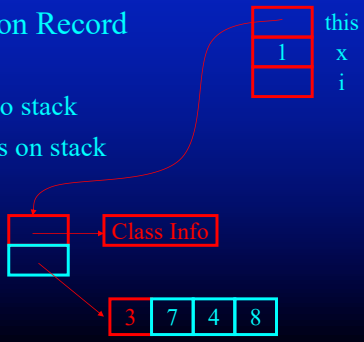
- Create Activation Record
  - this onto stack
  - parameters onto stack



Invoking Vector Add Method

vect.add(1);

- Create Activation Record
  - this onto stack
  - parameters onto stack
  - space for locals on stack



Executing Vector Add Method

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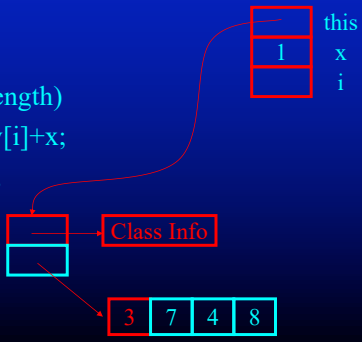
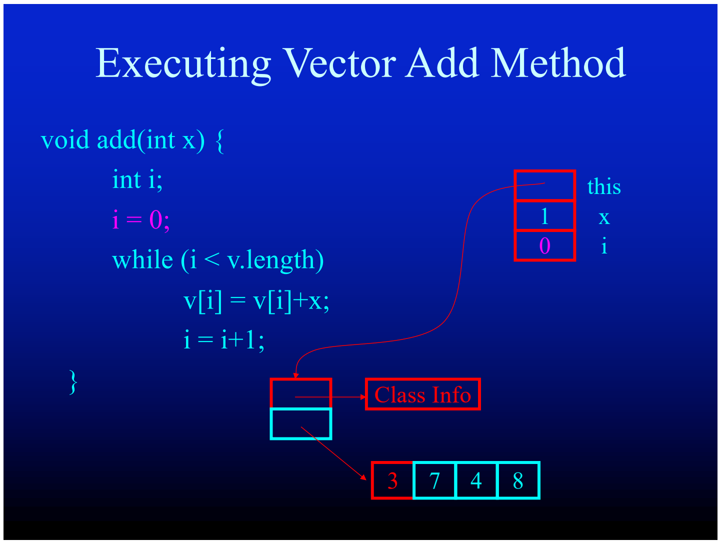
void add(int x) {
        int i;
        i = 0;
        while (i < v.length)
                v[i] = v[i]+x;
                i = i+1;
  }
```

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i
Class Info
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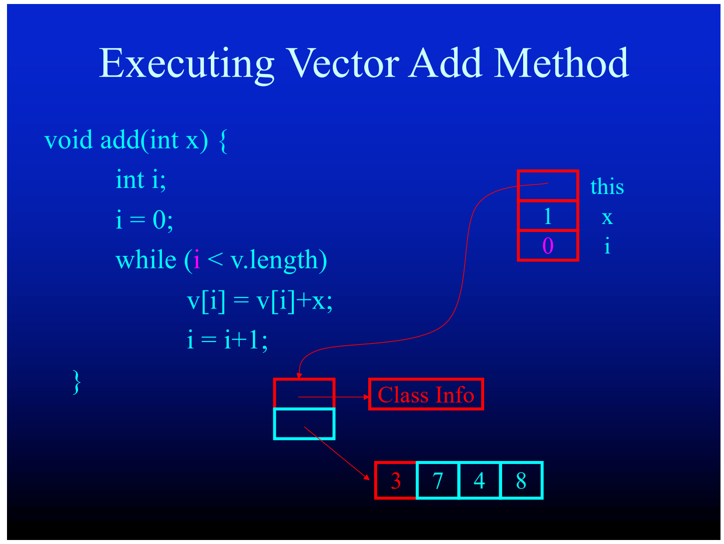
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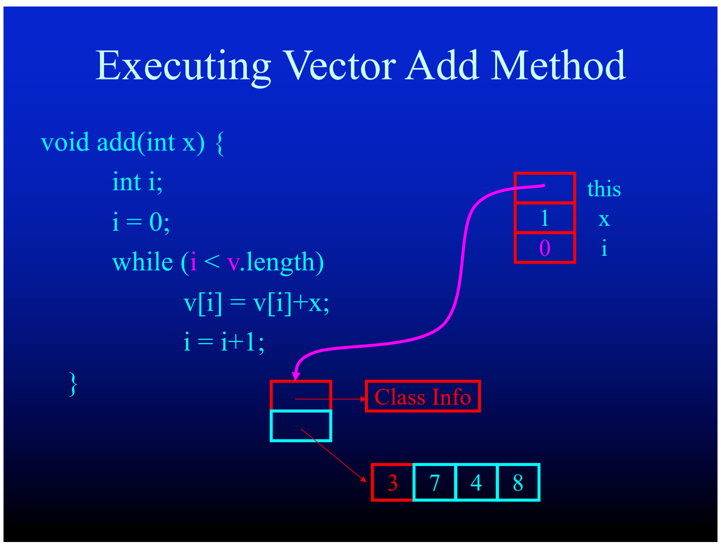
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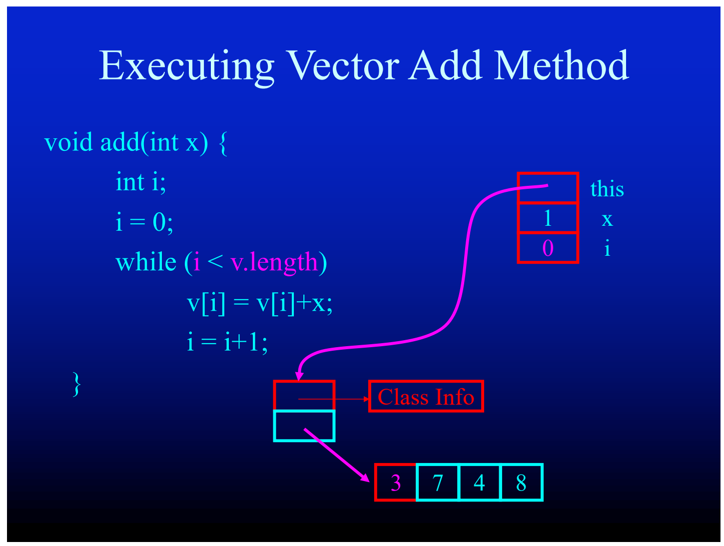
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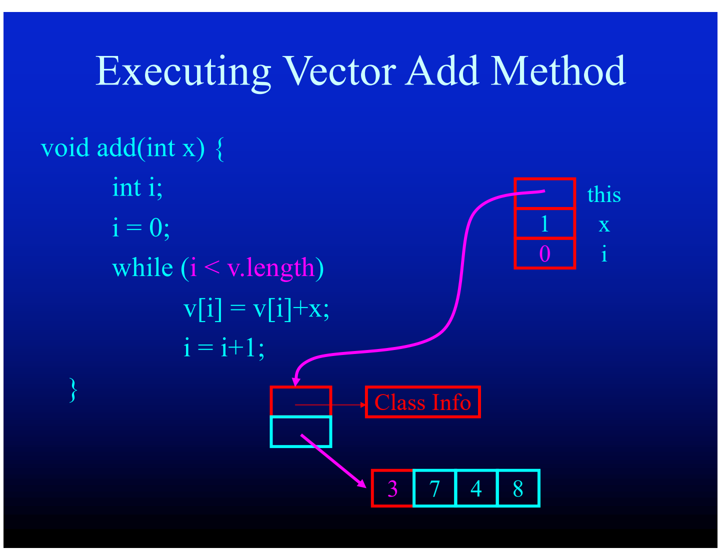
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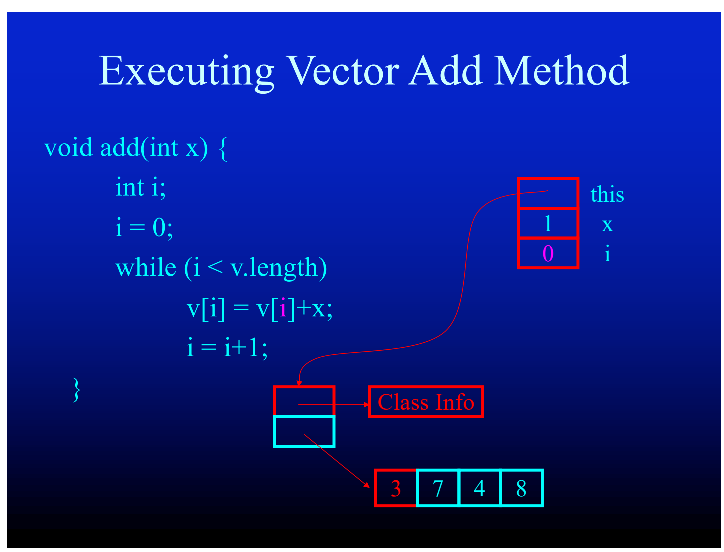
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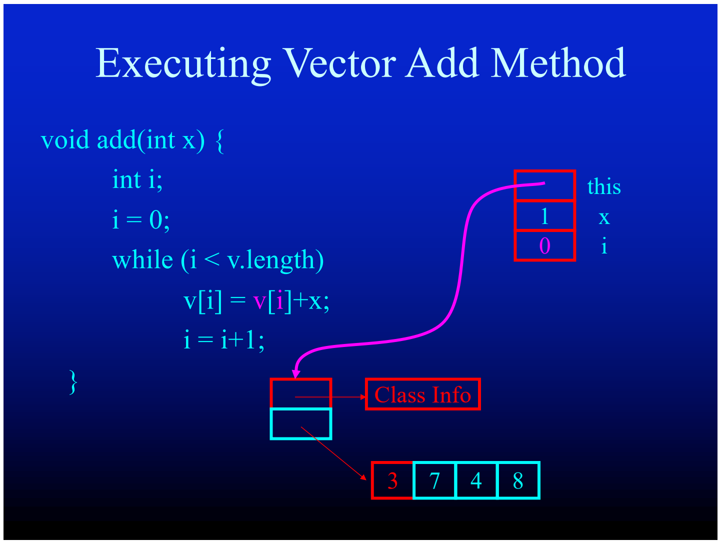
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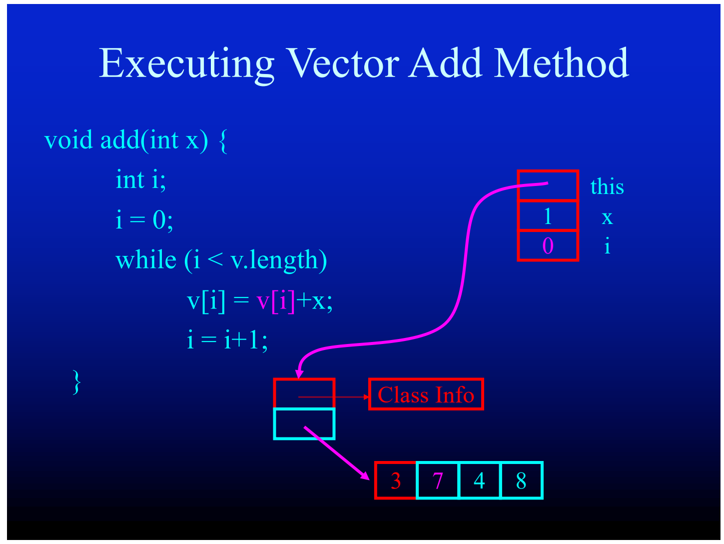
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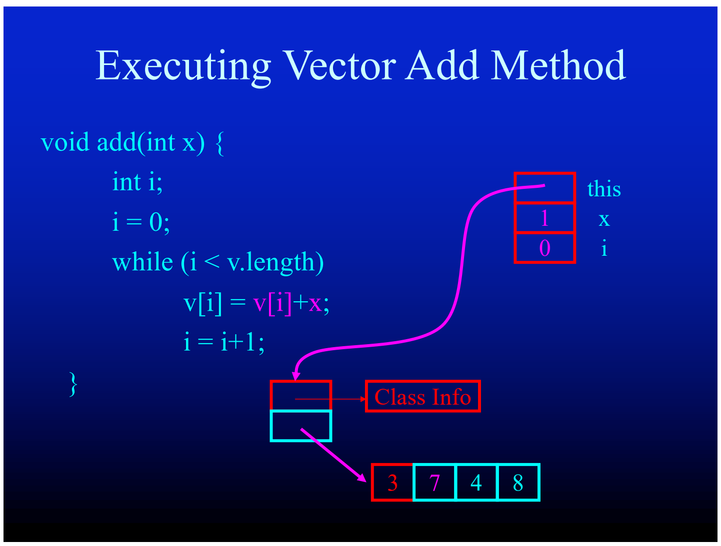
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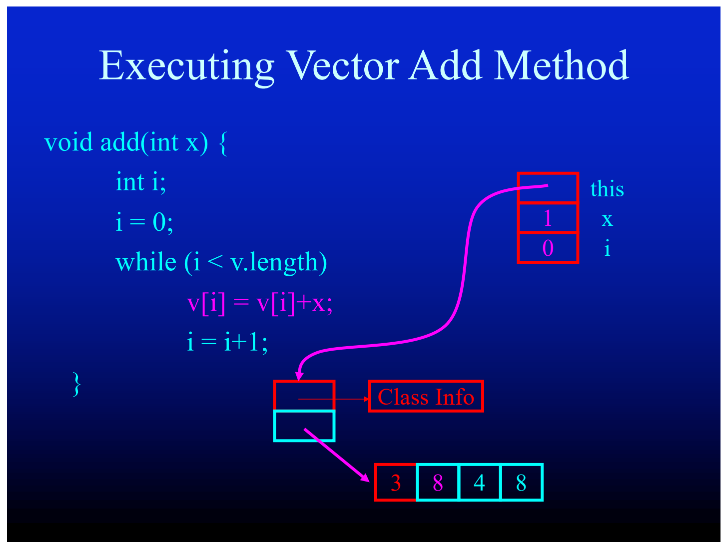
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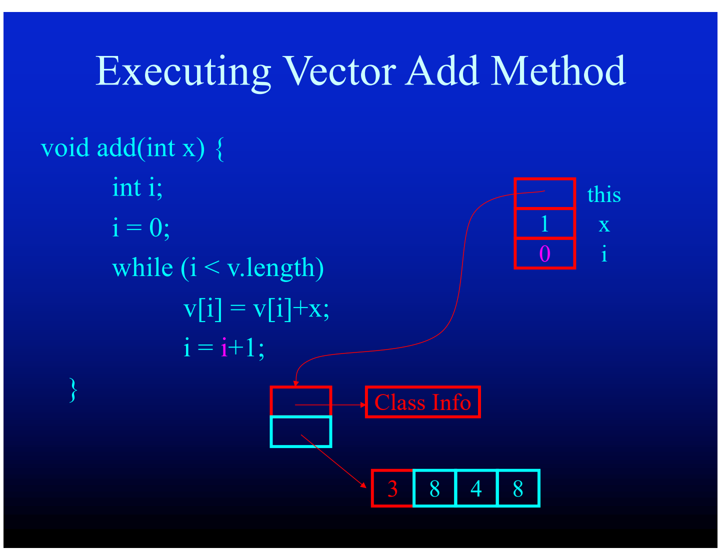
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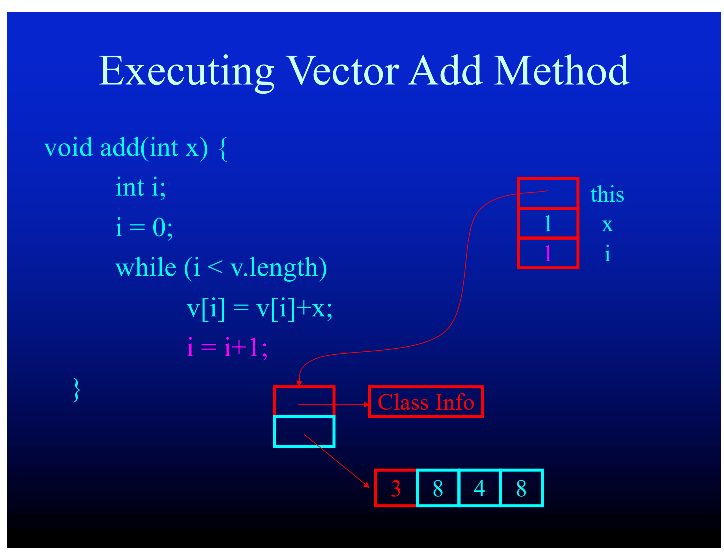
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Executing Vector Add Method

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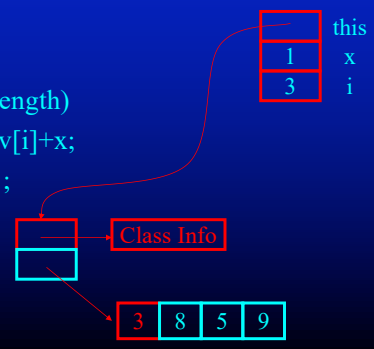


What does the compiler have to do to make all of this work?

Compilation Tasks

- Determine Format of Objects and Arrays
- Determine Format of Call Stack
- Generate Code to Read Values
  - this, parameters, locals, array elements, object fields
- Generate Code to Evaluate Expressions
- Generate Code to Write Values
- Generate Code for Control Constructs

Symbol Tables - Key Concept in Compilation

- Compiler Uses Symbol Tables to Produce
  - Object Layout in Memory
  - Code to
    - Access Object Fields
    - Access Local Variables
    - Access Parameters
    - Invoke Methods

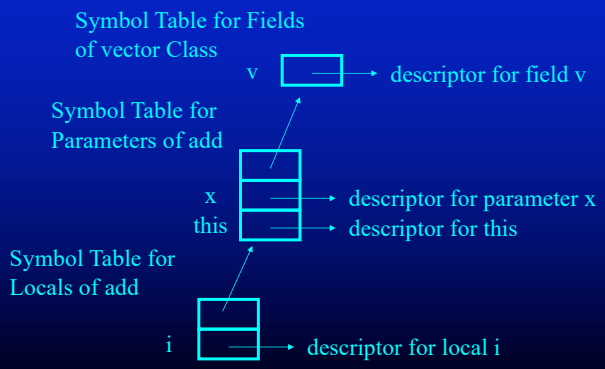
Symbol Tables During Translation From Parse Tree to IR

- Symbol Tables Map Identifiers (strings) to Descriptors (information about identifiers)
- Basic Operation: Lookup
  - Given A String, find Descriptor
  - Typical Implementation: Hash Table
- Examples
  - Given a class name, find class descriptor
  - Given variable name, find descriptor
    - local descriptor, parameter descriptor, field descriptor

Hierarchy In Symbol Tables

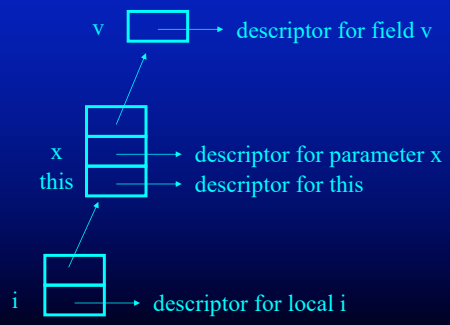
- Hierarchy Comes From
  - Nested Scopes - Local Scope Inside Field Scope
  - Inheritance - Child Class Inside Parent Class
- Symbol Table Hierarchy Reflects These Hierarchies
- Lookup Proceeds Up Hierarchy Until Descriptor is Found

Hierarchy in vector add Method



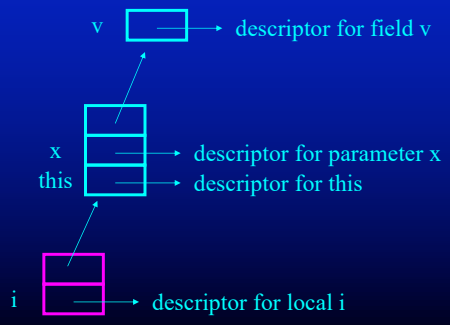
Lookup In vector Example

- v[i] = v[i]+x;



Lookup i In vector Example

- v[i] = v[i]+x;



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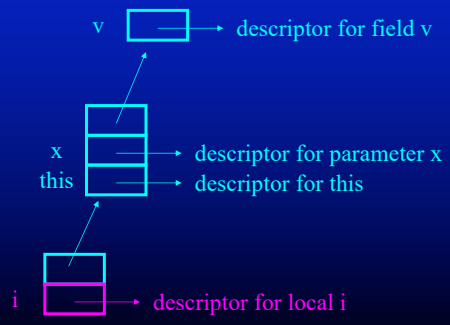
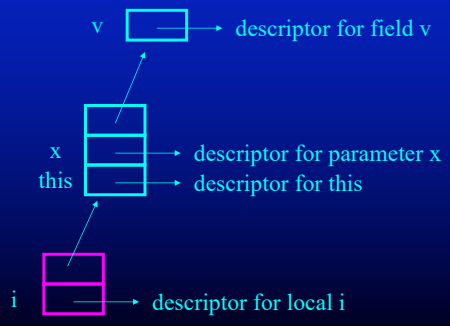


Lookup x In vector Example

- v[i] = v[i]+x;



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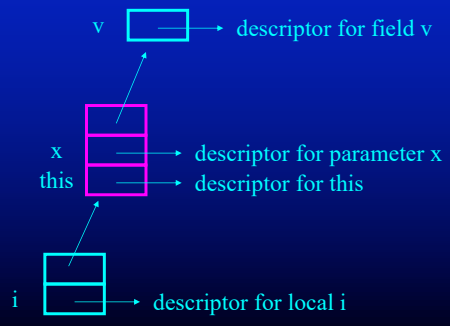

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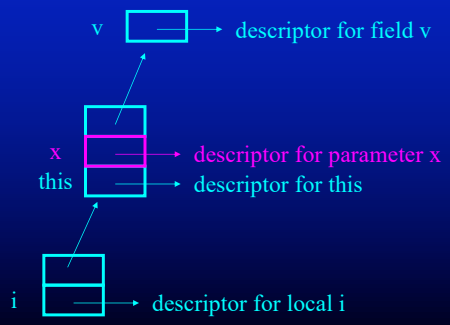


Descriptors

- What do descriptors contain?
- Information used for code generation and semantic analysis
  - local descriptors - name, type, stack offset
  - field descriptors - name, type, object offset
  - method descriptors
    - signature (type of return value, receiver, and parameters)
    - reference to local symbol table
    - reference to code for method

Program Symbol Table

- Maps class names to class descriptors
- Typical Implementation: Hash Table

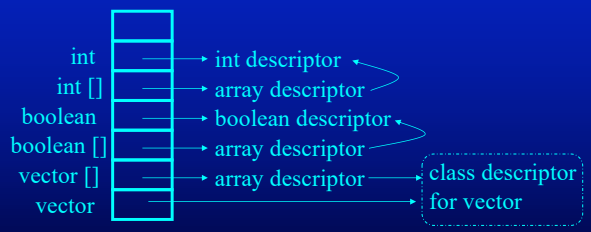
Class Descriptor

- Has Two Symbol Tables
  - Symbol Table for Methods
    - Parent Symbol Table is Symbol Table for Methods of Parent Class
  - Symbol Table for Fields
    - Parent Symbol Table is Symbol Table for Fields of Parent Class
- Reference to Descriptor of Parent Class

Field, Parameter and Local and Type Descriptors

- Field, Parameter and Local Descriptors Refer to Type Descriptors
  - Base type descriptor: int, boolean
  - Array type descriptor, which contains reference to type descriptor for array elements
  - Class descriptor
- Relatively Simple Type Descriptors
- Base Type Descriptors and Array Descriptors Stored in Type Symbol Table

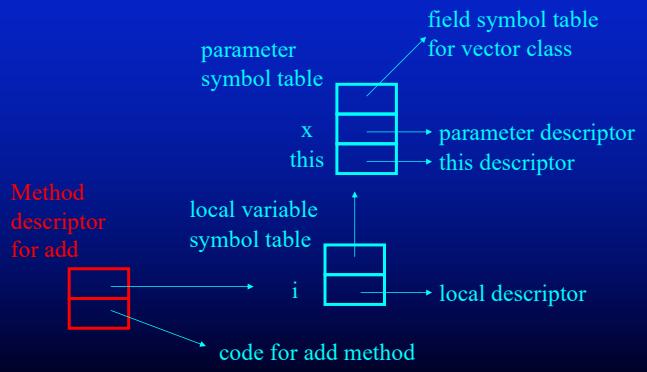
Example Type Symbol Table



Method Descriptors

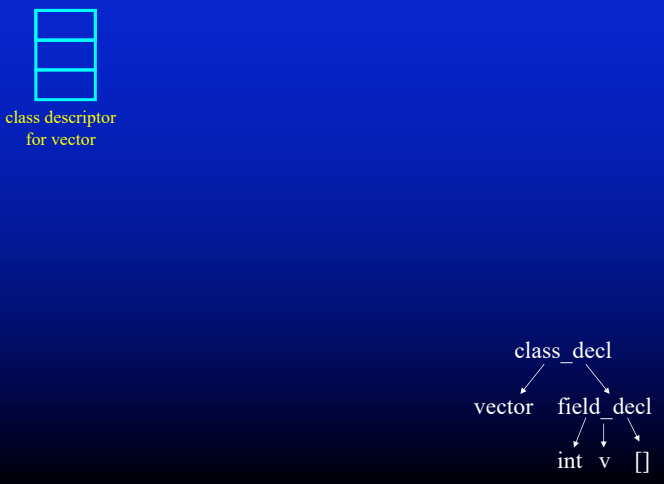
- Contain Reference to Code for Method
- Contain Reference to Local Symbol Table for Local Variables of Method
- Parent Symbol Table of Local Symbol Table is Parameter Symbol Table for Parameters of Method

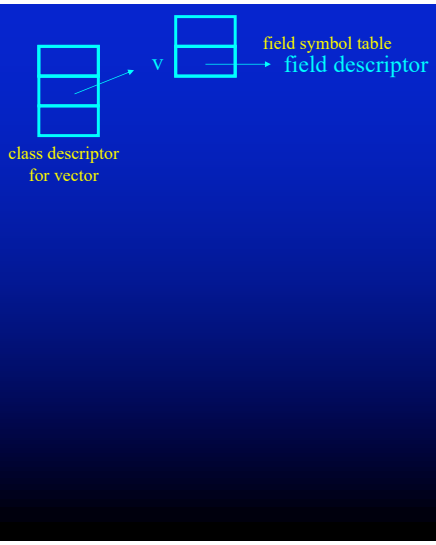
Method Descriptor for add Method

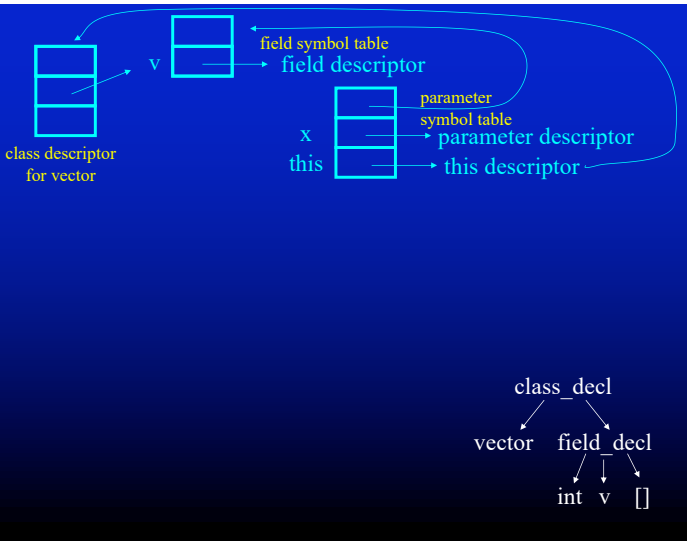


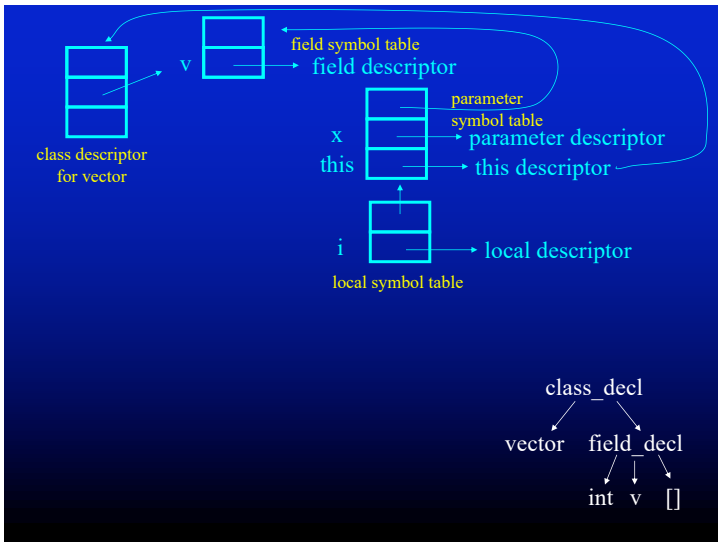
Symbol Table Summary

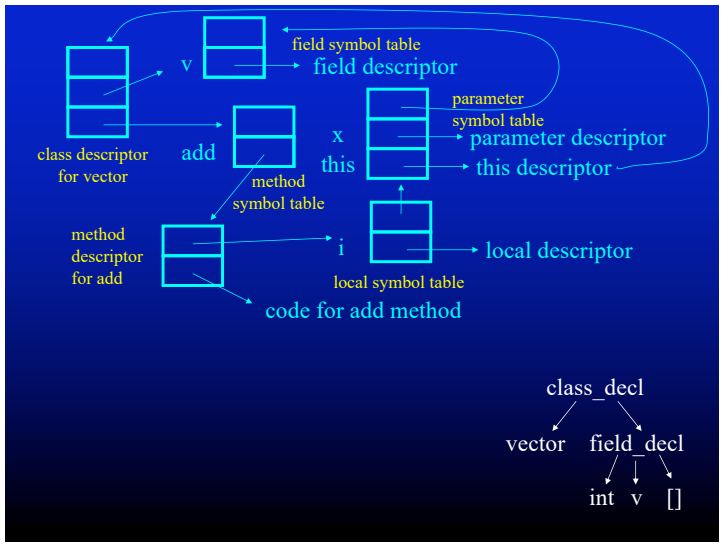
- Program Symbol Table (Class Descriptors)
- Class Descriptors
  - Field Symbol Table (Field Descriptors)
    - Field Symbol Table for SuperClass
  - Method Symbol Table (Method Descriptors)
    - Method Symbol Table for Superclass
- Method Descriptors
  - Local Variable Symbol Table (Local Variable Descriptors)
    - Parameter Symbol Table (Parameter Descriptors)
      - Field Symbol Table of Receiver Class
- Local, Parameter and Field Descriptors
  - Type Descriptors in Type Symbol Table or Class Descriptors

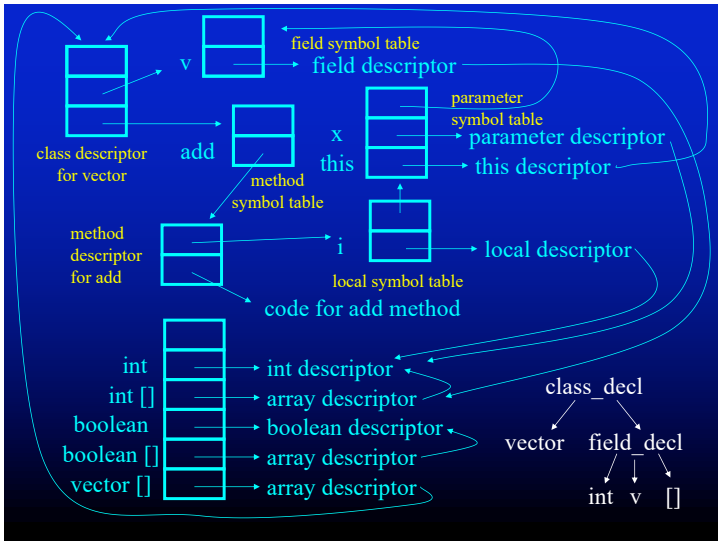


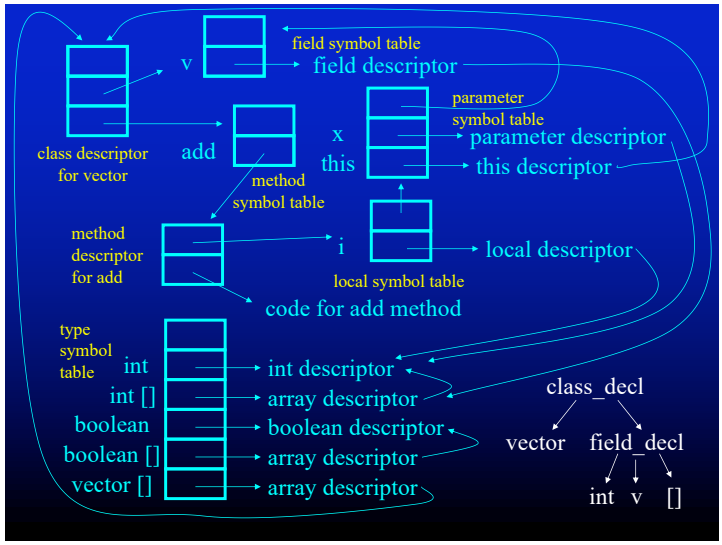












Representing Code in High-Level Intermediate Representation

Basic Idea

- Move towards assembly language
- Preserve high-level structure
  - object format
  - structured control flow
  - distinction between parameters, locals and fields
- High-level abstractions of assembly language
  - load and store nodes
  - access abstract locals, parameters and fields, not memory locations directly

What is a Parse Tree?

- Parse Tree Records Results of Parse
- External nodes are terminals/tokens
- Internal nodes are non-terminals

class_decl::=‘class’ name ‘{’field_decl method_decl‘}’
field_decl::= ‘int’ name ‘[];’
method_decl::= ‘void’ name ‘(’ param_decl ‘) ’
‘{‘ var_decl stats ‘}’

Abstract Versus Concrete Trees

- Remember grammar hacks
  - left factoring, ambuguity elimination, precedence of binary operators
- Hacks lead to a tree that may not reflect cleanest interpretation of program
- May be more convenient to work with abstract syntax tree (roughly, parse tree from grammar before hacks)

Building IR Alternatives

- Build concrete parse tree in parser, translate to abstract syntax tree, translate to IR
- Build abstract syntax tree in parser, translate to IR
- Roll IR construction into parsing

FromAbstract Syntax Trees to Symbol Tables

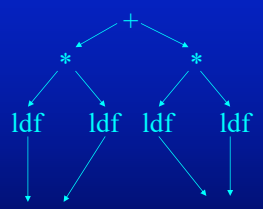
- Recursively Traverse Tree
- Build Up Symbol Tables As Traversal Visits Nodes

Representing Expressions

- Expression Trees Represent Expressions
  - Internal Nodes - Operations like +, -, etc.
  - Leaves - Load Nodes Represent Variable Accesses
- Load Nodes
  - ldf node for field accesses - field descriptor
    - (implicitly accesses this - could add a reference to accessed object)
  - ldl node for local variable accesses - local descriptor
  - ldp node for parameter accesses - parameter descriptor
  - lda node for array accesses
    - expression tree for array
    - expression tree for index

Example

x*x + y*y

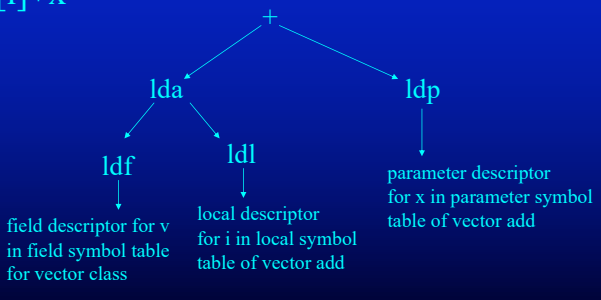


field descriptor for x in field symbol table for cartesianPoint class

field descriptor for y in field symbol table for cartesianPoint class

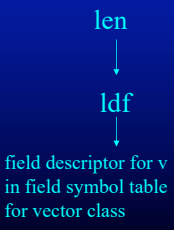
Example

v[i]+x



Special Case: Array Length Operator

- len node represents length of array
  - expression tree for array
- Example: v.length



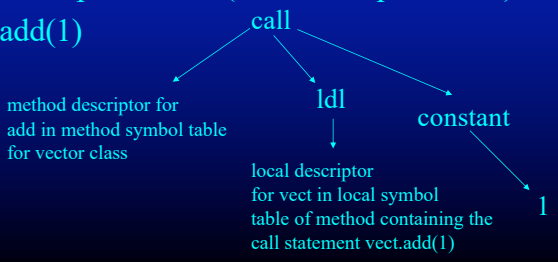
Representing Assignment Statements

- Store Nodes
  - stf for stores to fields
    - field descriptor
    - expression tree for stored value
  - stl for stores to local variables
    - local descriptor
    - expression tree for stored value
  - sta for stores to array elements
    - expression tree for array
    - expression tree for index
    - expression tree for stored value

Representing Procedure Calls

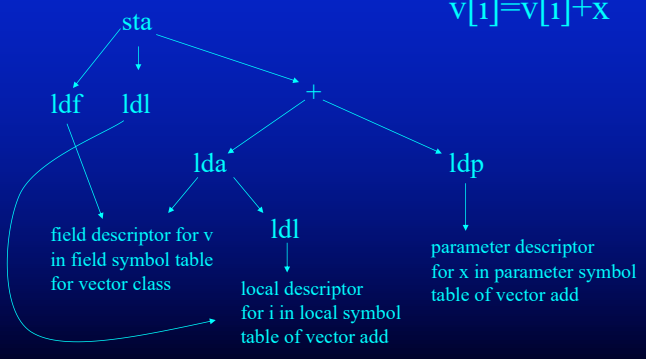
- Call statement
- Refers to method descriptor for invoked method
- Has list of parameters (this is first parameter)

vect.add(1)



Example

v[i]=v[i]+x

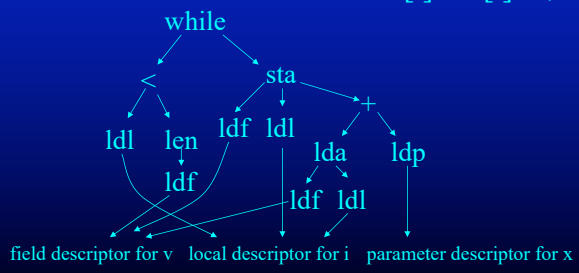


Representing Flow of Control

- Statement Nodes
  - sequence node - first statement, next statement
  - if node
    - expression tree for condition
    - then statement node and else statement node
  - while node
    - expression tree for condition
    - statement node for loop body
  - return node
    - expression tree for return value

Example

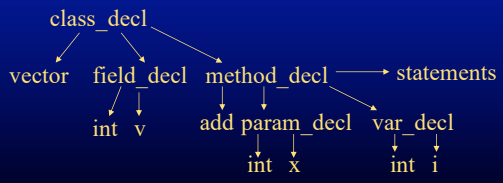
while (i < v.length)
v[i] = v[i]+x;

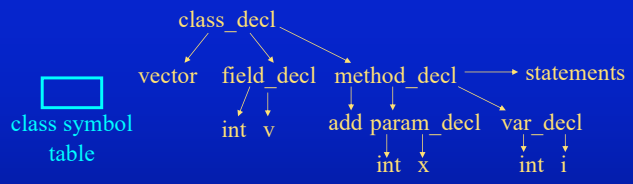


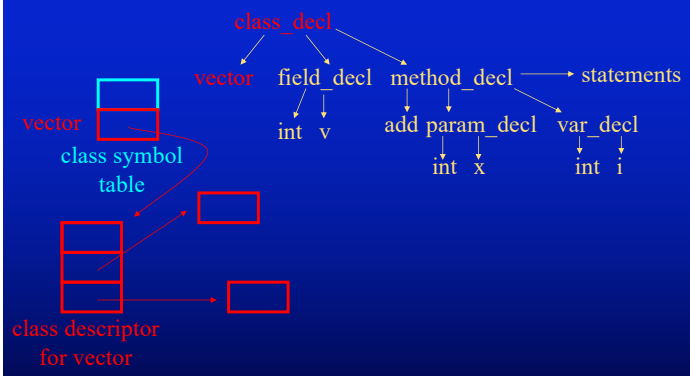
Translating from Abstract Syntax Trees to Symbol Tables

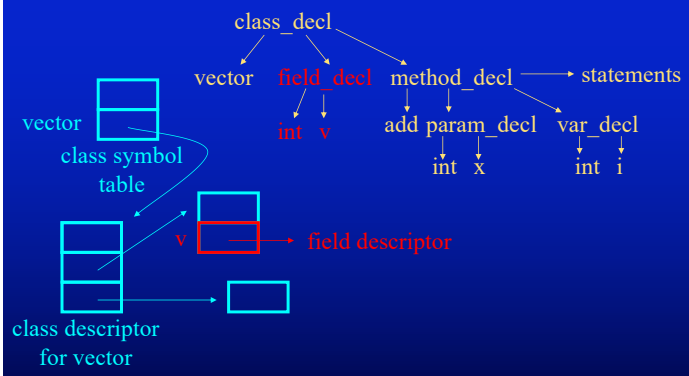
Example Abstract Syntax Tree

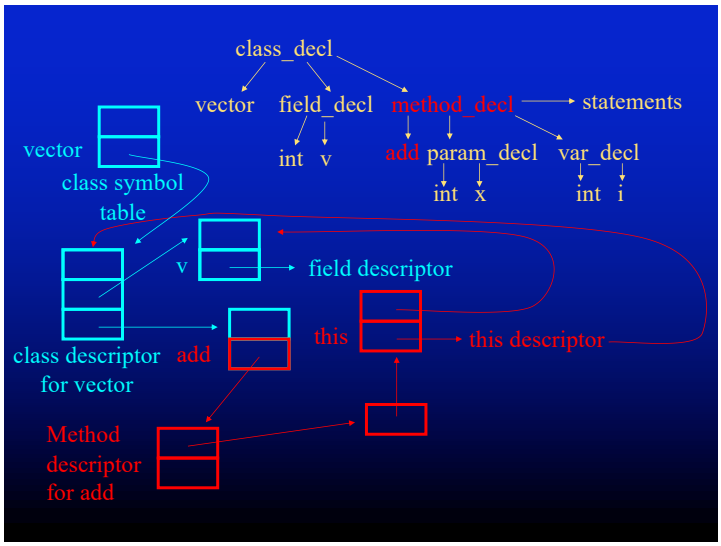
```
class vector {
    int v[];
    void add(int x) {
        int i; i = 0;
        while (i < v.length) { v[i] = v[i]+x; i = i+1; }
    }
}
```

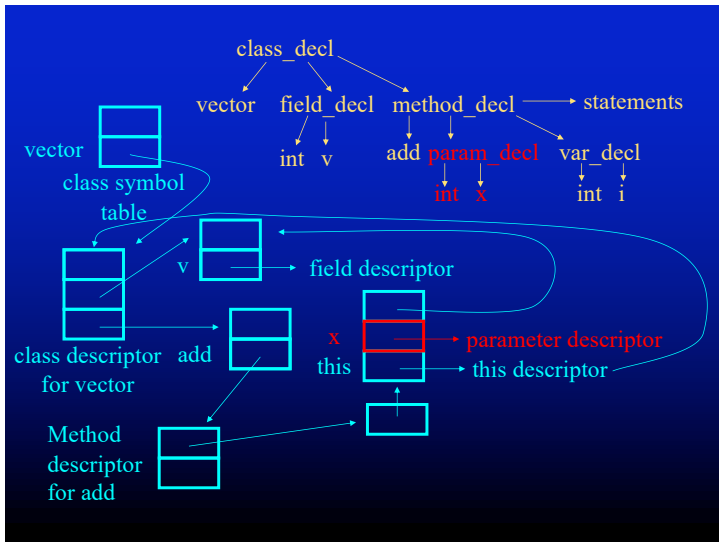


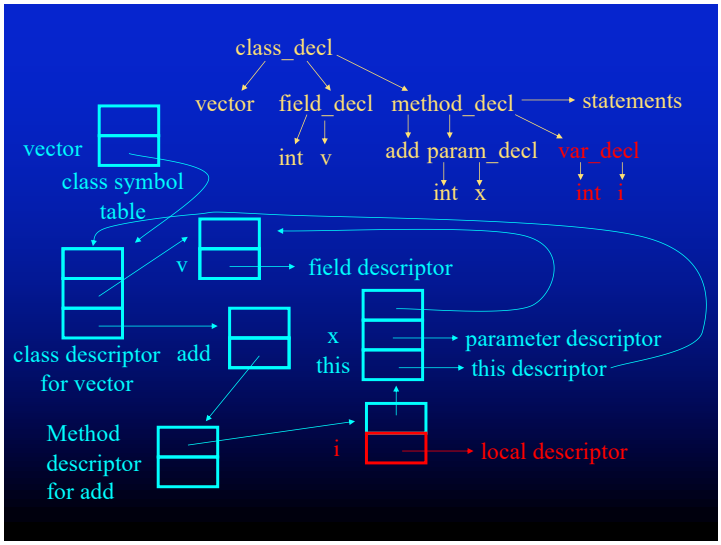












From Abstract Syntax Trees to Intermediate Representation

```
while (i < v.length)
v[i] = v[i]+x;
```

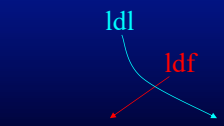
field descriptor for v local descriptor for i parameter descriptor for x

```
while (i < v.length)
v[i] = v[i]+x;
```

ldl

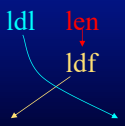
field descriptor for v local descriptor for i parameter descriptor for x

while (i < v.length)
v[i] = v[i]+x;



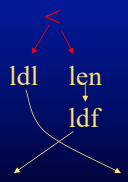
field descriptor for v local descriptor for i parameter descriptor for x

while (i < v.length)
v[i] = v[i]+x;



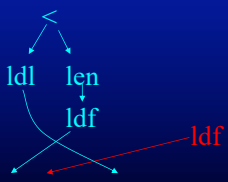
field descriptor for v local descriptor for i parameter descriptor for x

while (i < v.length)
v[i] = v[i]+x;



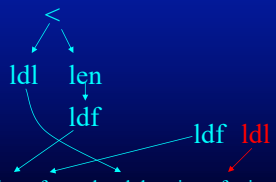
field descriptor for v local descriptor for i parameter descriptor for x

while (i < v.length)
v[i] = v[i]+x;



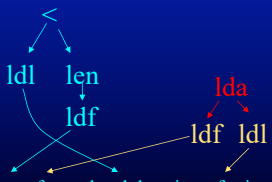
field descriptor for v local descriptor for i parameter descriptor for x

while (i < v.length)
v[i] = v[i]+x;



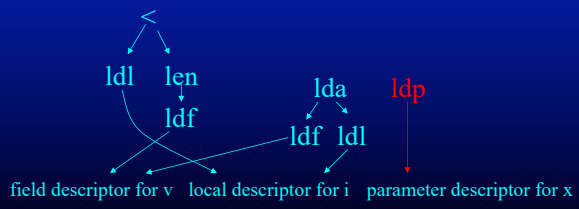
field descriptor for v local descriptor for i parameter descriptor for x

while (i < v.length)
v[i] = v[i]+x;

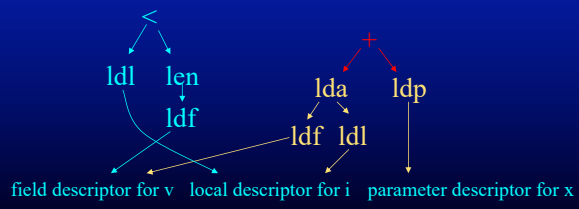


field descriptor for v local descriptor for i parameter descriptor for x

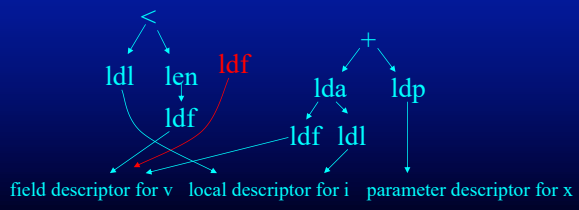
while (i < v.length)
v[i] = v[i]+x;



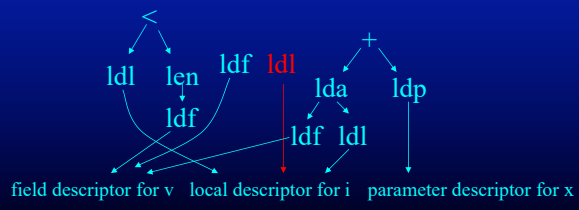
while (i < v.length)
v[i] = v[i]+x;



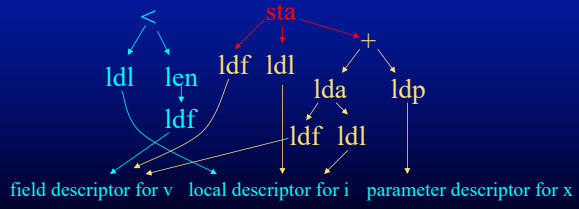
while (i < v.length)
v[i] = v[i]+x;



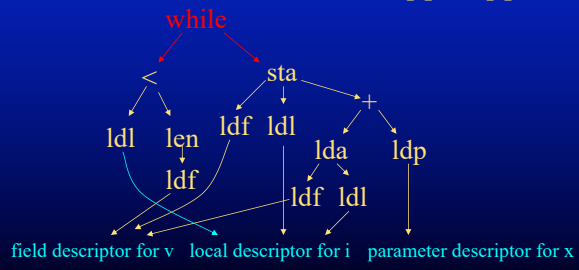
while (i < v.length)
v[i] = v[i]+x;



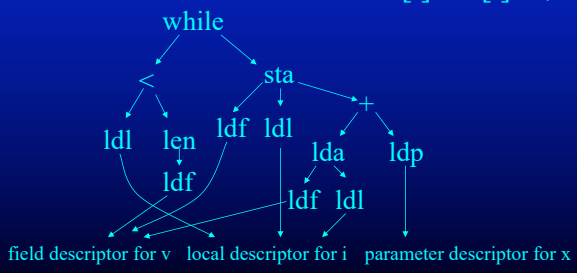
while (i < v.length)
v[i] = v[i]+x;



while (i < v.length)
v[i] = v[i]+x;

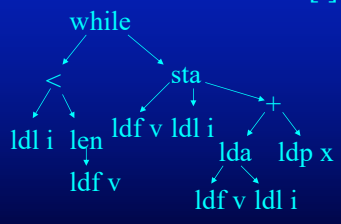


while (i < v.length)
v[i] = v[i]+x;



Abbreviated Notation

while (i < v.length)
v[i] = v[i]+x;



From Abstract Syntax Trees to IR

- Recursively Traverse Abstract Syntax Tree
- Build Up Representation Bottom-Up Manner
  - Look Up Variable Identifiers in Symbol Tables
  - Build Load Nodes to Access Variables
  - Build Expressions Out of Load Nodes and Operator Nodes
  - Build Store Nodes for Assignment Statements
  - Combine Store Nodes with Flow of Control Nodes

Summary

High-Level Intermediate Representation

- Goal: represent program in an intuitive way that supports future compilation tasks
- Representing program data
  - Symbol tables
  - Hierarchical organization
- Representing computation
  - Expression trees
  - Various types of load and store nodes
  - Structured flow of control
- Traverse abstract syntax tree to build IR

Further Complication - Inheritance

Object Extension

Inheritance Example - Point Class

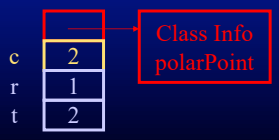
```
class point {
  int c;
  int getColor() { return(c); }
  int distance() { return(0); }
}
```

Point Subclasses

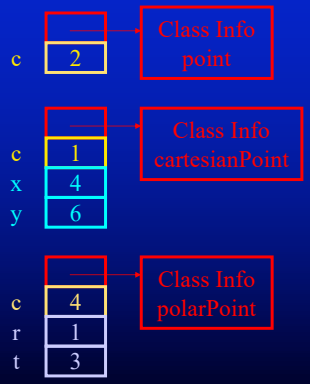
```
class cartesianPoint extends point{
    int x, y;
    int distance() { return(x*x + y*y); }
}
class polarPoint extends point {
    int r, t;
    int distance() { return(r*r); }
    int angle() { return(t); }
}
```

Implementing Object Fields

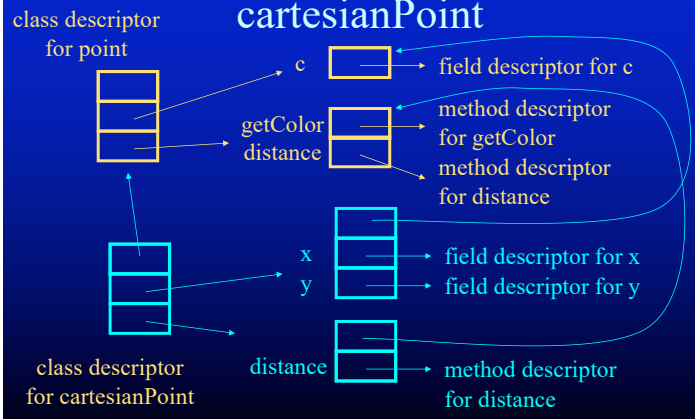
- Each object is a contiguous piece of memory
- Fields from inheritance hierarchy allocated sequentially in piece of memory
- Example: polarPoint object



Point Objects



Class Descriptors for point and cartesianPoint



Dynamic Dispatch

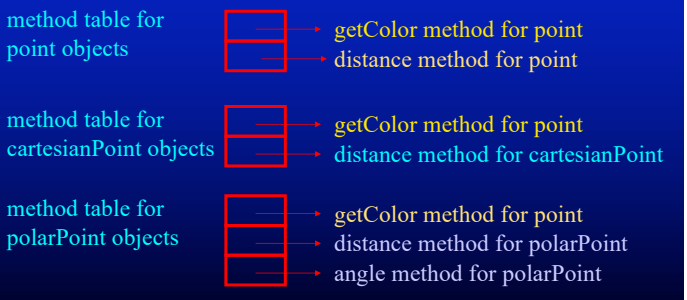
```
if (x == 0) {
    p = new point();
} else if (x < 0) {
    p = new cartesianPoint(x,y);
} else if (x > 0) {
    p = new polarPoint(r,t);
}
y = p.distance();
```

Which distance method is invoked?

- if p is a point
  return(0)
- if p is a cartesianPoint
  return(x*x + y*y)
- if p is a polarPoint
  return(r*r)
- Invoked Method Depends on Type of Receiver!

Implementing Dynamic Dispatch

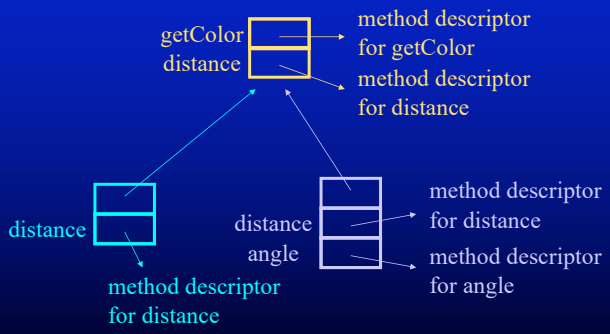
- Basic Mechanism: Method Table



Invoking Methods

- Compiler Numbers Methods In Each Inheritance Hierarchy
  - getColor is Method 0, distance is Method 1, angle is Method 2
- Method Invocation Sites Access Corresponding Entry in Method Table
- Works For Single Inheritance Only
  - not for multiple inheritance, multiple dispatch, or interfaces

Hierarchy in Method Symbol Tables for Points



Lookup In Method Symbol Tables

- Starts with method table of declared class of receiver object
- Goes up class hierarchy until method found
  - point p; p = new point(); p.distance();
    - finds distance in point method symbol table
  - point p; p = new cartesianPoint(); p.distance();
    - finds distance in point method symbol table
  - cartesianPoint p; p = new cartesianPoint(); p.getColor();
    - finds getColor in point method symbol table

Static Versus Dynamic Lookup

- Static lookup done at compile time for type checking and code generation
- Dynamic lookup done when program runs to dispatch method call
- Static and dynamic lookup results may differ!
  - point p; p = new cartesianPoint(); p.distance();
    - Static lookup finds distance in point method table
    - Dynamic lookup invokes distance in cartesianPoint class
    - Dynamic dispatch mechanism used to make this happen

Static and Dynamic Tables

- Static Method Symbol Table
  - Used to look up method definitions at compile time
  - Index is method name
  - Lookup starts at method symbol table determined by declared type of receiver object
  - Lookup may traverse multiple symbol tables
- Dynamic Method Table
  - Used to look up method to invoke at run time
  - Index is method number
  - Lookup simply accesses a single table element