Incrementalized Pointer and Escape Analysis

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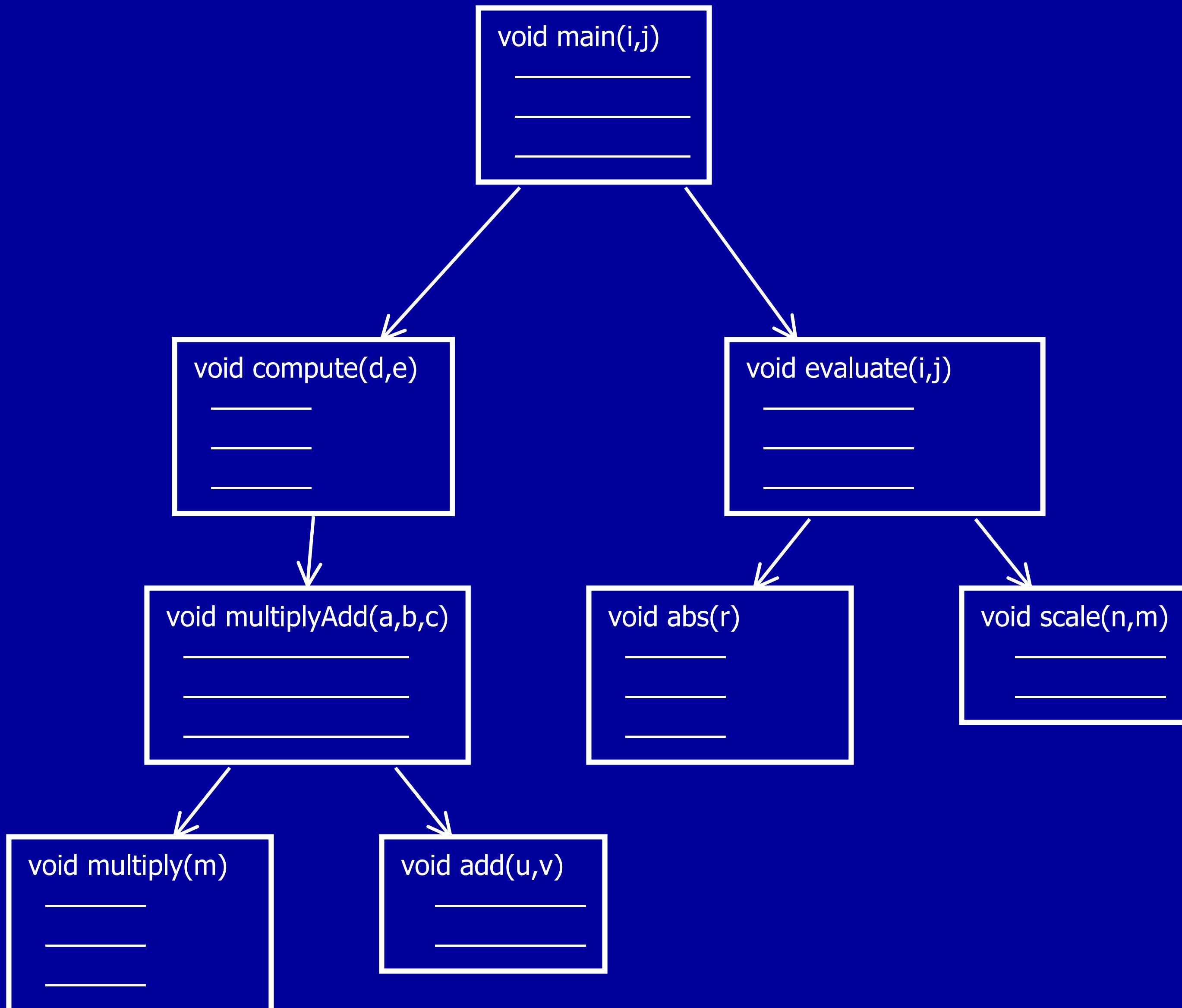
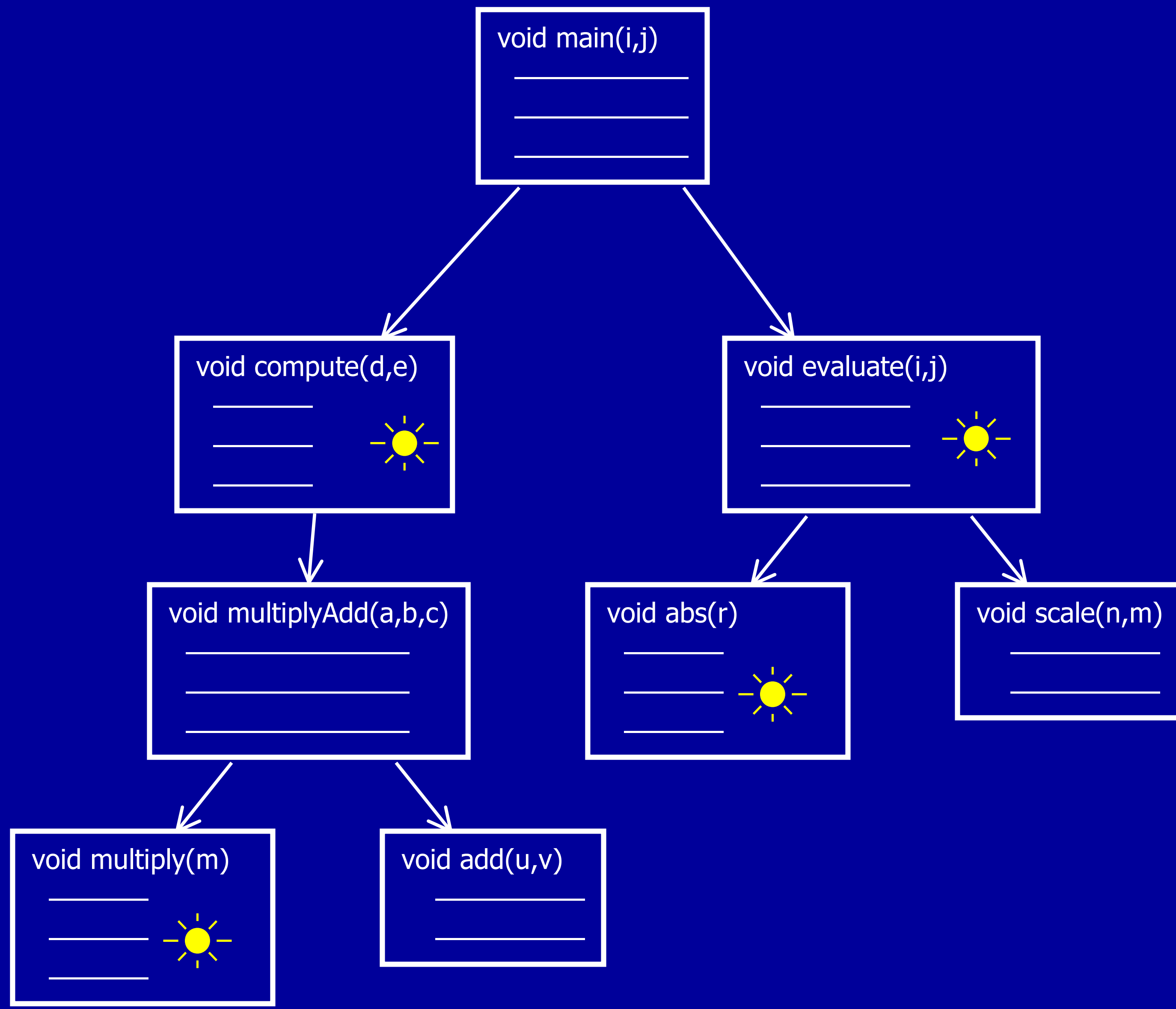
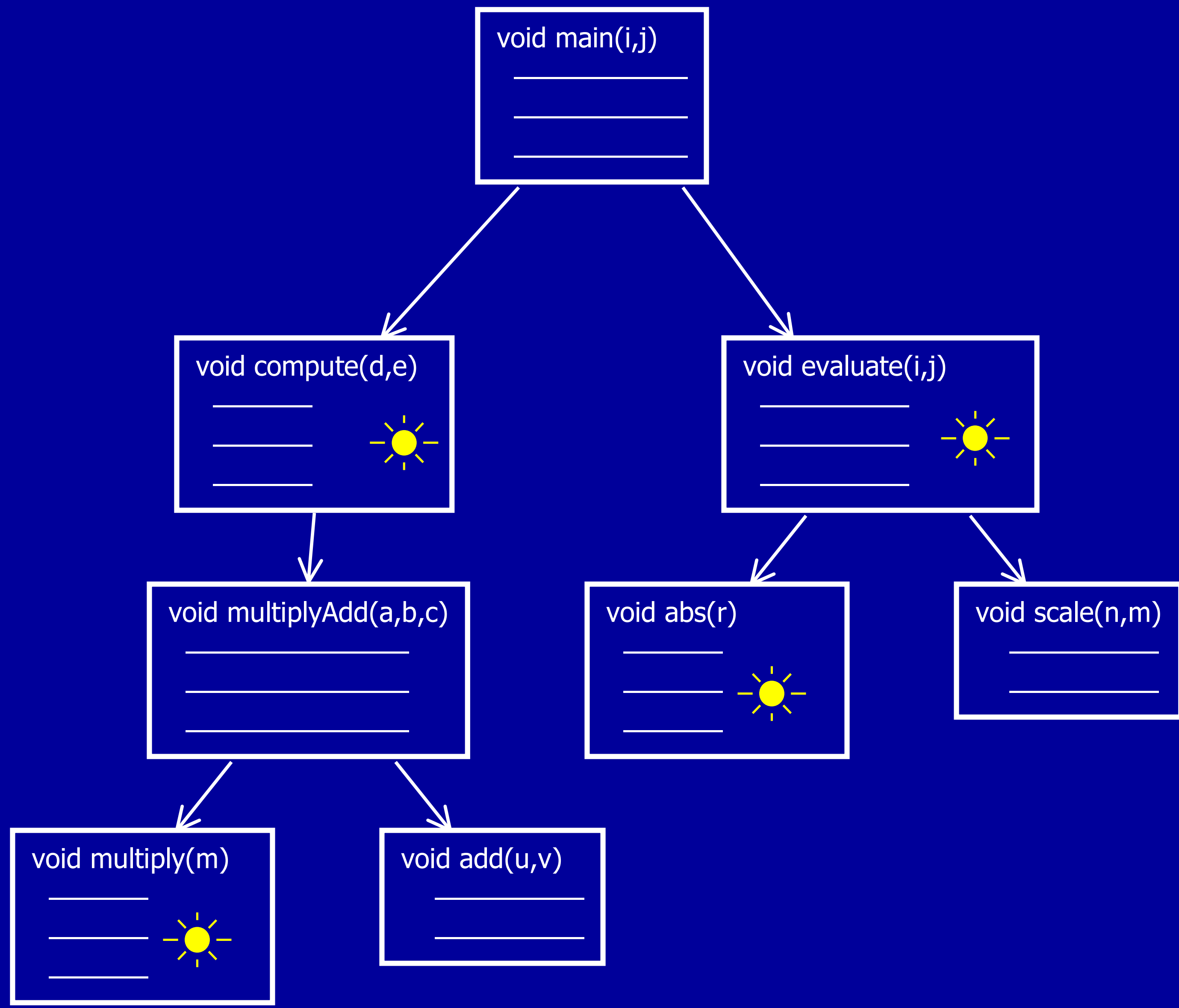
Start with a program



Lots of allocation sites

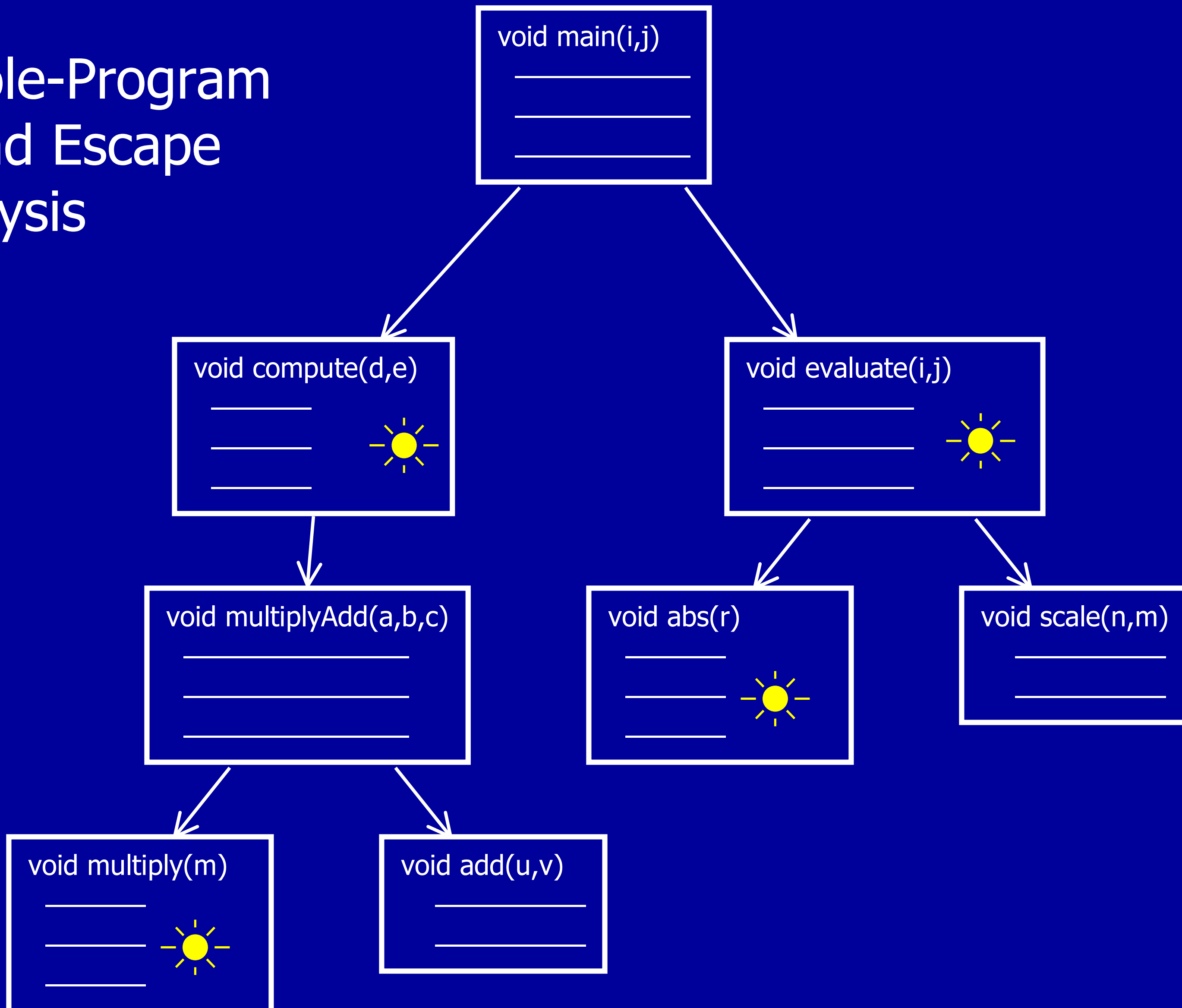


Stack Allocation Optimization



Stack Allocation Optimization

Precise Whole-Program Pointer and Escape Analysis

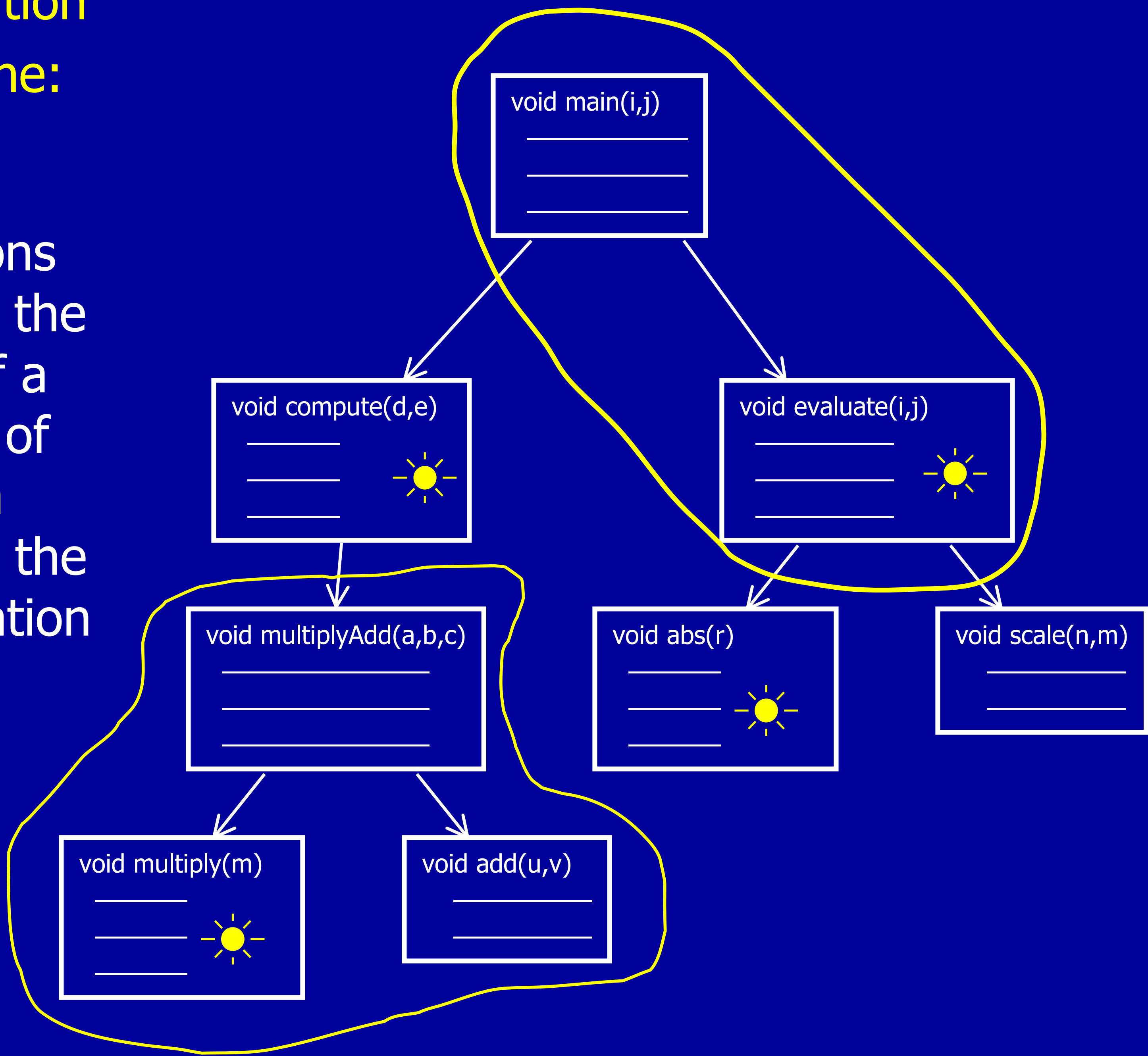


Drawbacks to Whole-Program Analysis

- Resource Intensive
  - Large analysis times
  - Large memory consumption
- Unsuitable for partial programs

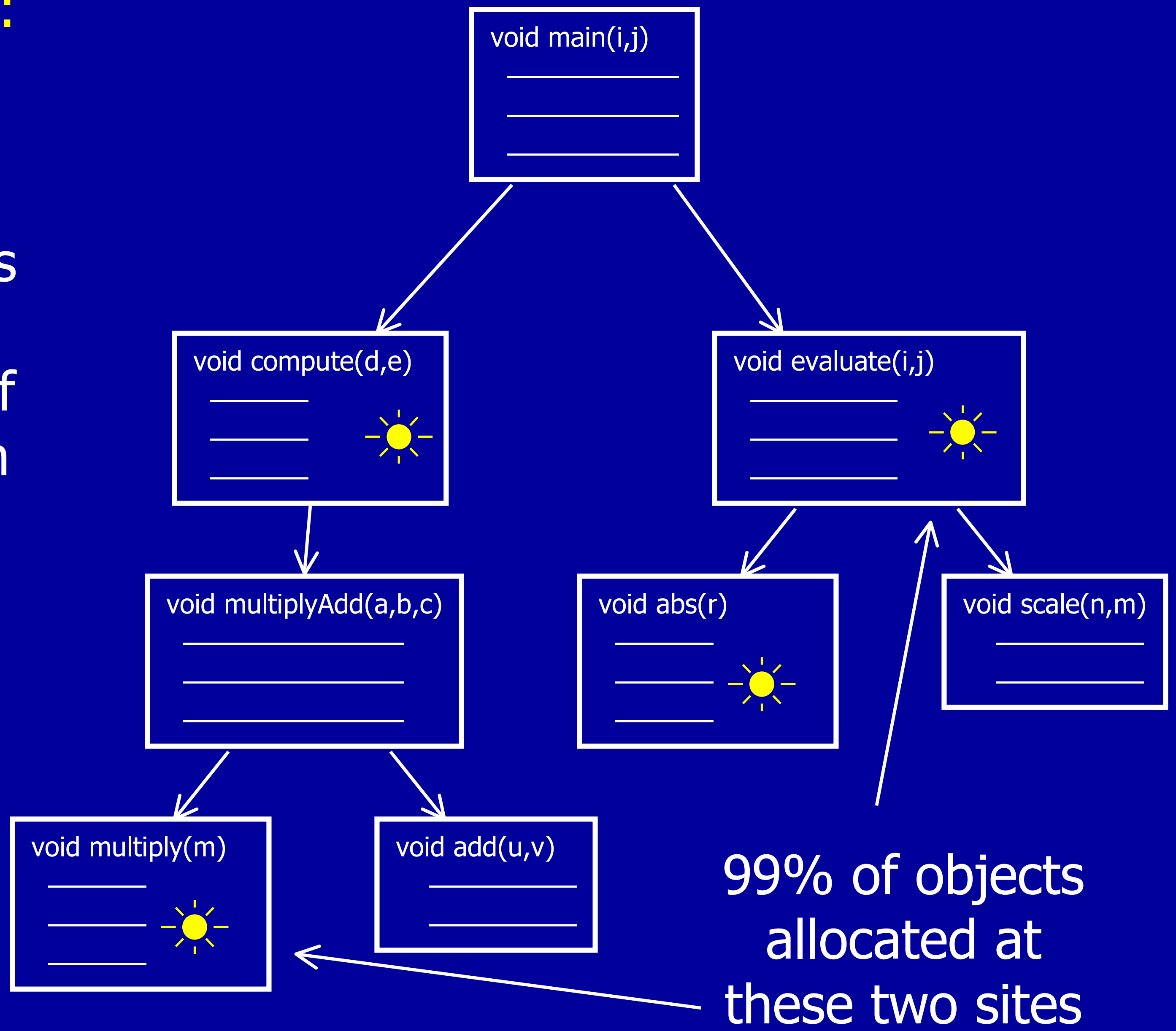
Key Observation Number One:

Most optimizations require only the analysis of a small part of program surrounding the object allocation site



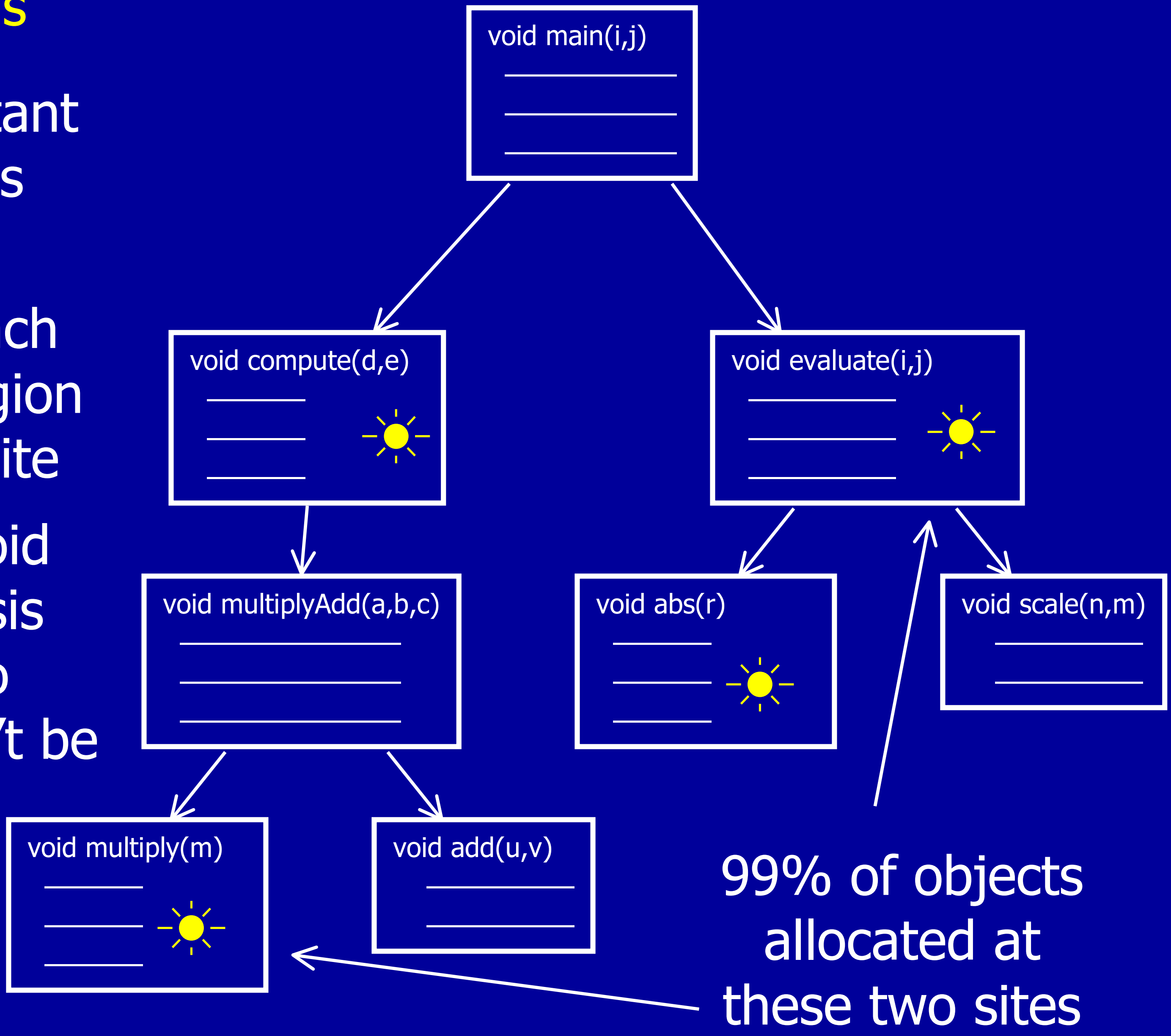
Key Observation Number Two:

Most of the optimization benefit comes from a small percentage of the allocation sites



Intuition for Better Analysis

- Locate important allocation sites
- Use demand-driven approach to analyze region surrounding site
- Somehow avoid sinking analysis resources into sites that can't be optimized



What This Talk is About

How we turned this intuition into an algorithm that usually

1) obtains almost all the benefit of the whole program analysis

2) analyzes a small fraction of program

3) consumes a small fraction of whole program analysis time

Structure of Talk

- Motivating Example
- Base whole program analysis (Whaley and Rinard, OOPSLA 99)
- Incrementalized analysis
- Analysis policy
- Experimental results
- Conclusion

Motivating Example

Employee Database Example

- Read in database of employee records
- Extract statistics like max salary

Employee Database Example

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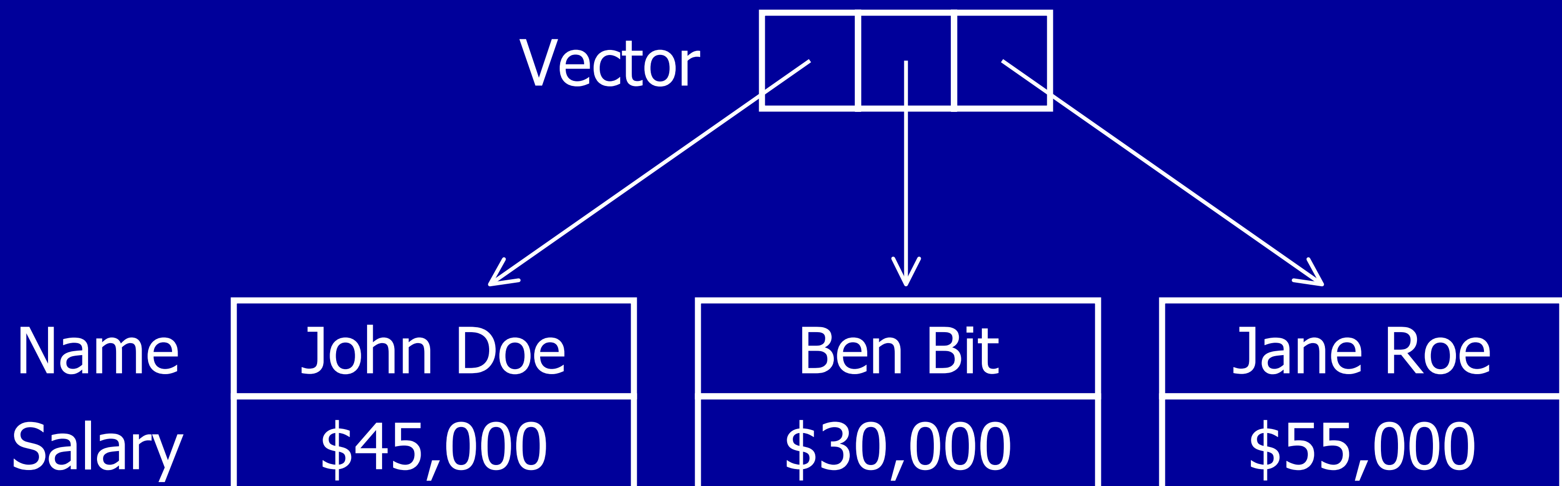
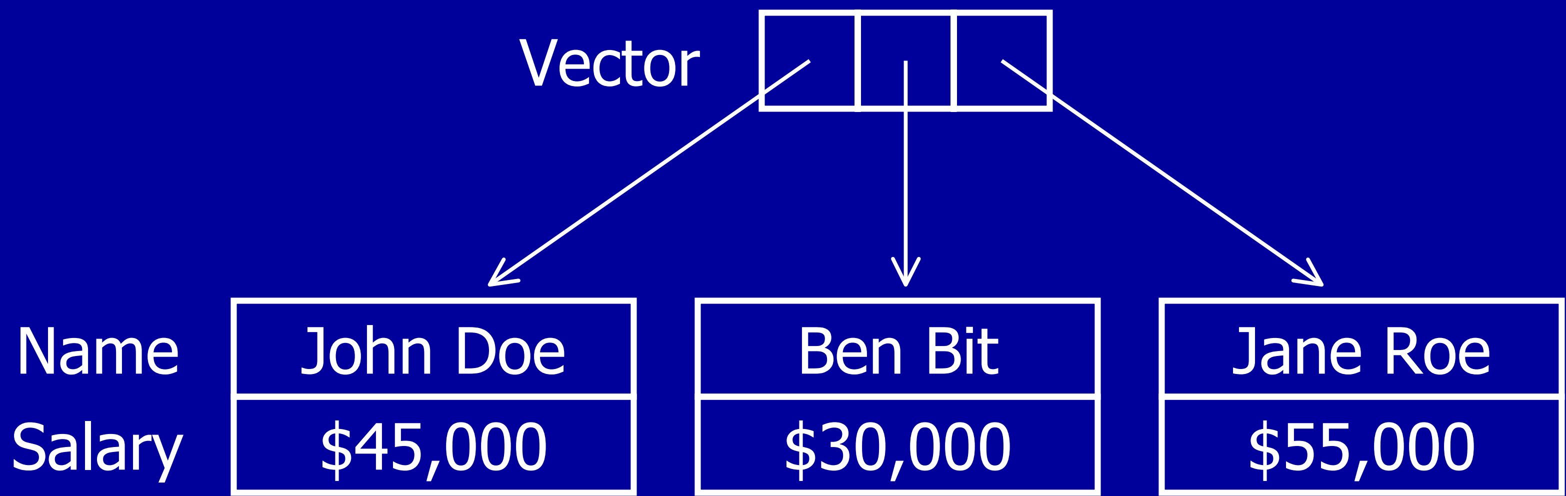
- Extract statistics like max salary



Computing Max Salary

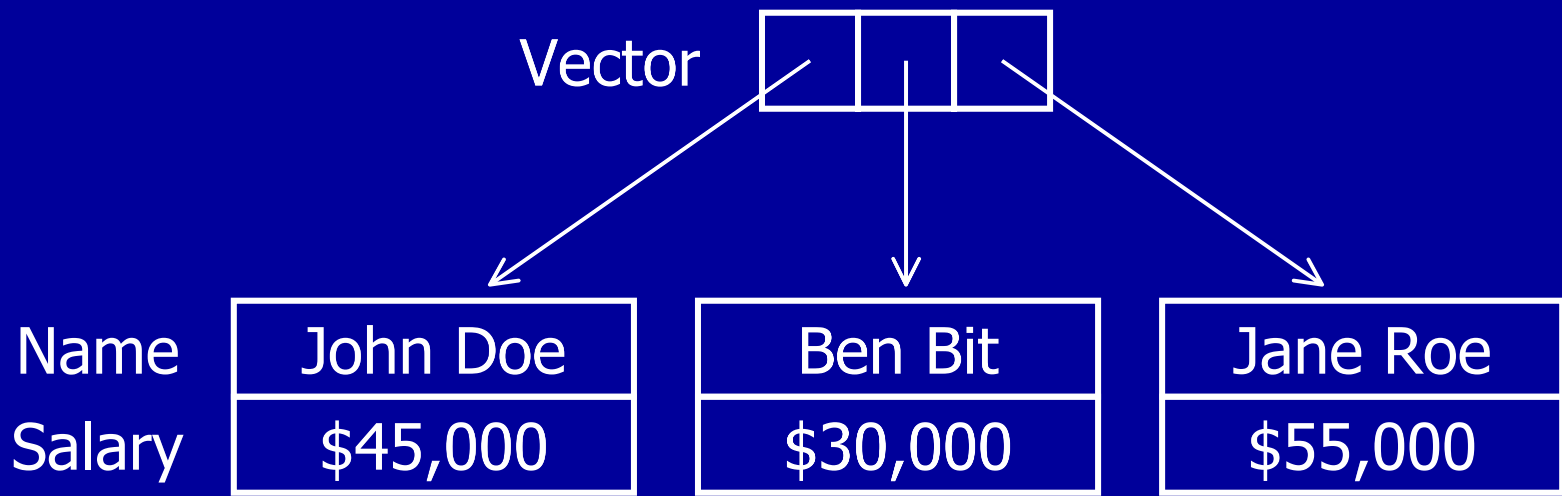
- Traverse Records to Find Max Salary



max = $0

Computing Max Salary

- Traverse Records to Find Max Salary

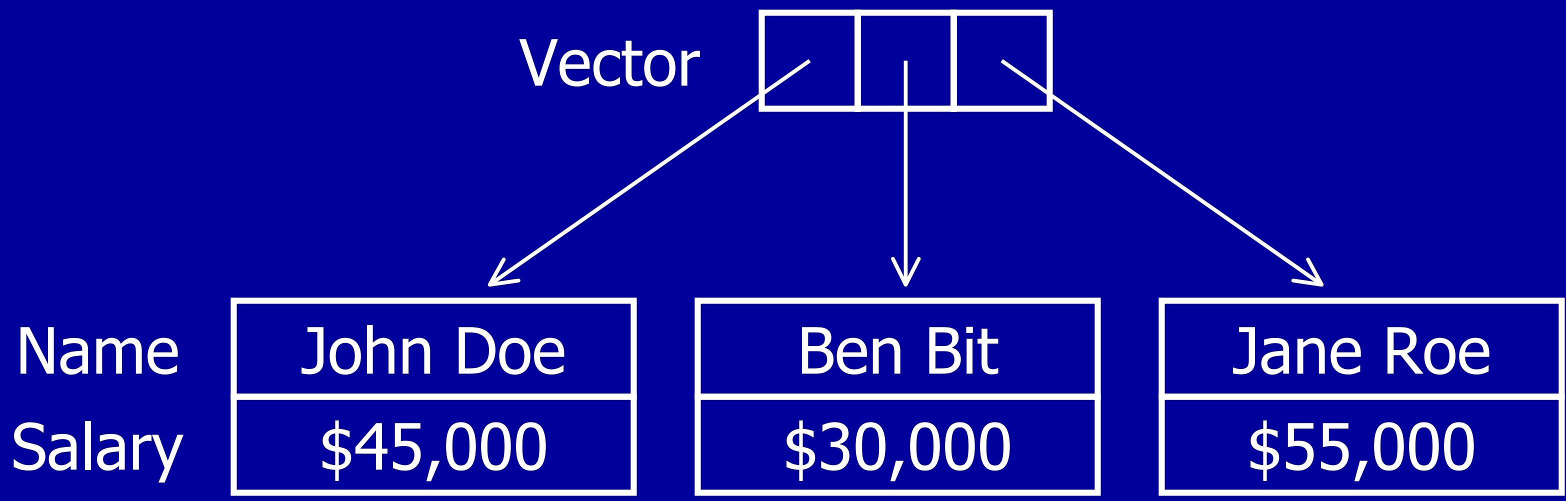


max = $45,000

who = John Doe

Computing Max Salary

- Traverse Records to Find Max Salary



max = $45,000

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Computing Max Salary

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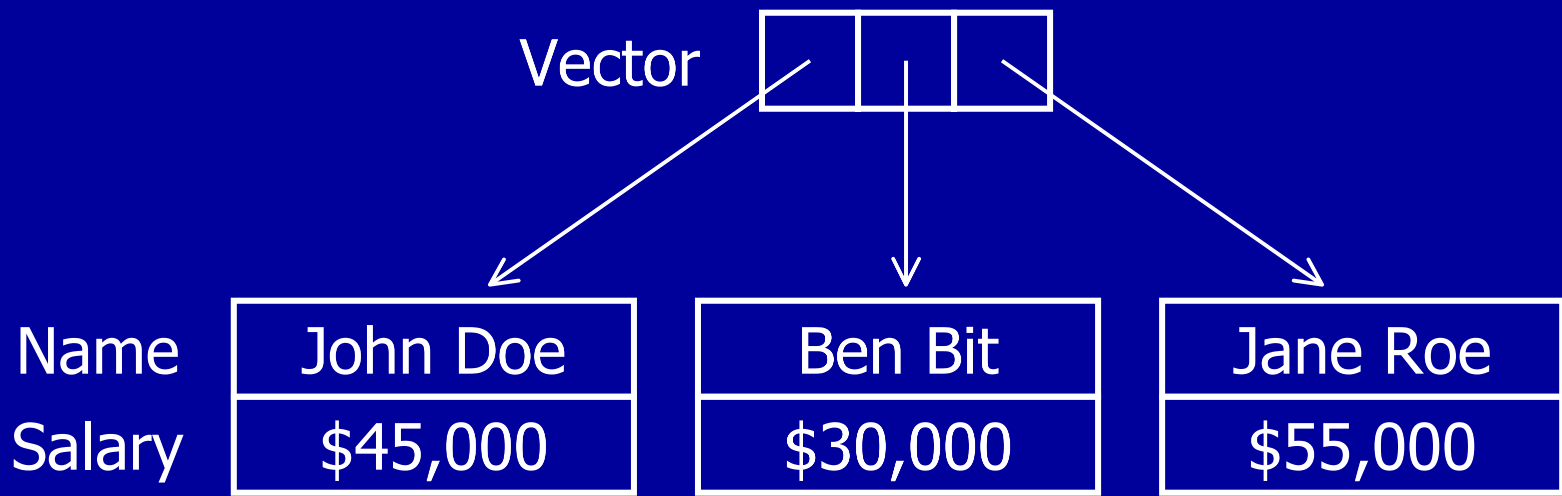
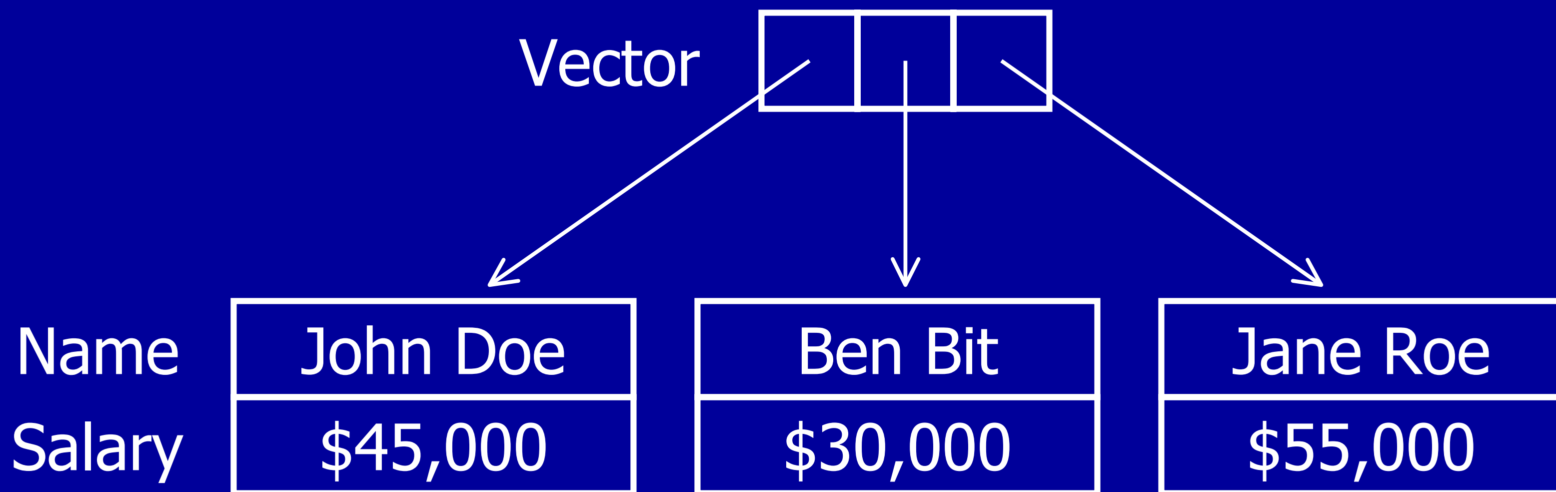


max = $55,000

who = Jane Roe

Computing Max Salary

- Traverse Records to Find Max Salary



max salary = $55,000

highest paid = Jane Roe

Coding Max Computation (in Java)

```
class EmployeeDatabase {
   Vector database = new Vector();
   Employee highestPaid;
   void computeMax() {
      int max = 0;
      Enumeration enum = database.elements();
      while (enum.hasMoreElements()) {
         Employee e = enum.nextElement();
         if (max < e.salary()) {
            max = e.salary(); highestPaid = e;
         }
      }
   }
}
```

Coding Max Computation (in Java)

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class EmployeeDatabase {
   Vector database = new Vector();
   Employee highestPaid;
   void computeMax() {
      int max = 0;
      Enumeration enum = database.elements();
      while (enum.hasMoreElements()) {
         Employee e = enum.nextElement();
         if (max < e.salary()) {
            max = e.salary(); highestPaid = e;
         }
      }
   }
}
```

Issues In Implementation

- Enumeration object allocated on heap
  - Increases heap memory usage
  - Increases garbage collection frequency
- Heap allocation is unnecessary
  - Enumeration object allocated inside max
  - Not accessible outside max
  - Should be able to use stack allocation

Basic Idea

Use pointer and escape analysis to recognize captured objects

Transform program to allocate captured objects on stack

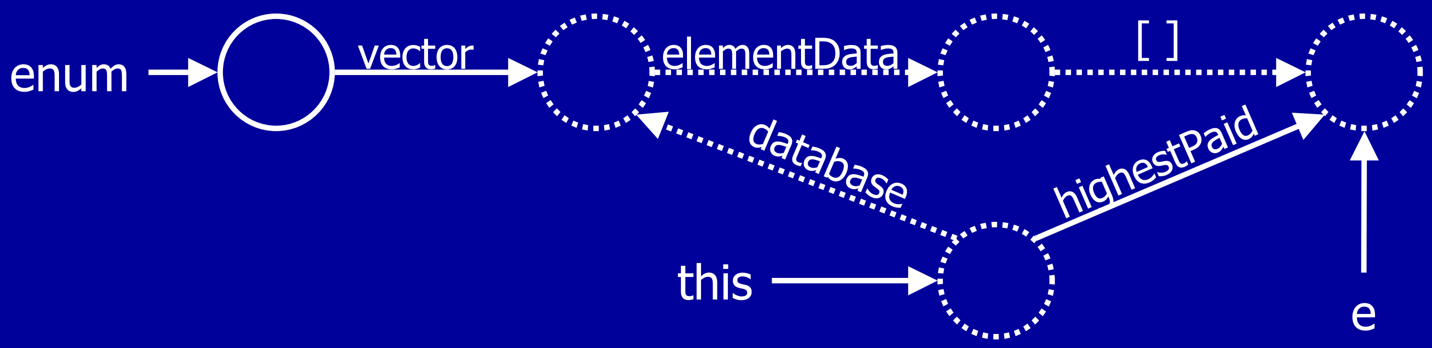
Base Analysis

Base Analysis

- Basic Abstraction: Points-to Escape Graph
- Intraprocedural Analysis
  - Flow sensitive abstract interpretation
  - Produces points-to escape graph at each program point
- Interprocedural Analysis
  - Bottom Up and Compositional
  - Analyzes each method once to obtain a single parameterized analysis result
  - Result is specialized for use at each call site

Points-to Escape Graph in Example

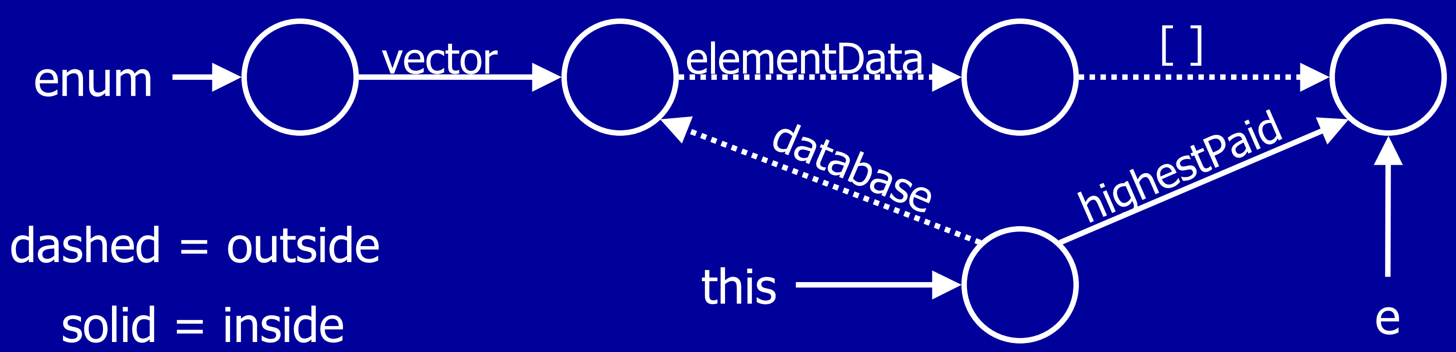
```
void computeMax() {
    int max = 0;
    Enumeration enum = database.elements();
    while (enum.hasMoreElements()) {
        Employee e = enum.nextElement();
        if (max < e.salary()) { max = e.salary(); highestPaid = e; }
    }
```



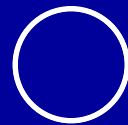
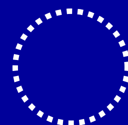

```
}
```

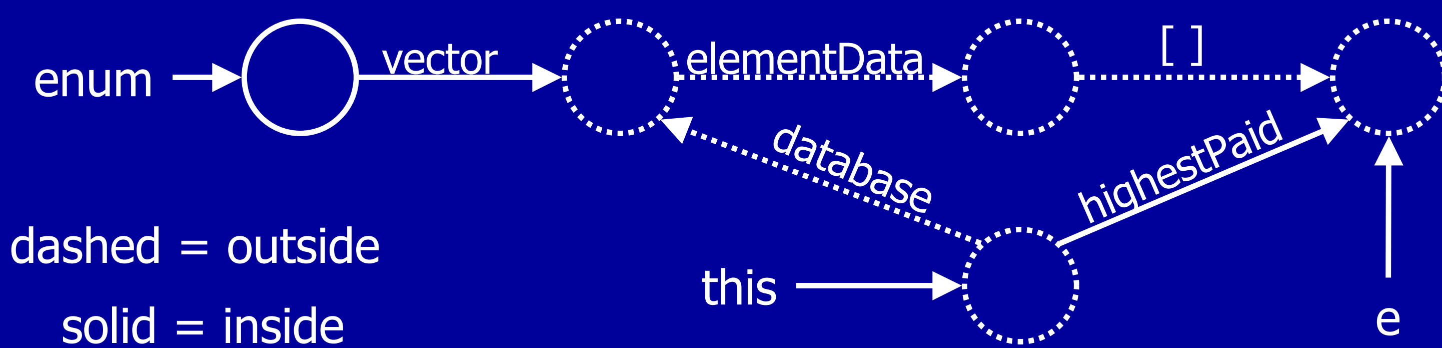
Edge Types

- Inside Edges:
  - created in currently analyzed part of program
- Outside Edges:
  - created outside currently analyzed part of program



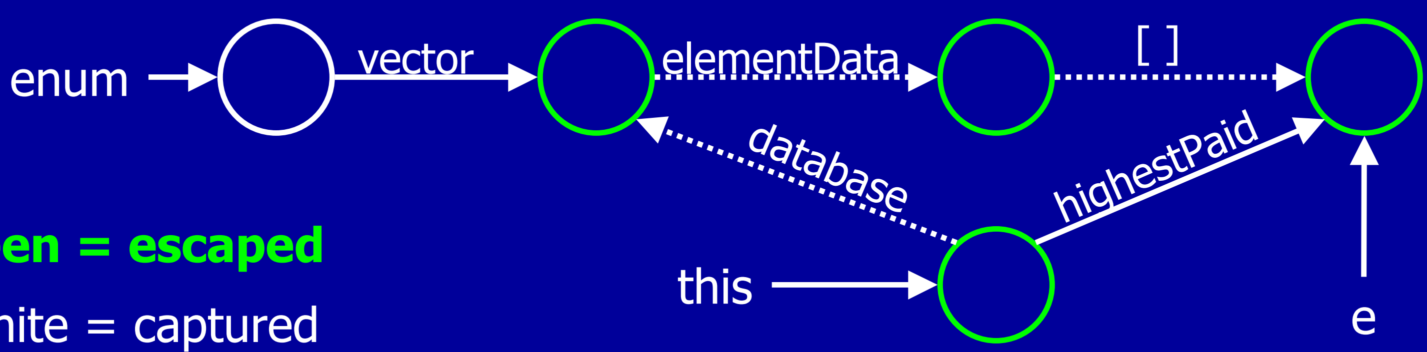
Node Types

- Inside Nodes: 
    - Represent objects created in currently analyzed part of program
- Outside Nodes: 
    - Parameter nodes – represent parameters
    - Load nodes - represent objects accessed via pointers created outside analyzed part



Escaped Nodes

- Escaped nodes
  - parameter nodes
  - thread nodes
  - returned nodes
  - *nodes reachable from other escaped nodes*
- Captured is the opposite of escaped

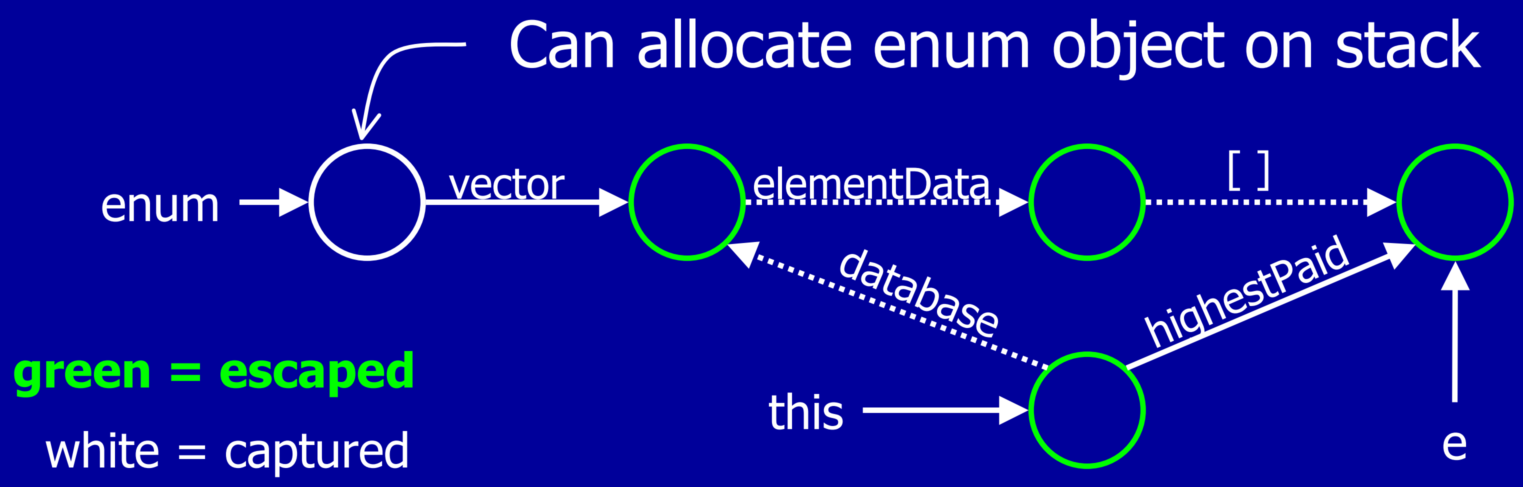


green = escaped

white = captured

Stack Allocation Optimization

- Examine graph from end of method
- If a node is captured in this graph
- Allocate corresponding objects on stack (may need to inline methods to apply optimization)



Interprocedural Analysis

```
void printStatistics(BufferedReader r) {
  EmployeeDatabase e = new EmployeeDatabase(r);



   e.computeMax();

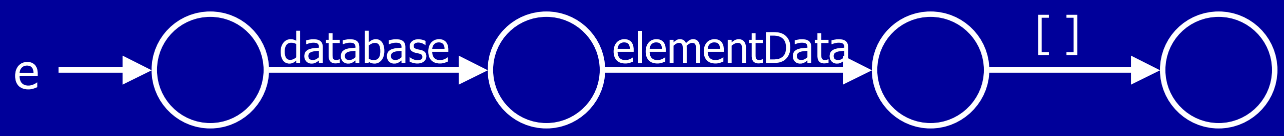



  System.out.println("max salary = " + e.highestPaid);
}
```

Start with graph before call site

```
void printStatistics(BufferedReader r) {
  EmployeeDatabase e = new EmployeeDatabase(r);
```

graph before
call site



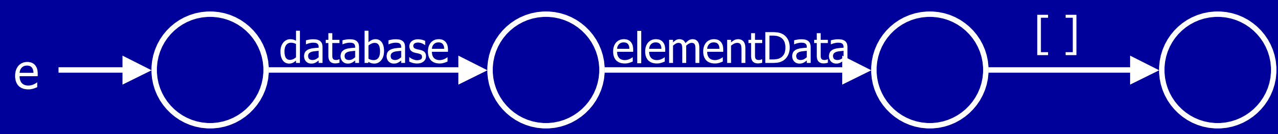

```
  e.computeMax();

  System.out.println("max salary = " + e.highestPaid);
}
```

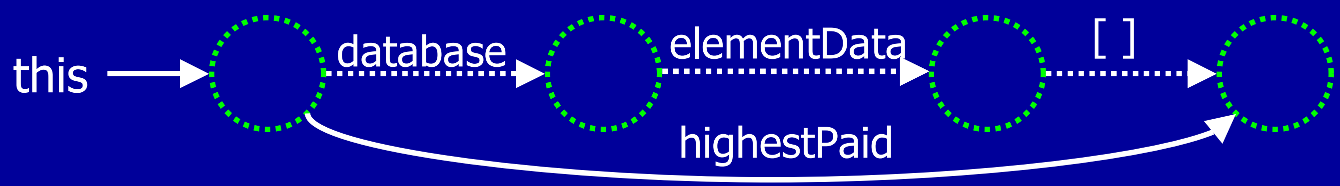
Retrieve graph from end of callee

```
void printStatistics(BufferedReader r) {
  EmployeeDatabase e = new EmployeeDatabase(r);
```

graph before call site



`e.computeMax();`

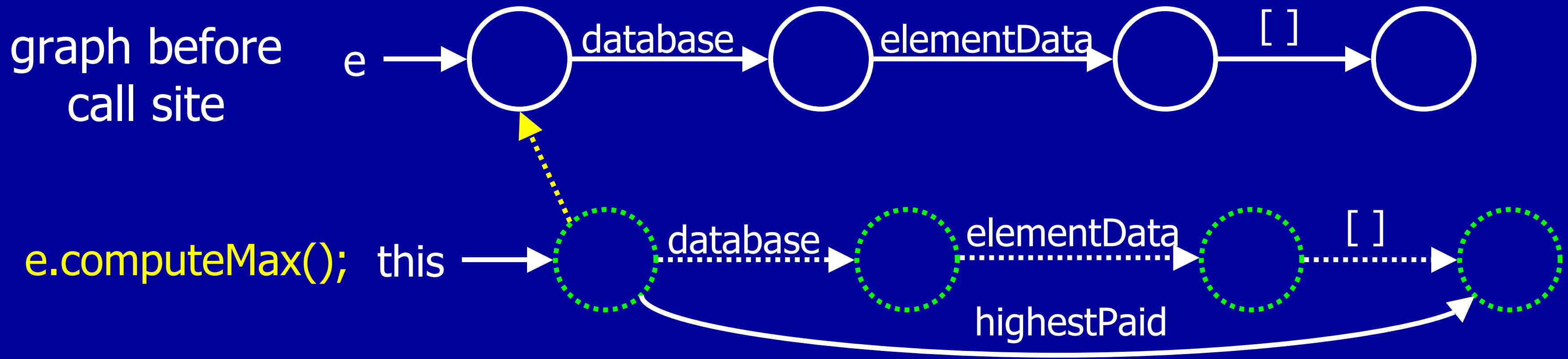


Enum object is not present because it was captured in the callee

```
  System.out.println("max salary = " + e.highestPaid);
}
```

Map formals to actuals

```
void printStatistics(BufferedReader r) {
  EmployeeDatabase e = new EmployeeDatabase(r);
```

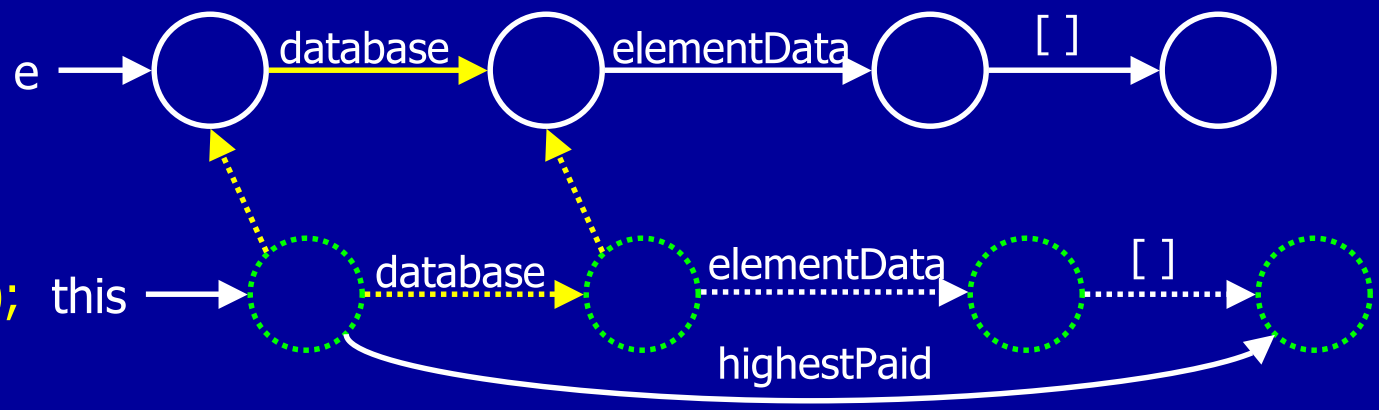



```
  System.out.println("max salary = " + e.highestPaid);
}
```

Match corresponding inside and outside edges to complete mapping

```
void printStatistics(BufferedReader r) {
  EmployeeDatabase e = new EmployeeDatabase(r);
```

graph before call site



e.computeMax();

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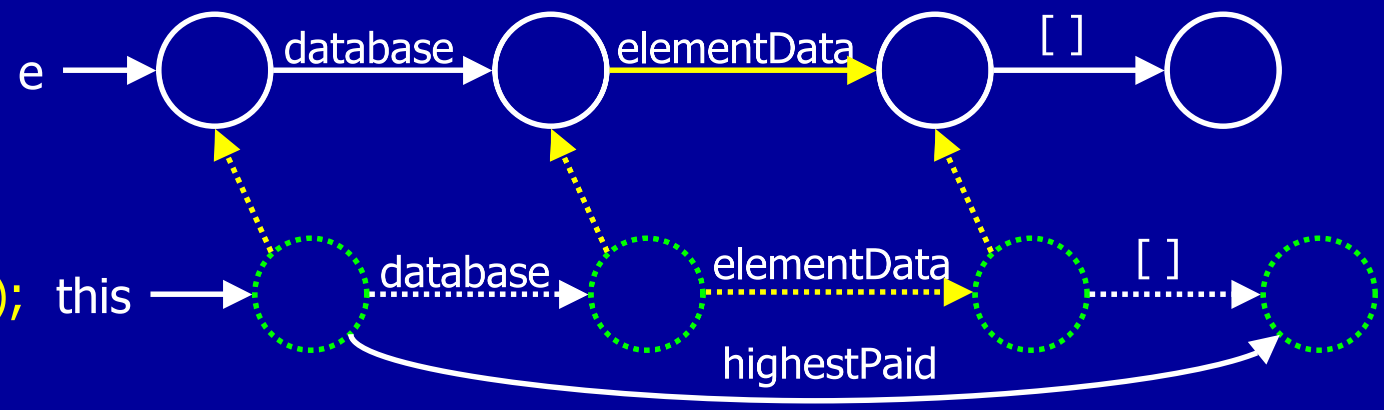

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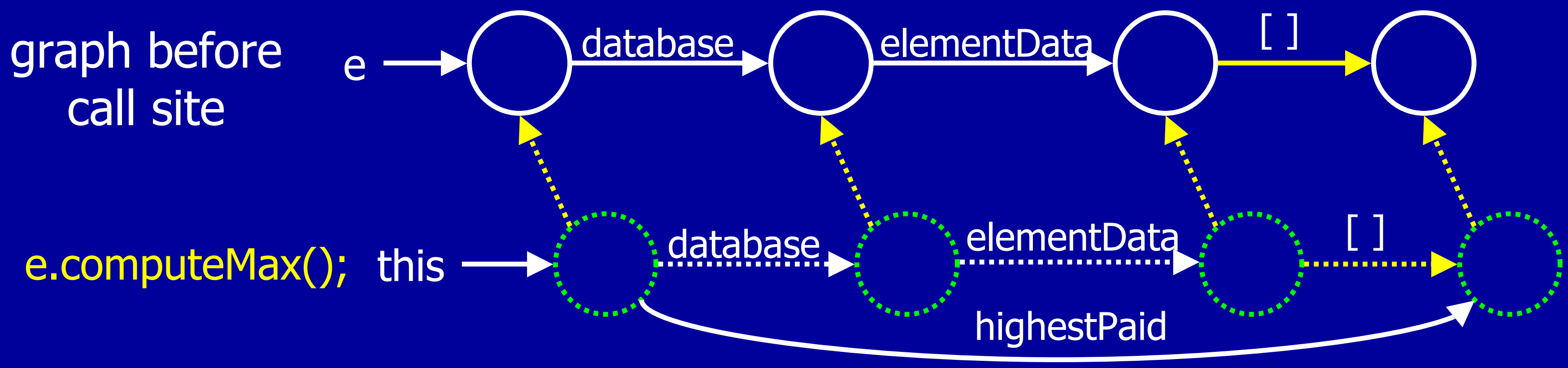


```
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}
```

Match corresponding inside and outside edges to complete mapping

```
void printStatistics(BufferedReader r) {
  EmployeeDatabase e = new EmployeeDatabase(r);
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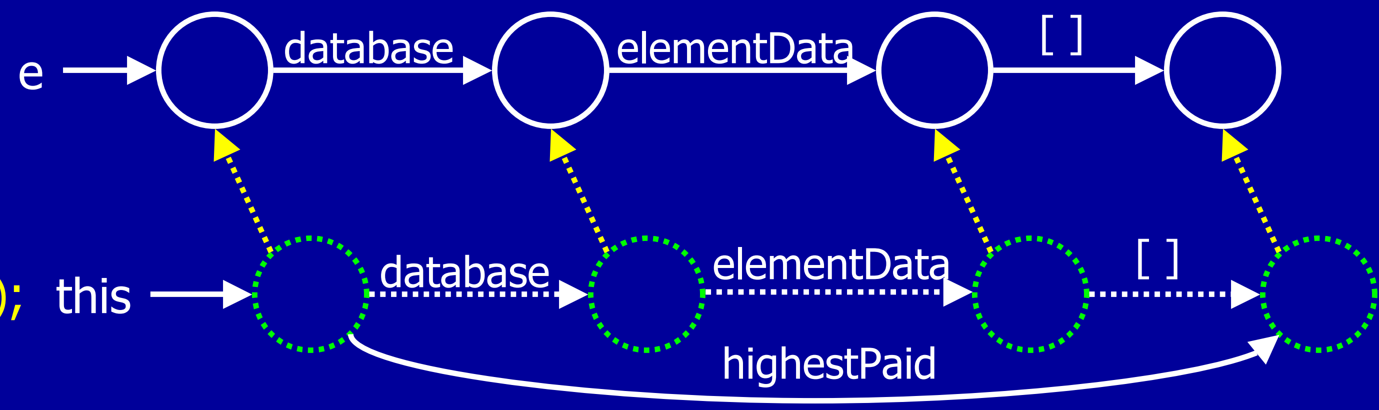
graph before call site

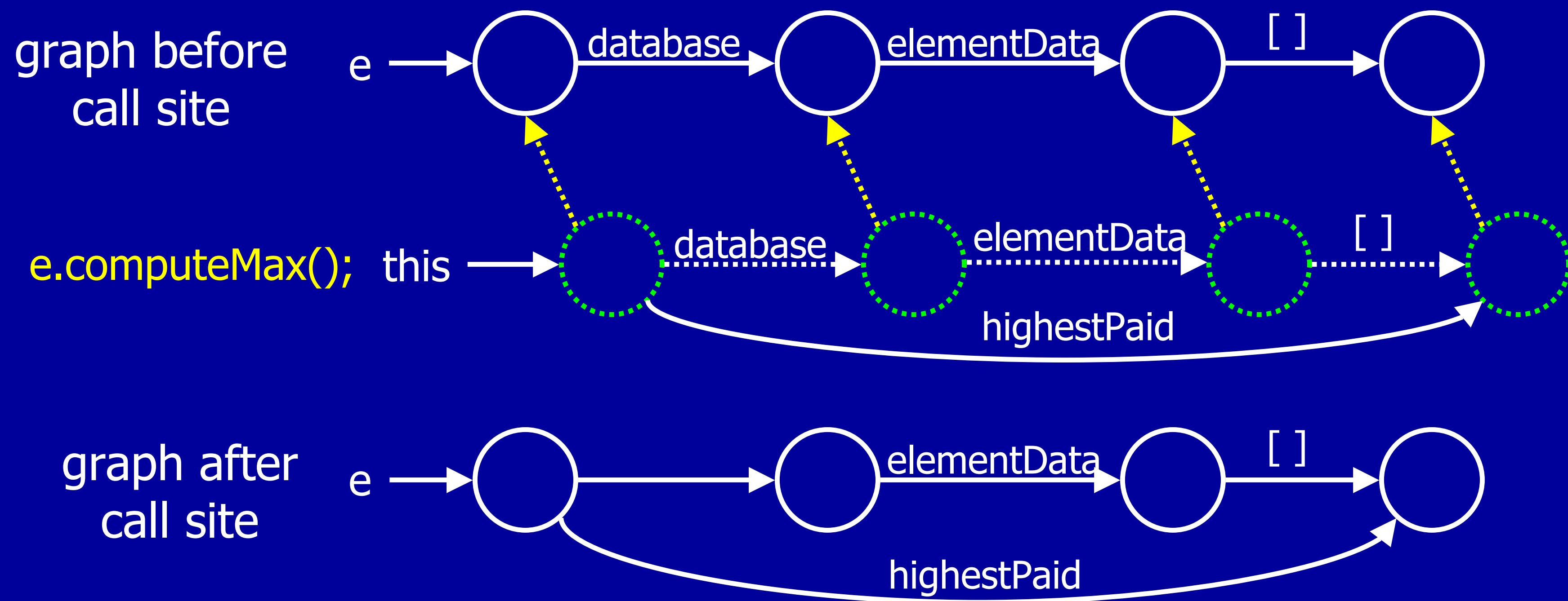
e.computeMax();




```
  System.out.println("max salary = " + e.highestPaid);
}
```

Combine graphs to obtain new graph after call site

```
void printStatistics(BufferedReader r) {
  EmployeeDatabase e = new EmployeeDatabase(r);
```

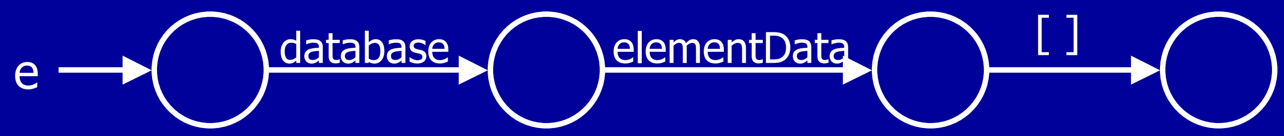



```
  System.out.println("max salary = " + e.highestPaid);
}
```

Continue analysis after call site

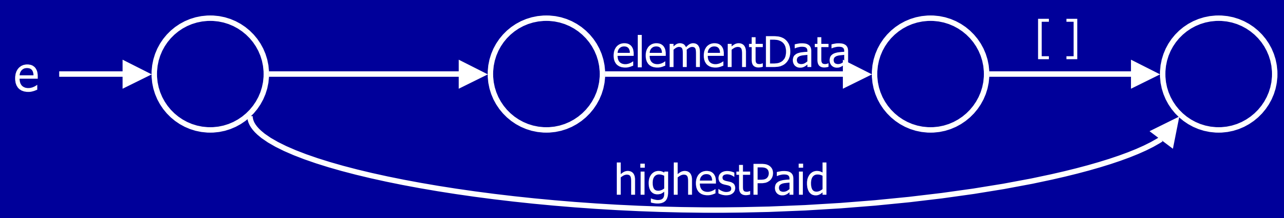
```
void printStatistics(BufferedReader r) {
  EmployeeDatabase e = new EmployeeDatabase(r);
```

graph before call site



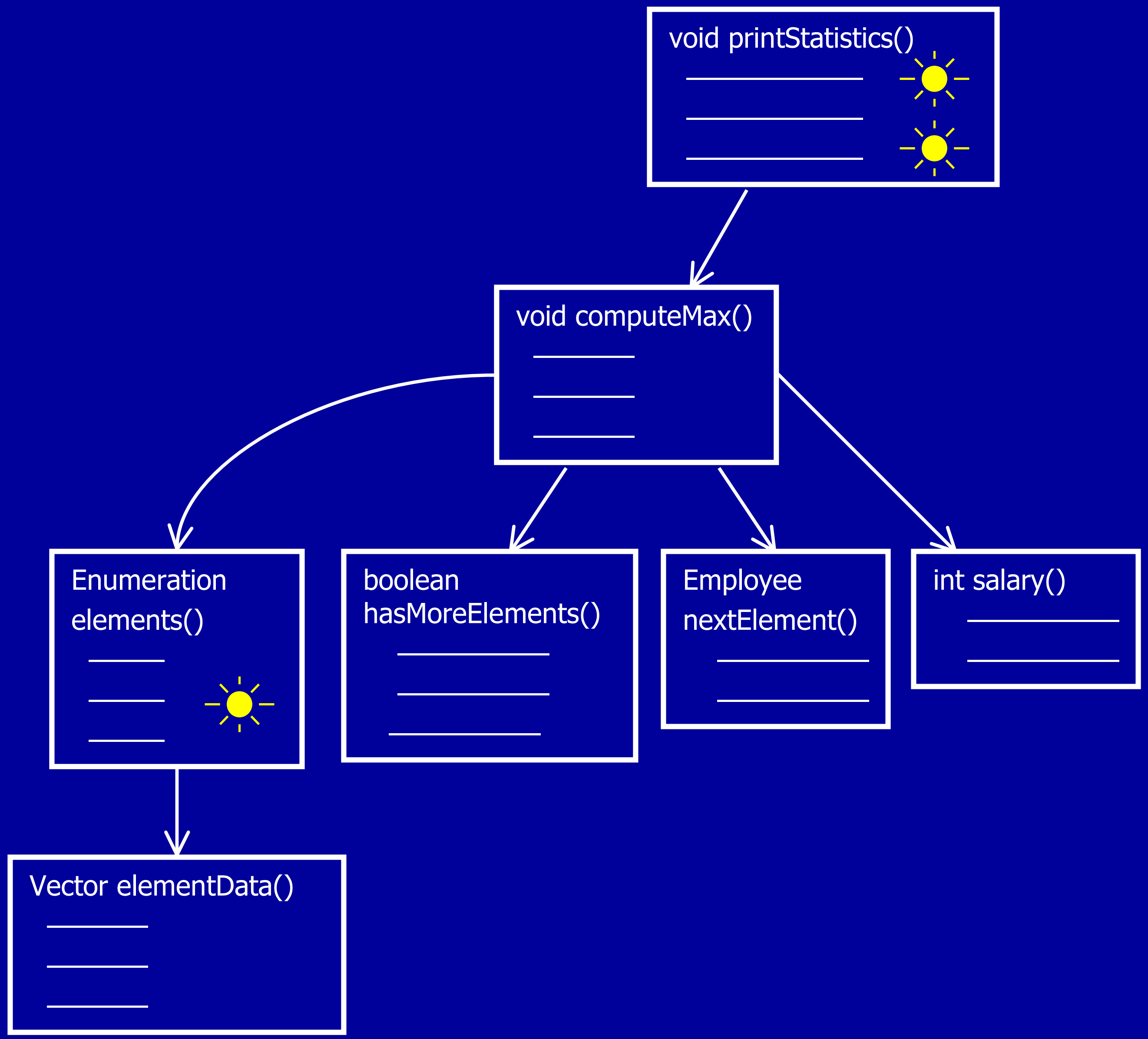

```
  e.computeMax();
```

graph after call site




```
  System.out.println("max salary = " + e.highestPaid);
}
```

Whole Program Analysis



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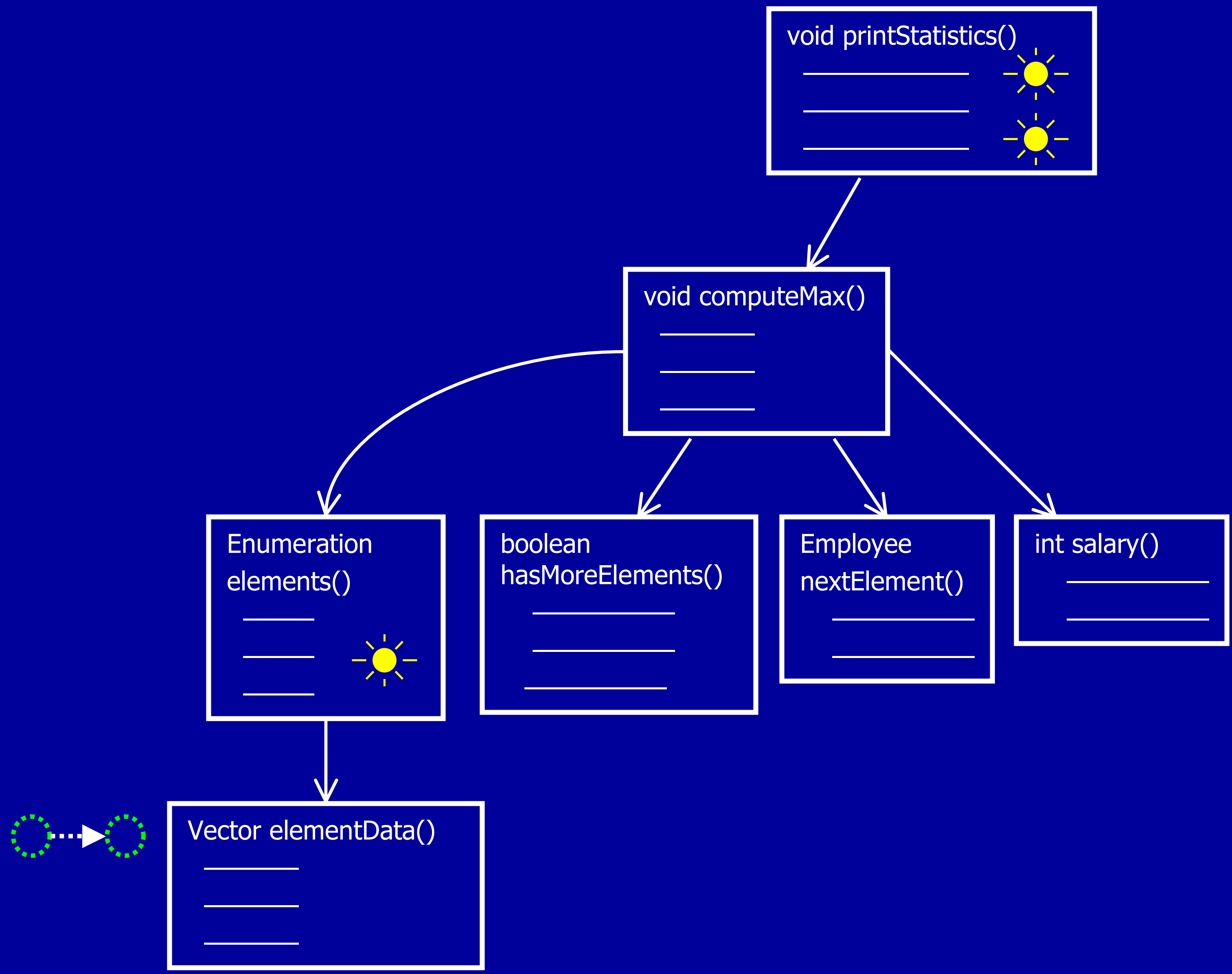

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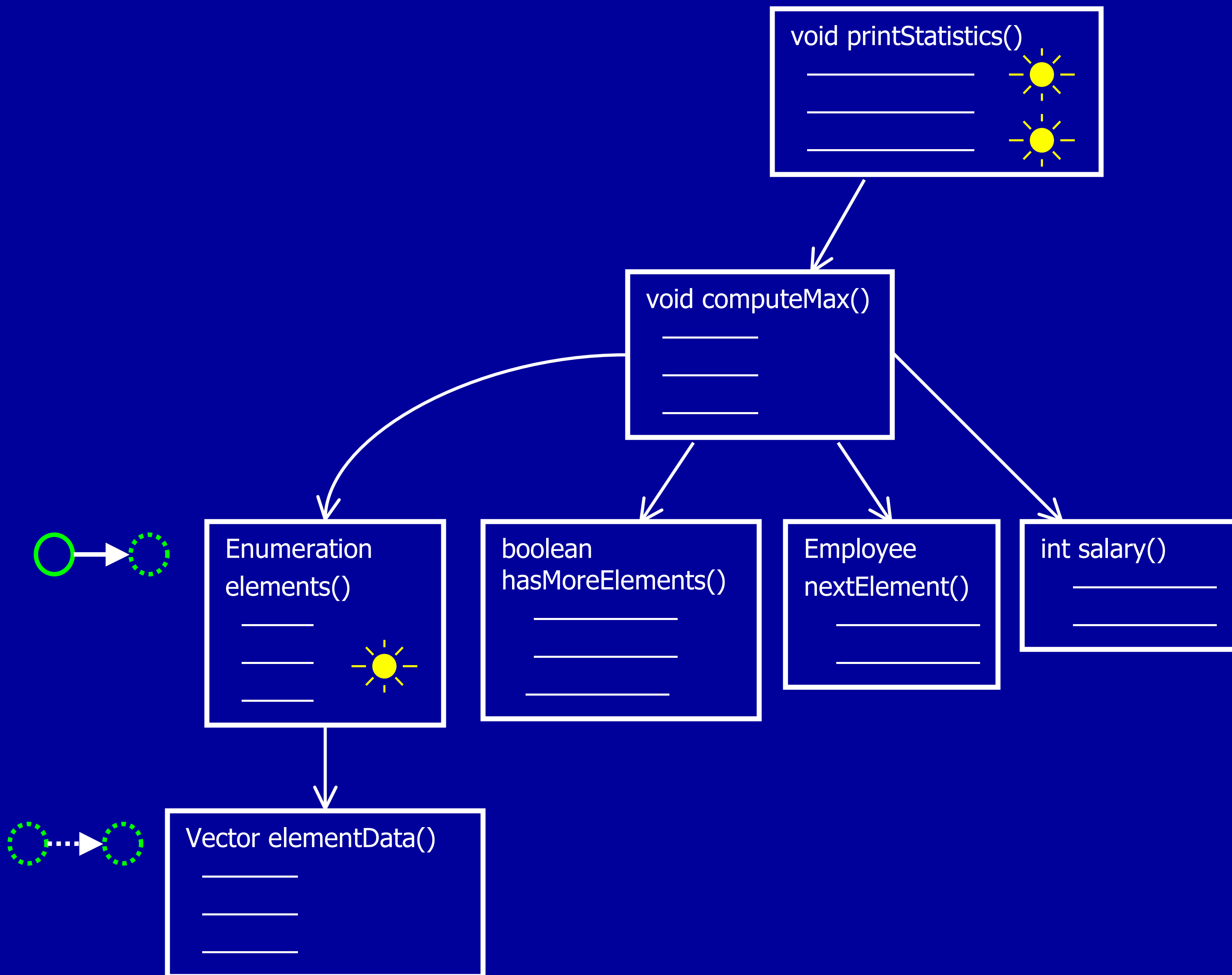

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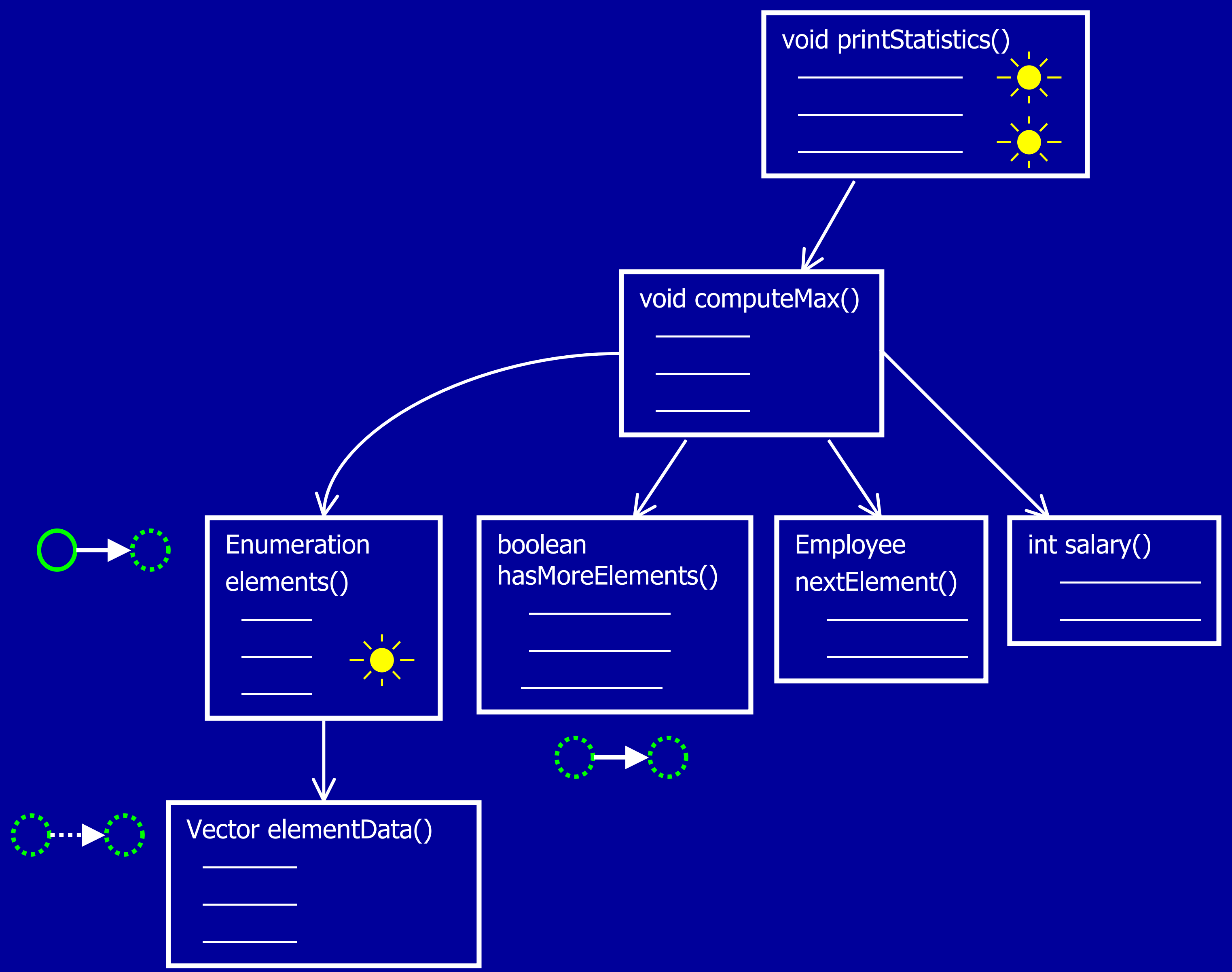

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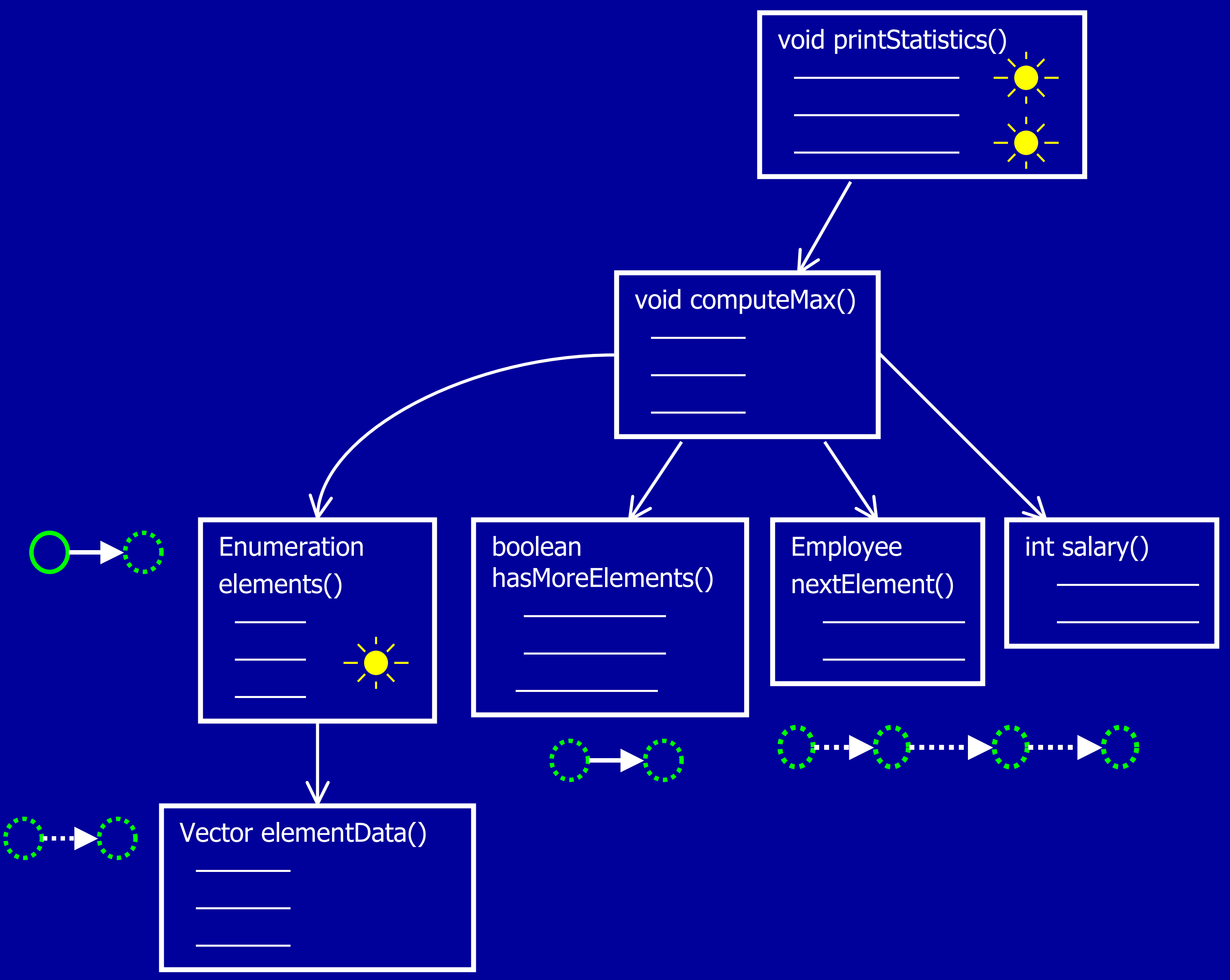

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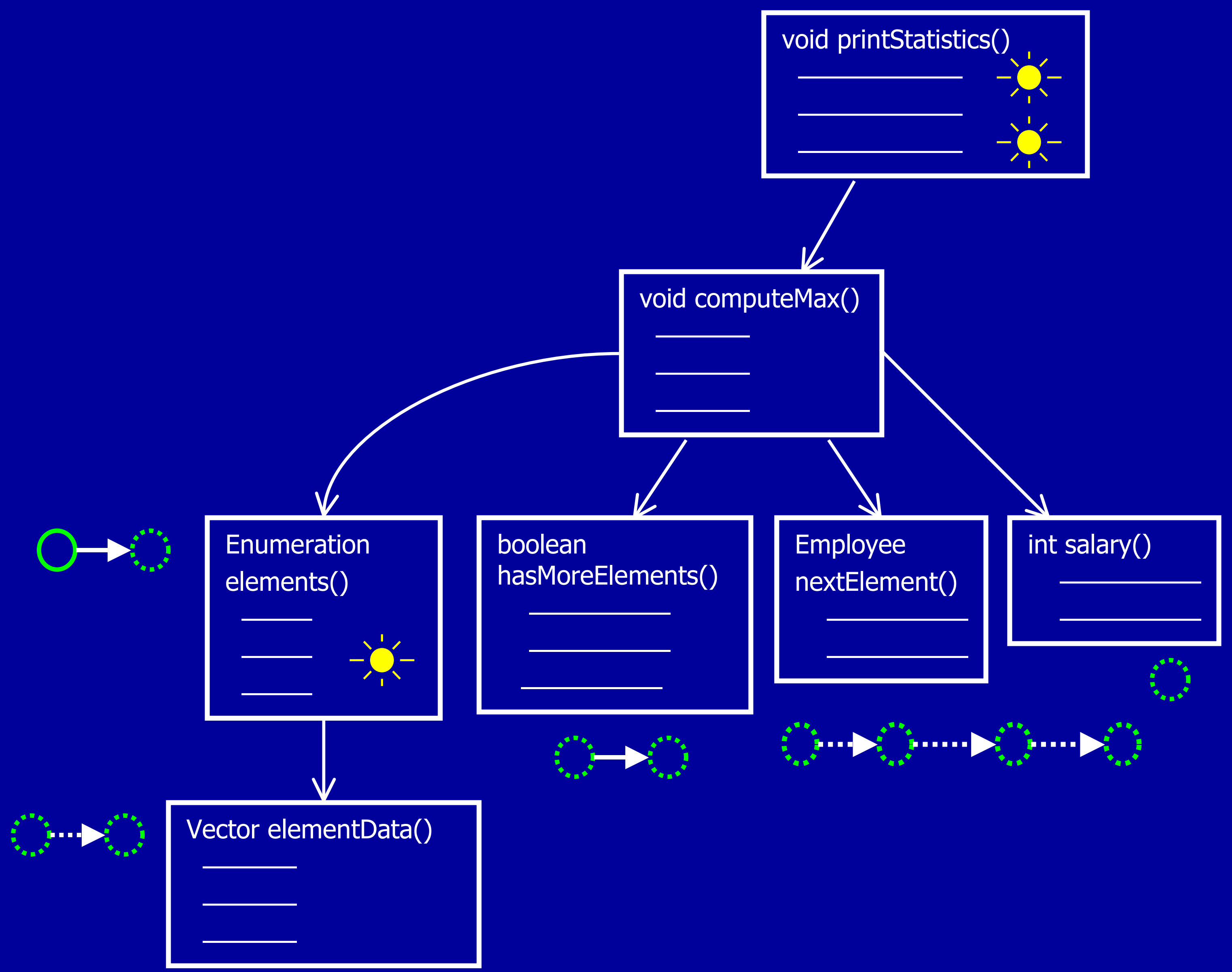

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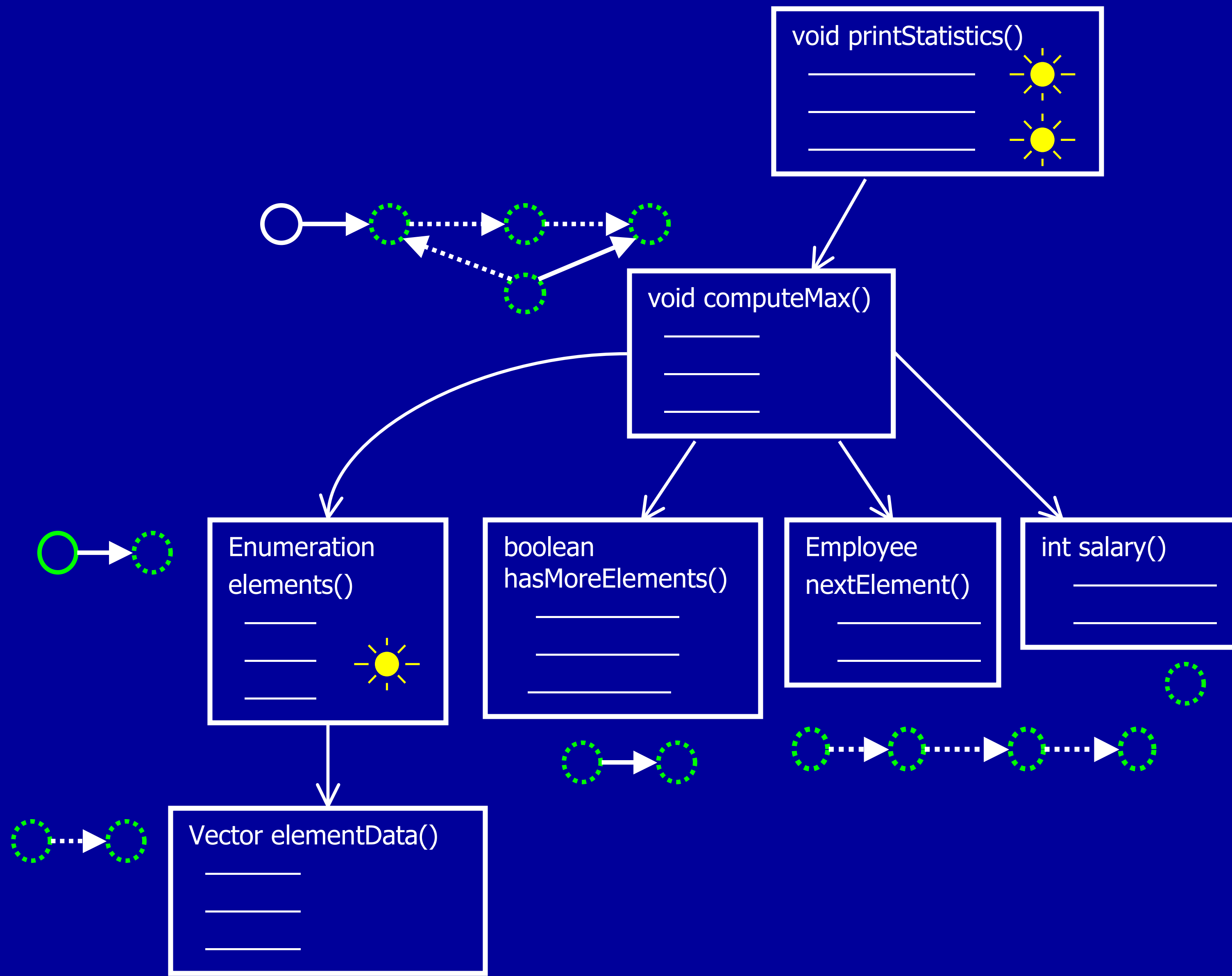

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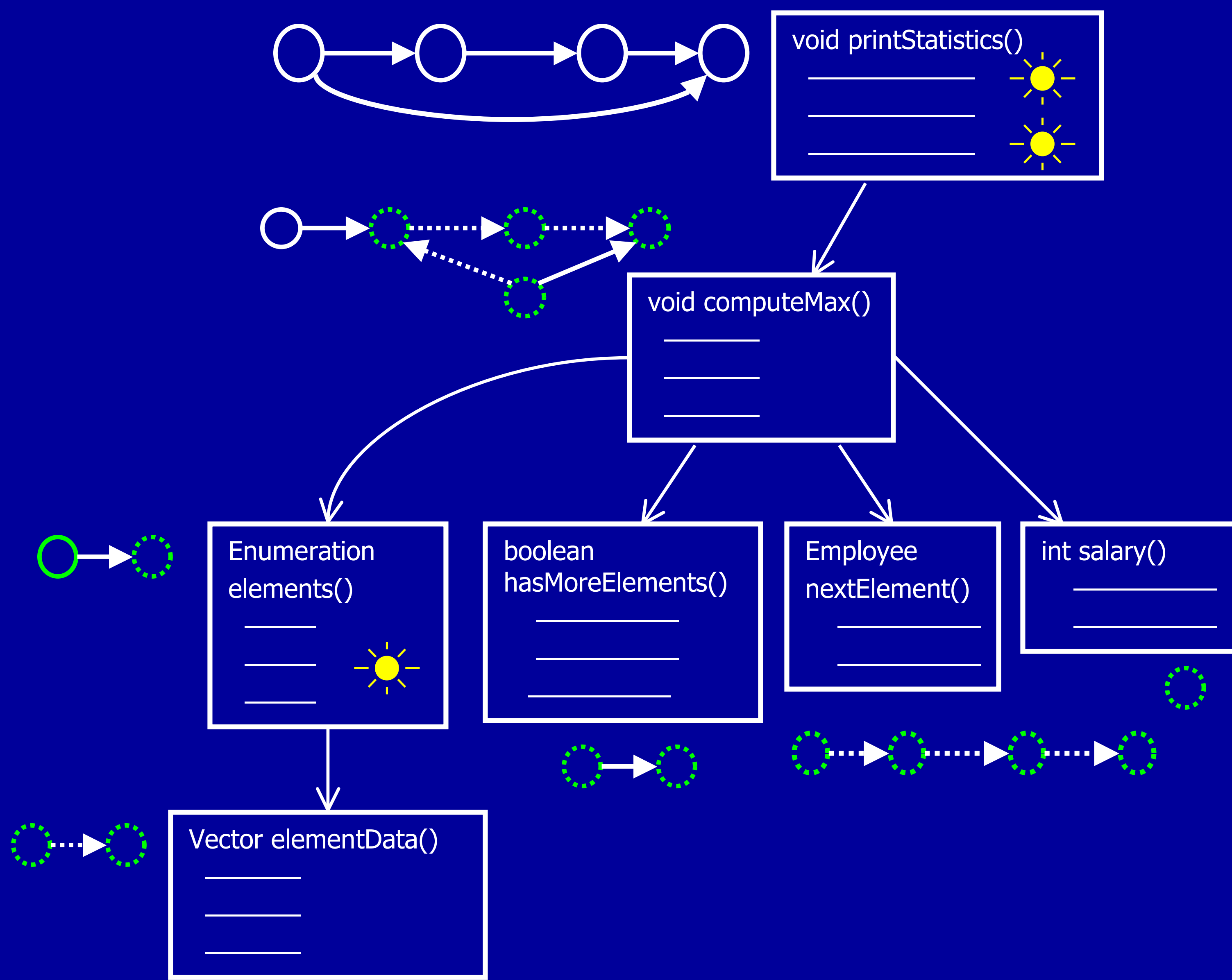


Incrementalized Analysis

Incrementalized Analysis Requirements

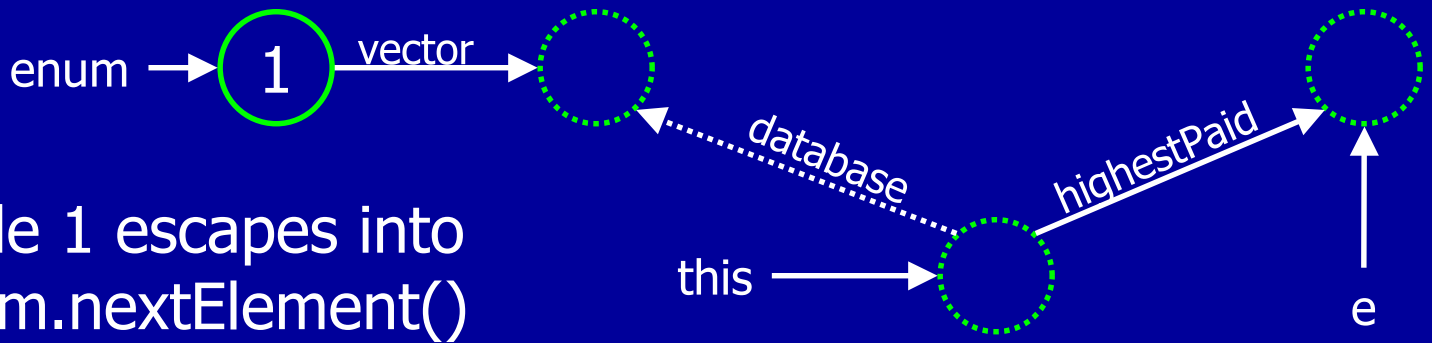
Must be able to

- Analyze method independently of callers
  - Base analysis is compositional
  - Already does this
- Skip analysis of invoked methods
- But later incrementally integrate analysis results if desirable to do so

First Extension to Base Analysis

- Skip the analysis of invoked methods
- Parameters are marked as escaping into skipped call site

Assume analysis skips enum.nextElement()

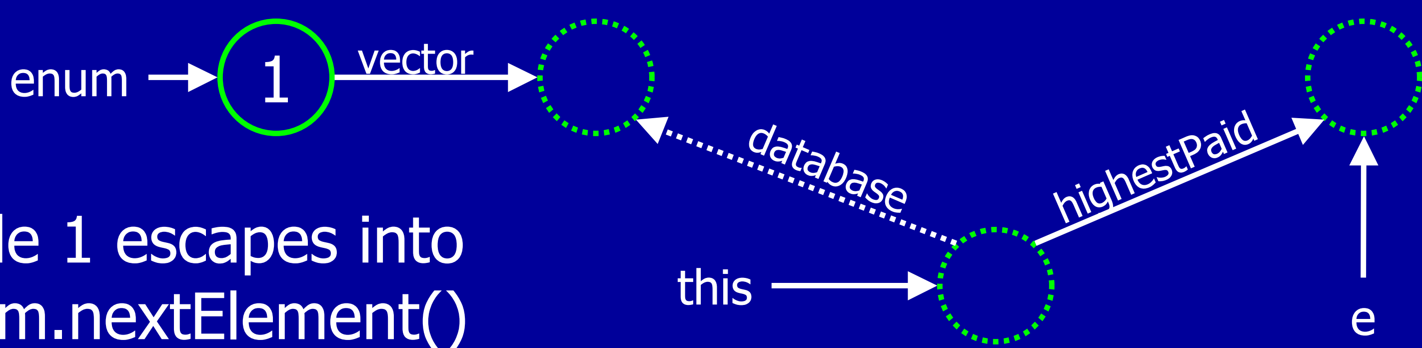


Node 1 escapes into enum.nextElement()

First Extension Almost Works

- Can skip analysis of invoked methods
- If allocation site is captured, great!
- If not, escape information tells you what methods you should have analyzed…

Should have analyzed enum.nextElement()



Node 1 escapes into enum.nextElement()

Second Extension to Base Algorithm

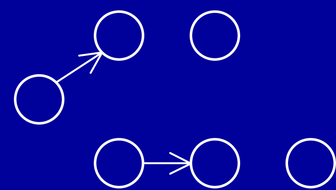
- Record enough information to undo skip and incorporate analysis into existing result
  - Parameter mapping at call site
  - Ordering information for call sites

Graphs from Whole Program Analysis

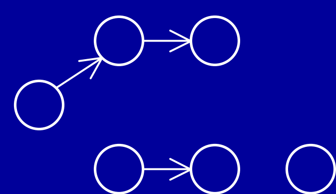
void compute() {

foo(x,y);

}

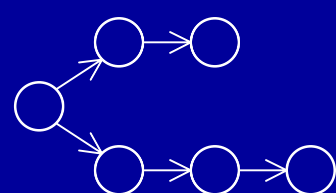


Graph before call site



Graph after call site

Generated during analysis



Graph at end of method

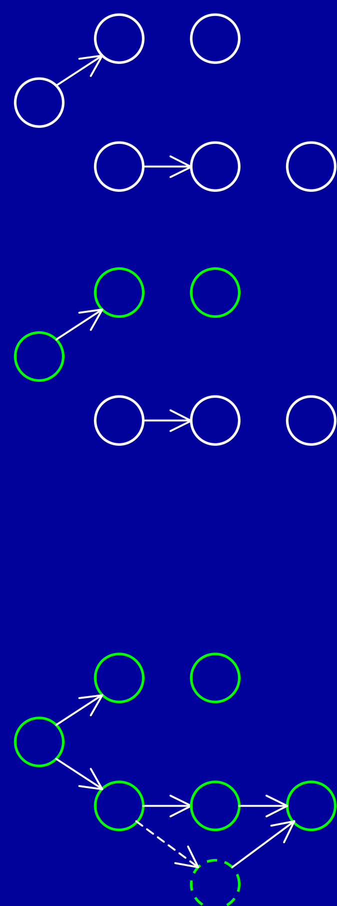
Used to apply stack allocation optimization

Graphs from Incrementalized Analysis

```
void compute() {

    foo(x,y);

}
```



Graph before call site

Graph after skipped call site

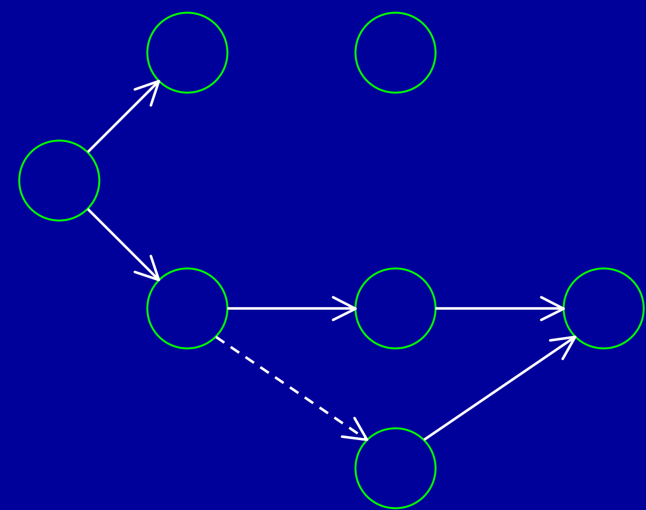
Generated during analysis

Graph at end of method

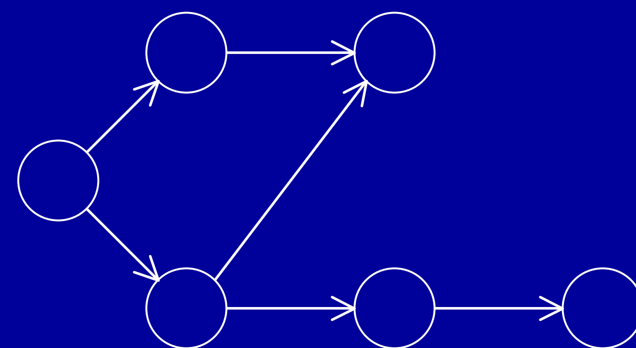
Used to apply stack allocation optimization

Incorporating Result from Skipped Call Site

Naive approach: use mapping algorithm directly on graph from end of caller method



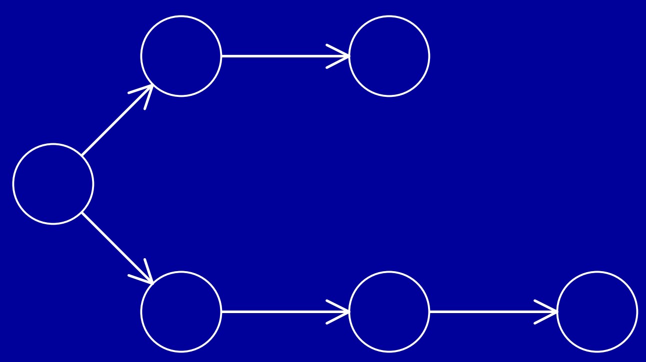
Before incorporating result from skipped call site



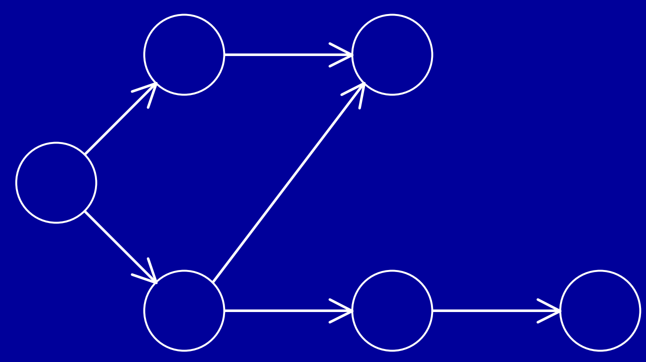
After incorporating result from skipped call site

Incorporating Result from Skipped Call Site

Naive approach: use mapping algorithm directly on graph from end of caller method



Graph from whole program analysis

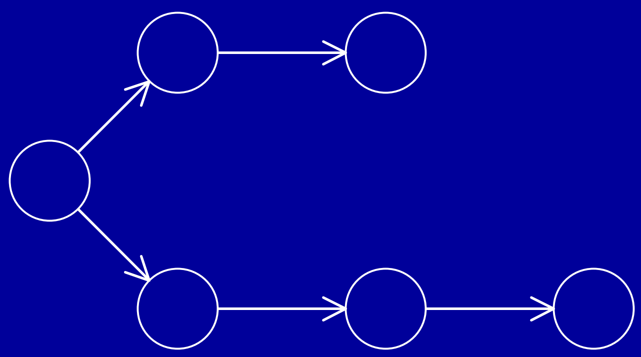


After incorporating result from skipped call site

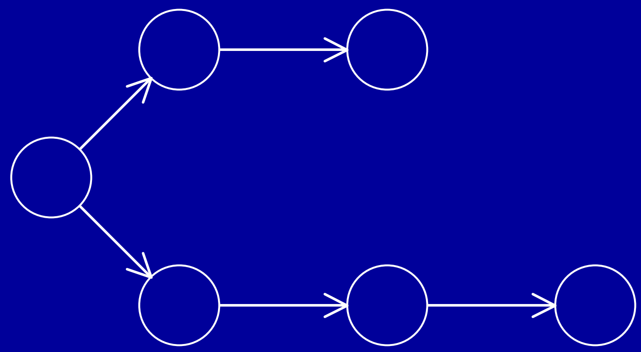
Basic Problem and Solution

- Problem: additional edges in graph from end of method make result less precise
- Solution: augment abstraction
  - For each call skipped call site, record
    - Edges which were present in the graph before the call site
    - Edges which were present after call site
  - Use this information when incorporating results from skipped call sites

After Augmenting Abstraction

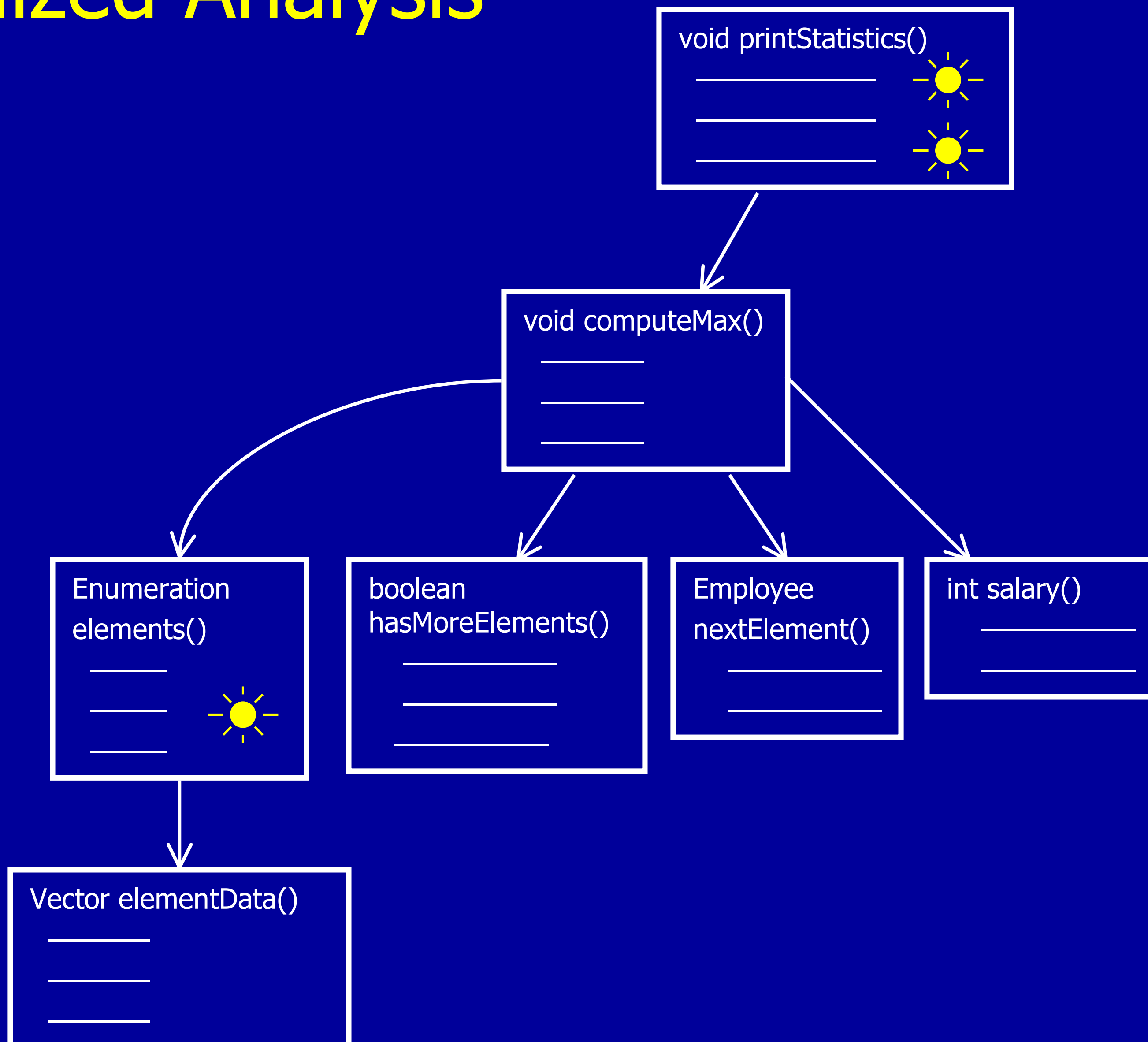


Graph from whole program analysis



After incorporating result from skipped call site

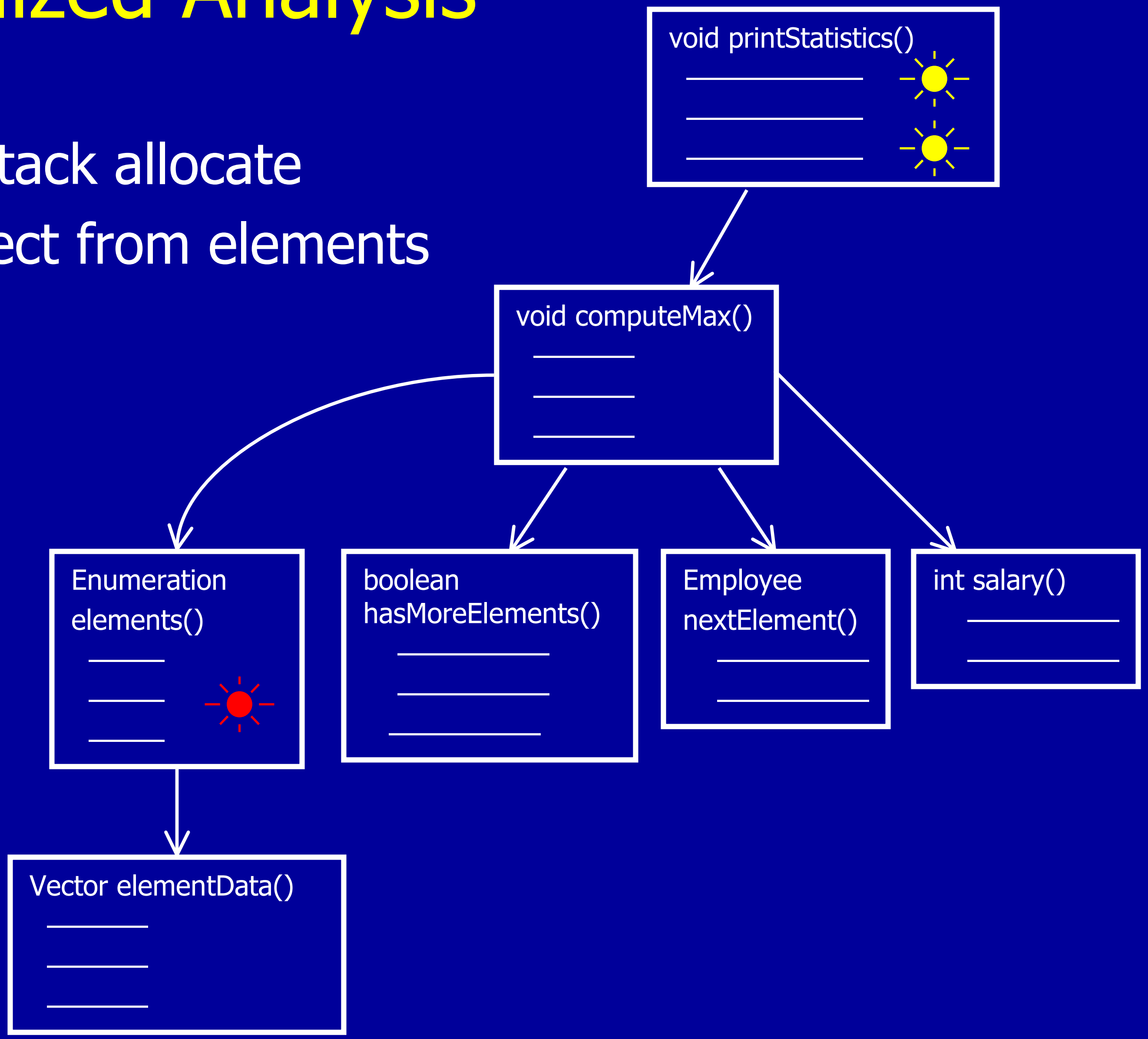
Incrementalized Analysis



Incrementalized Analysis

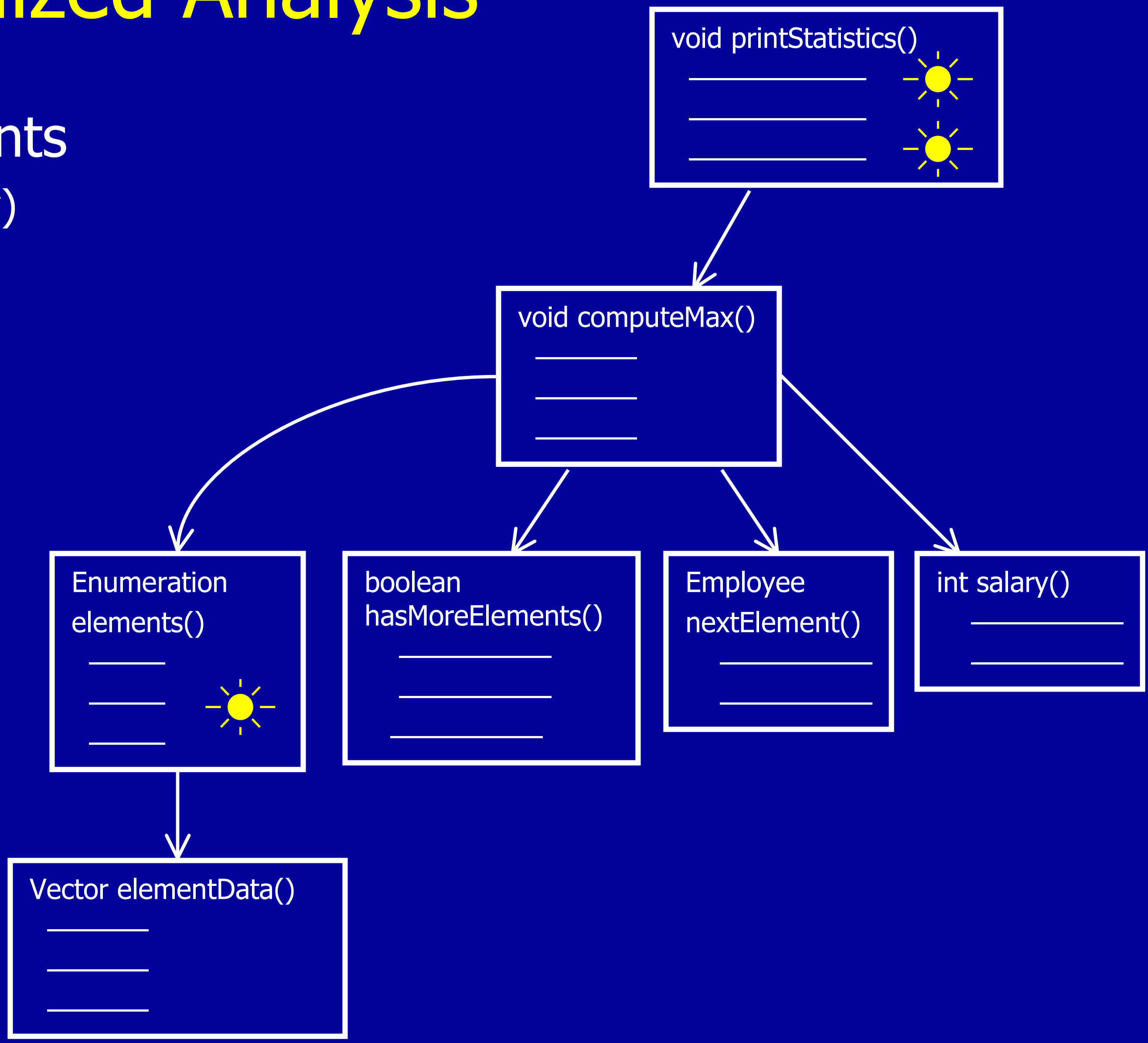
Attempt to stack allocate

Enumeration object from elements



Incrementalized Analysis

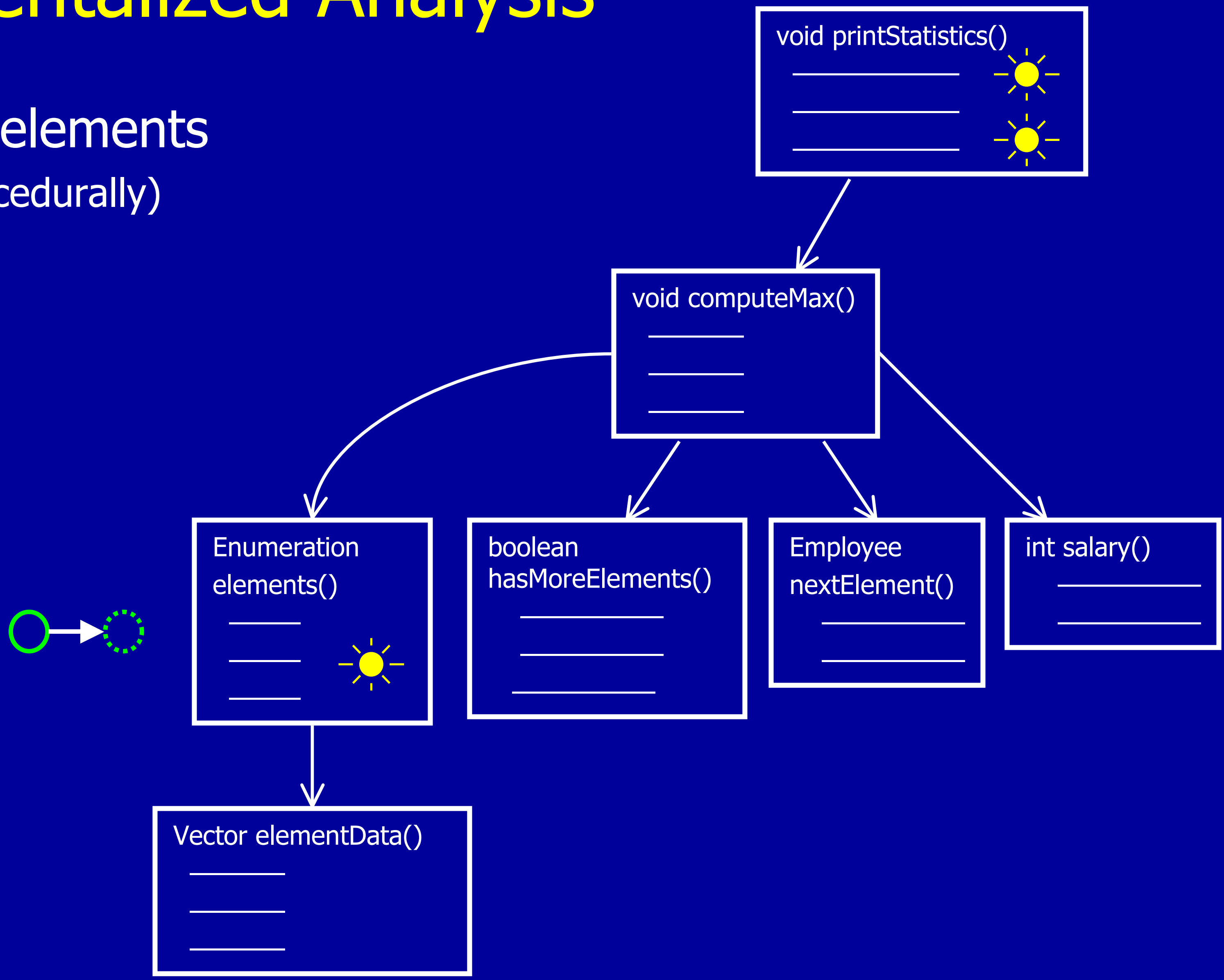
Analyze elements
(intraprocedurally)



Incrementalized Analysis

Analyze elements

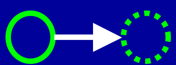
(intraprocedurally)

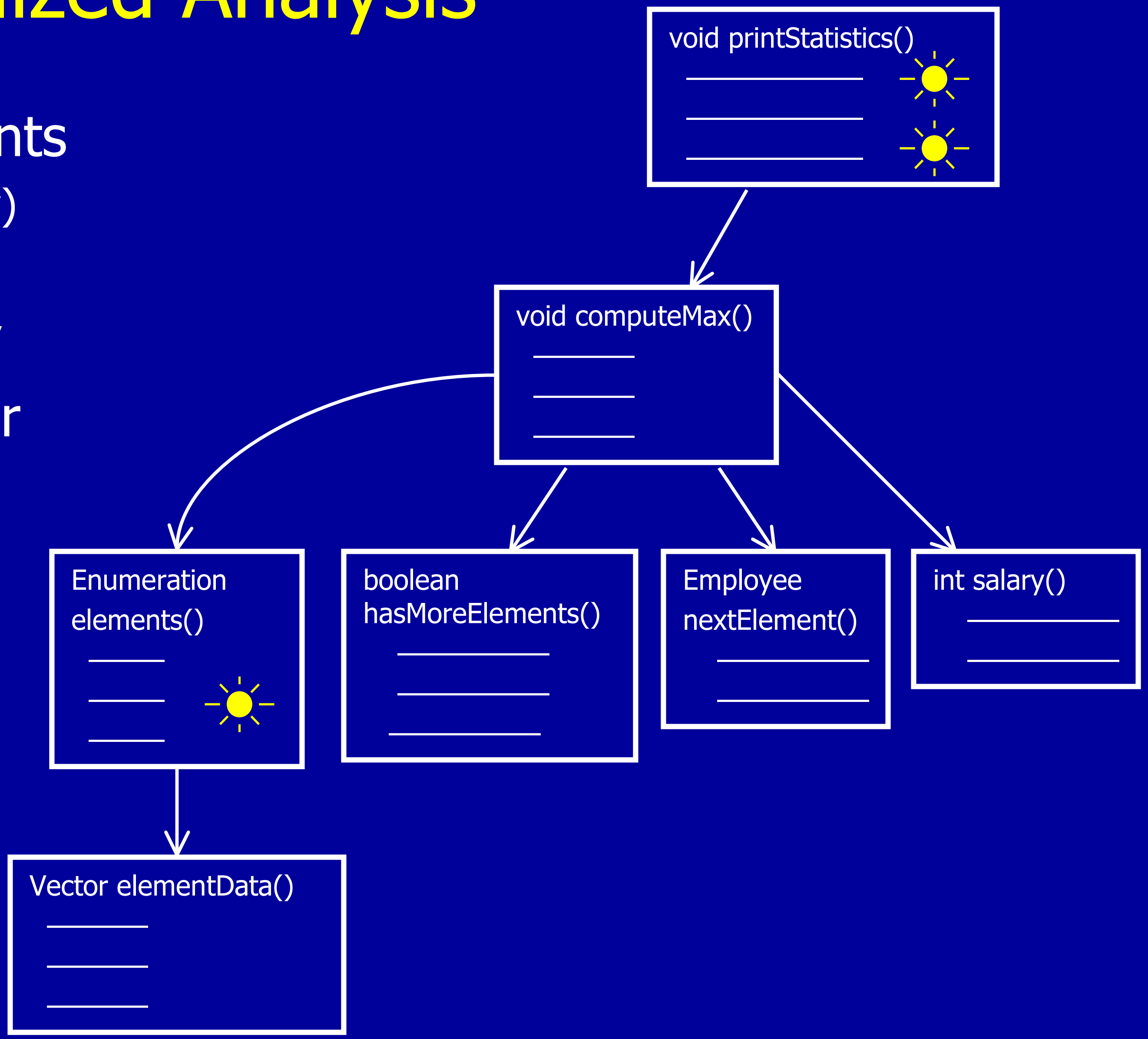


Incrementalized Analysis

Analyze elements
(intraprocedurally)

Escapes only
into the caller

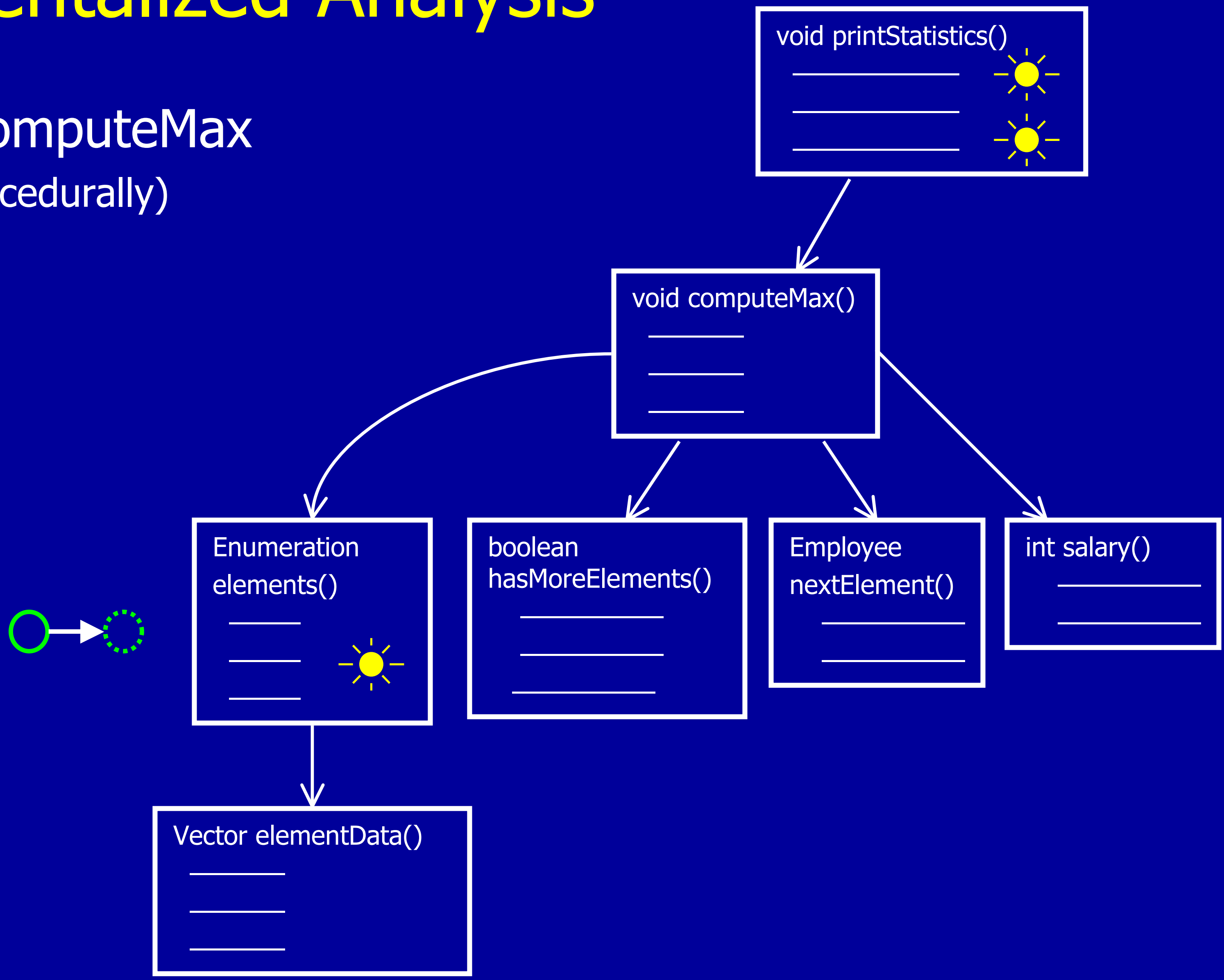




Incrementalized Analysis

Analyze computeMax

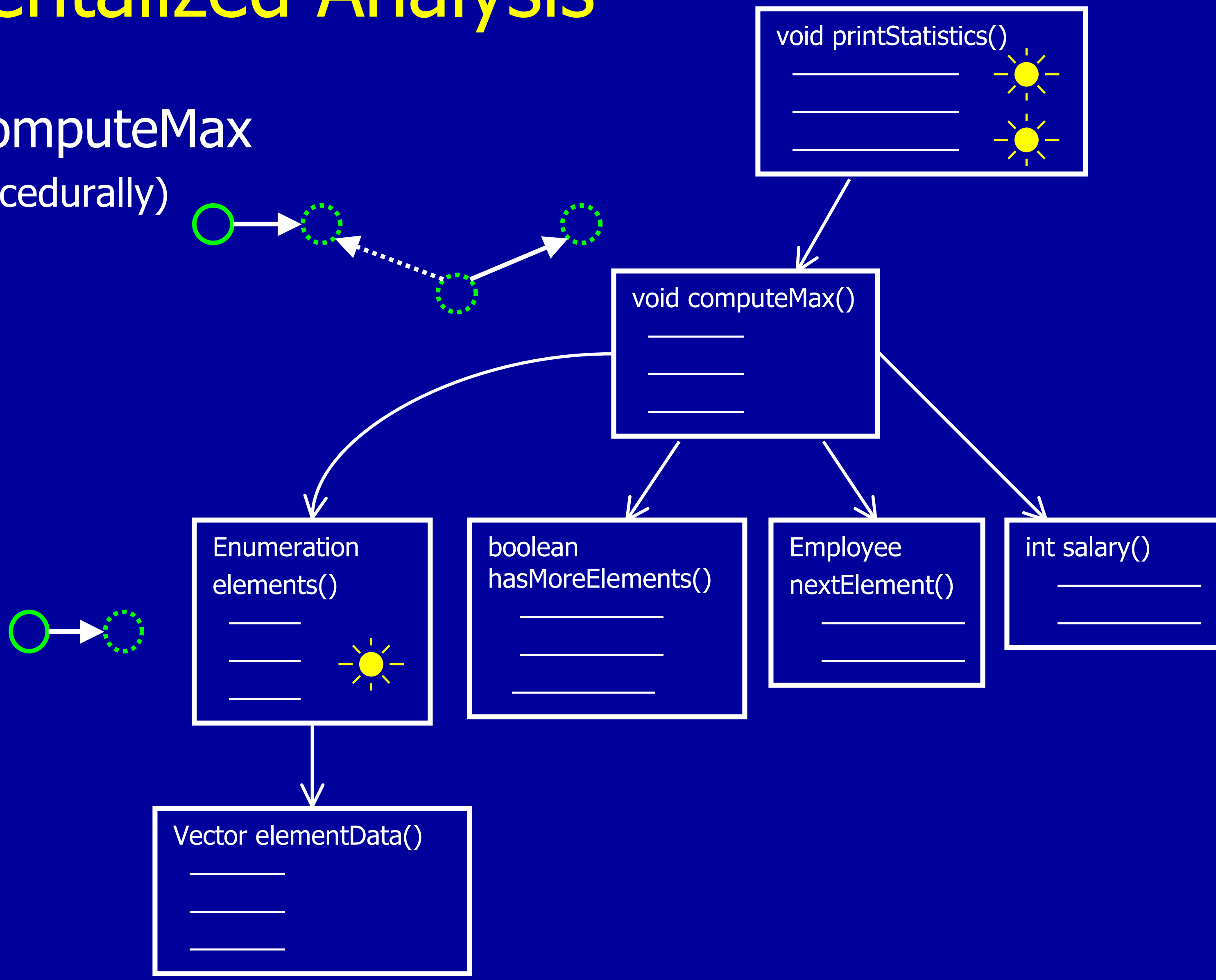
(intraprocedurally)



Incrementalized Analysis

Analyze computeMax

(intraprocedurally)



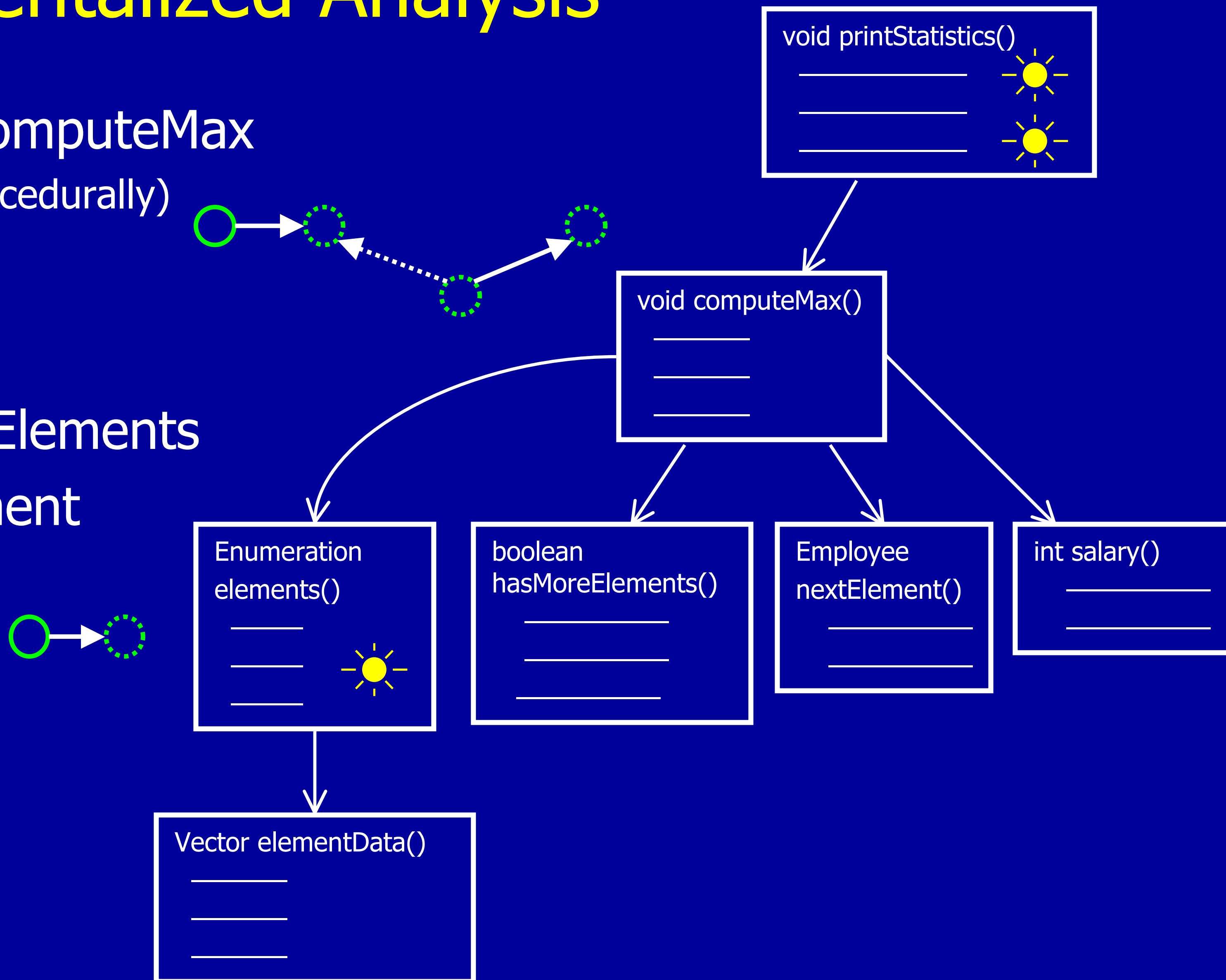
Incrementalized Analysis

Analyze computeMax

(intraprocedurally)

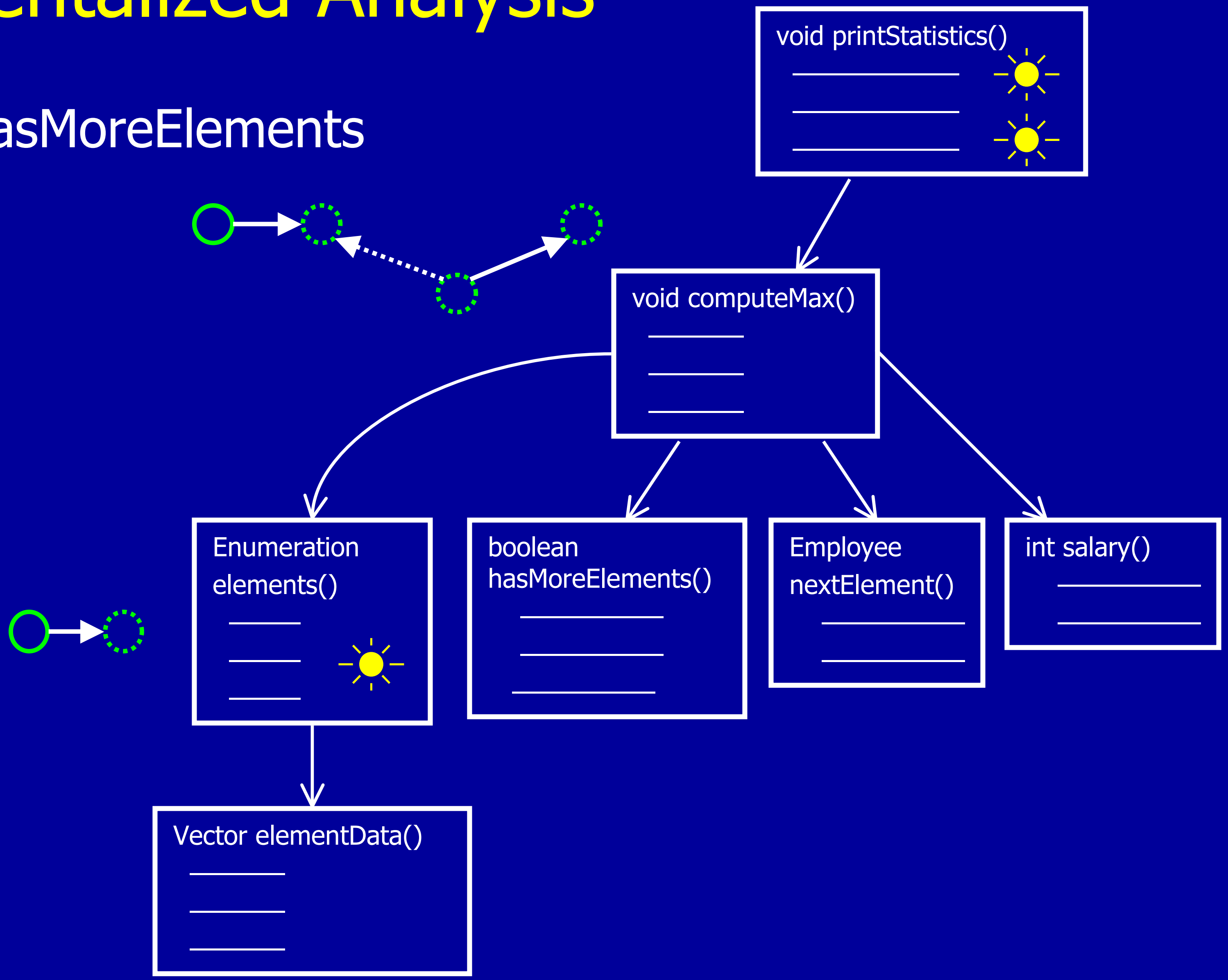
Escapes to

- hasMoreElements
- nextElement



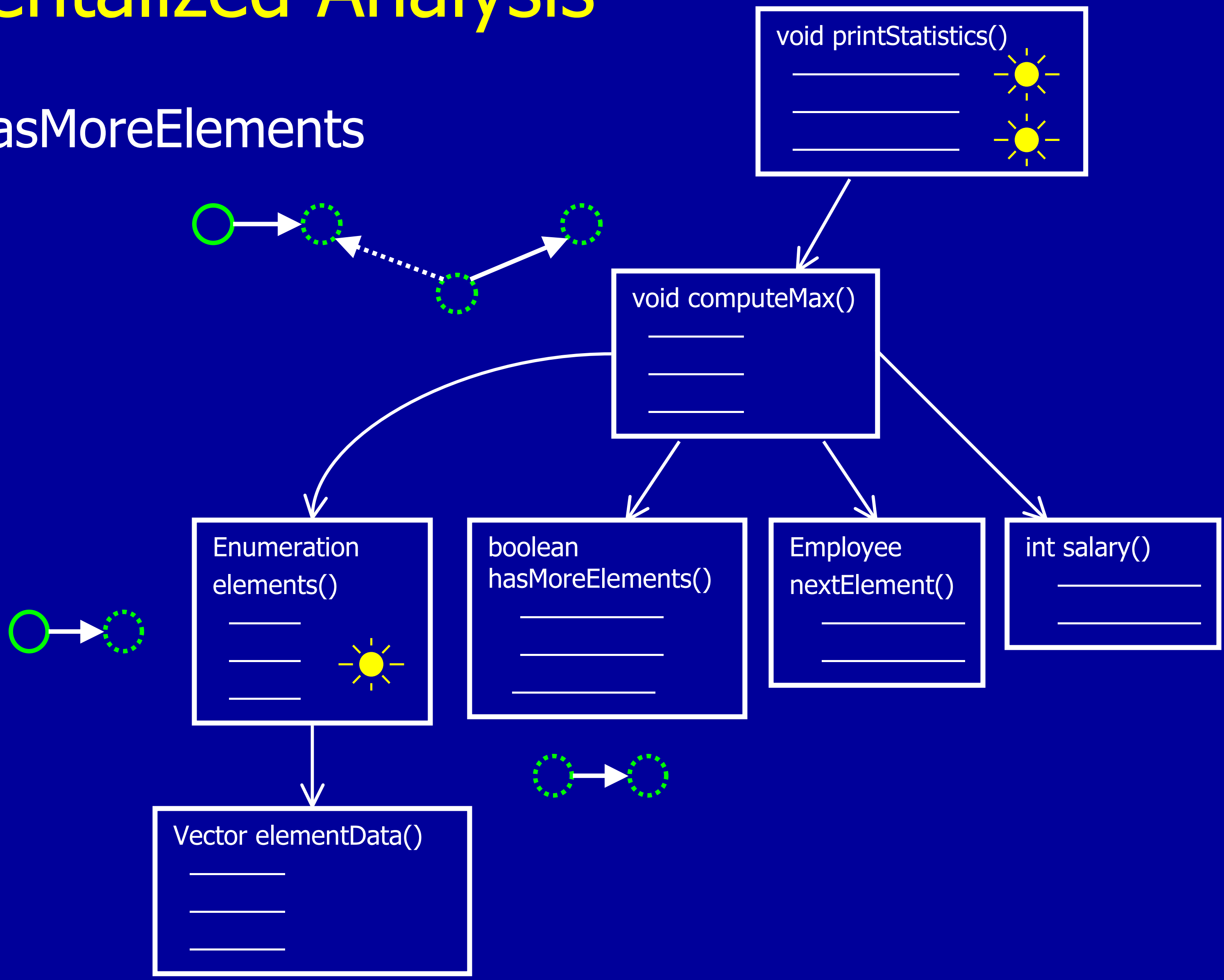
Incrementalized Analysis

Analyze hasMoreElements



Incrementalized Analysis

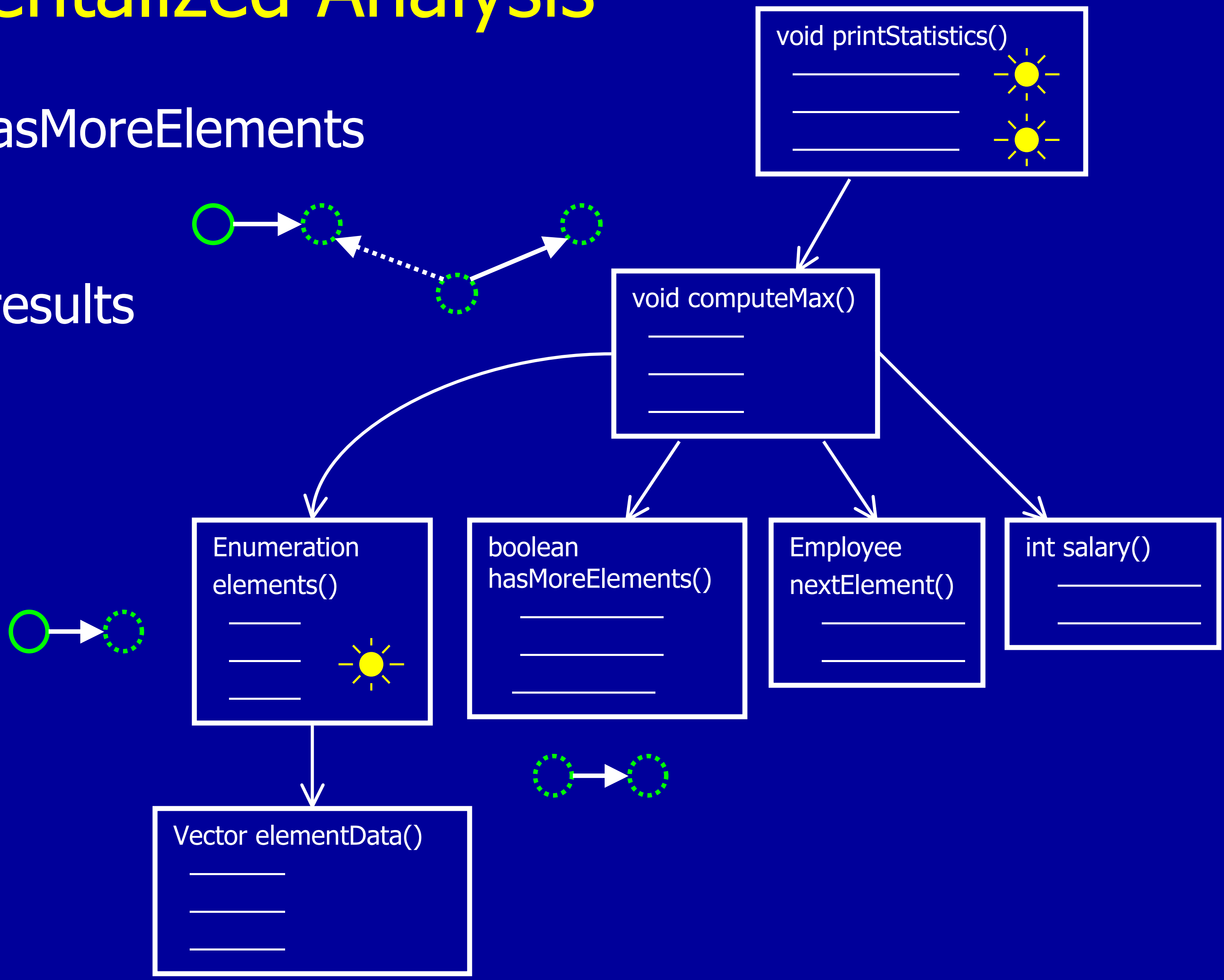
Analyze hasMoreElements



Incrementalized Analysis

Analyze hasMoreElements

Combine results



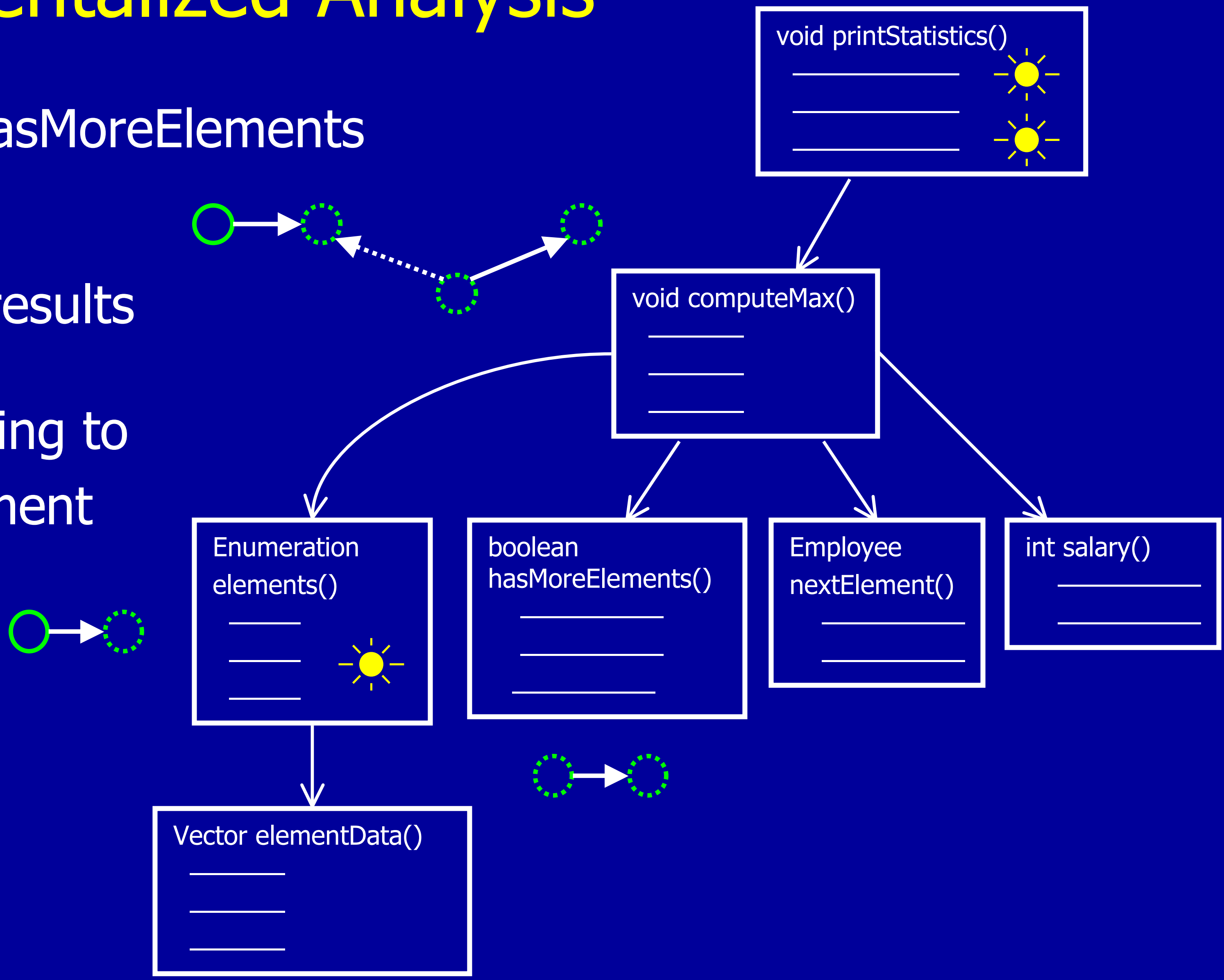
Incrementalized Analysis

Analyze hasMoreElements

Combine results

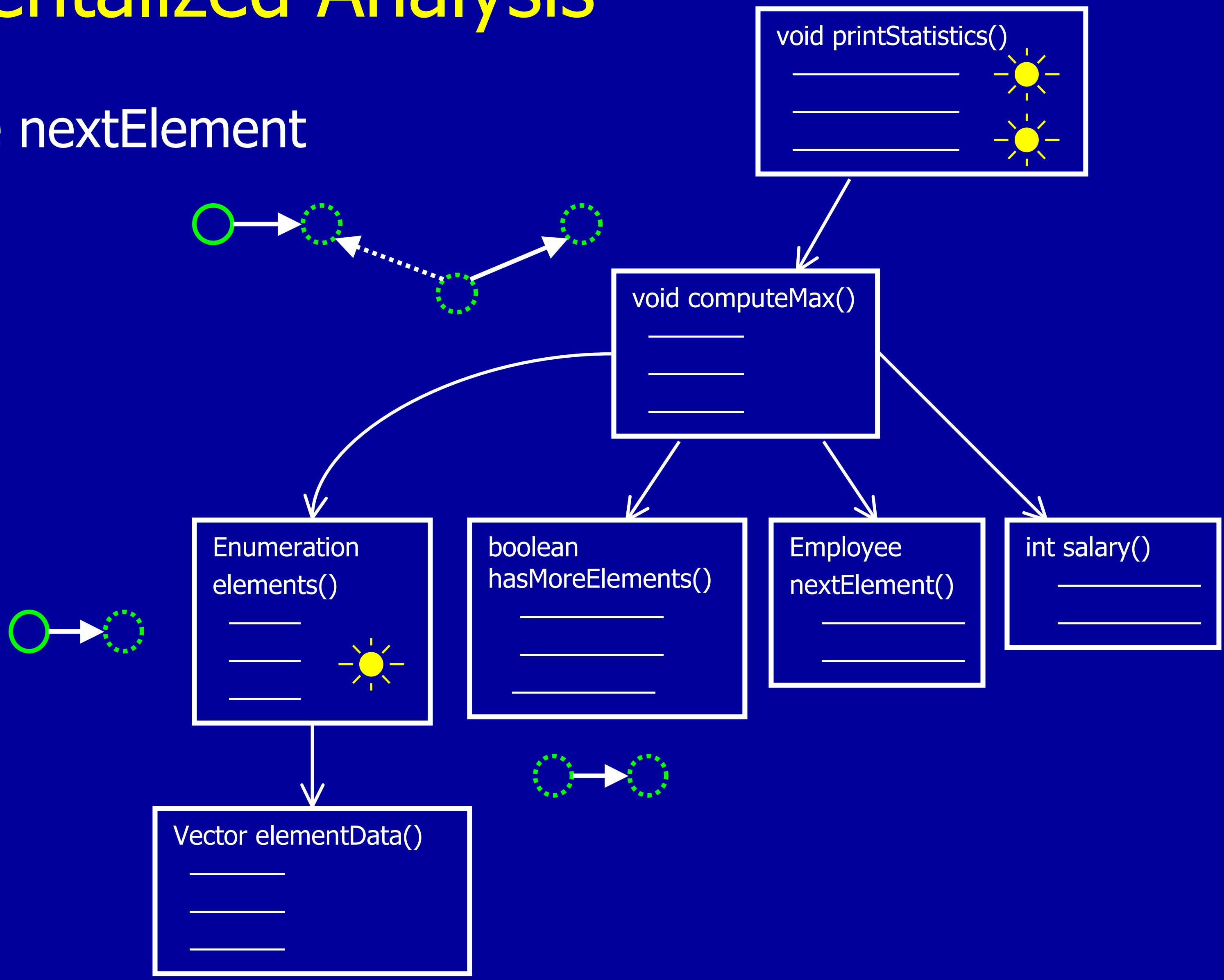
Still escaping to

- nextElement



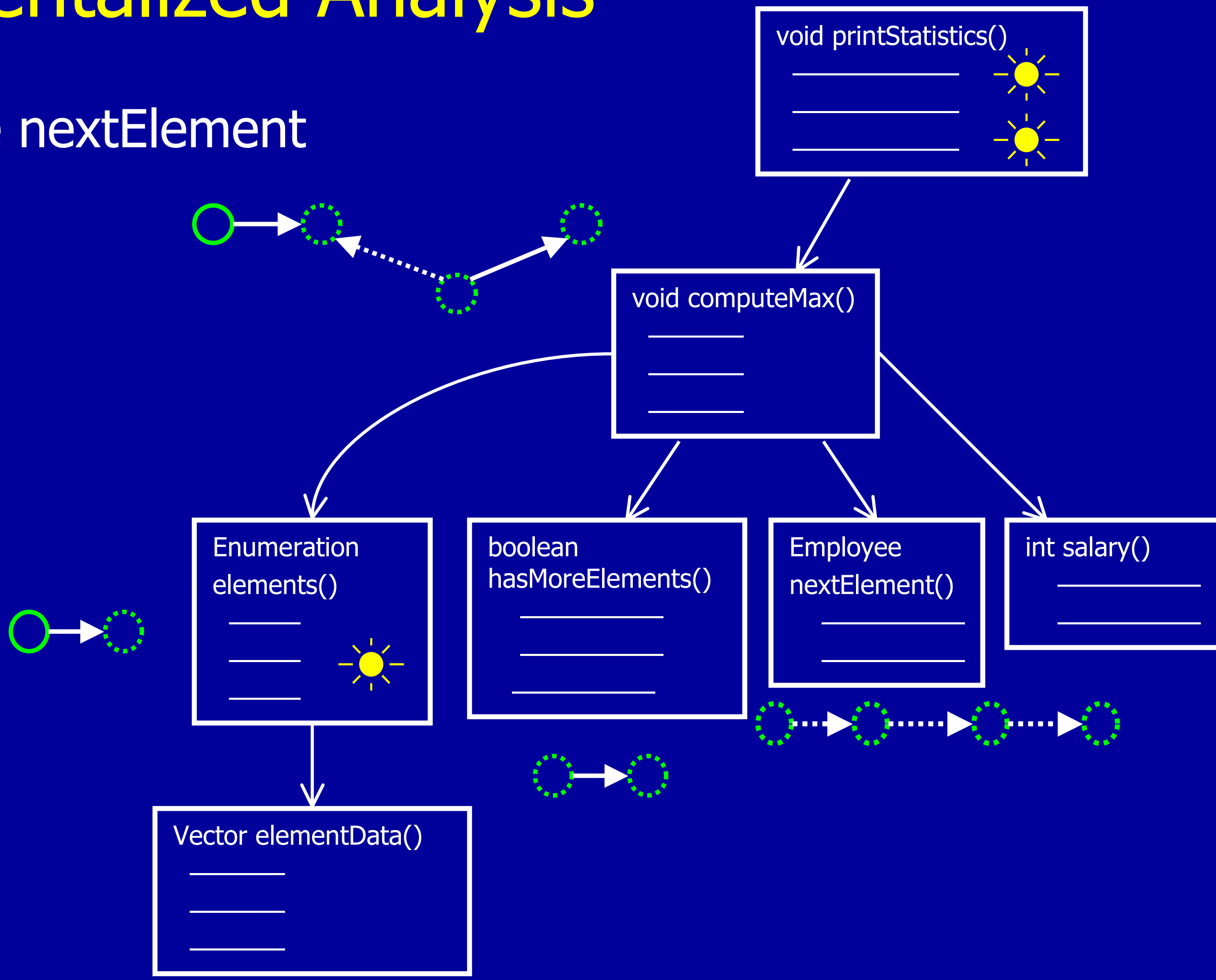
Incrementalized Analysis

Analyze nextElement



Incrementalized Analysis

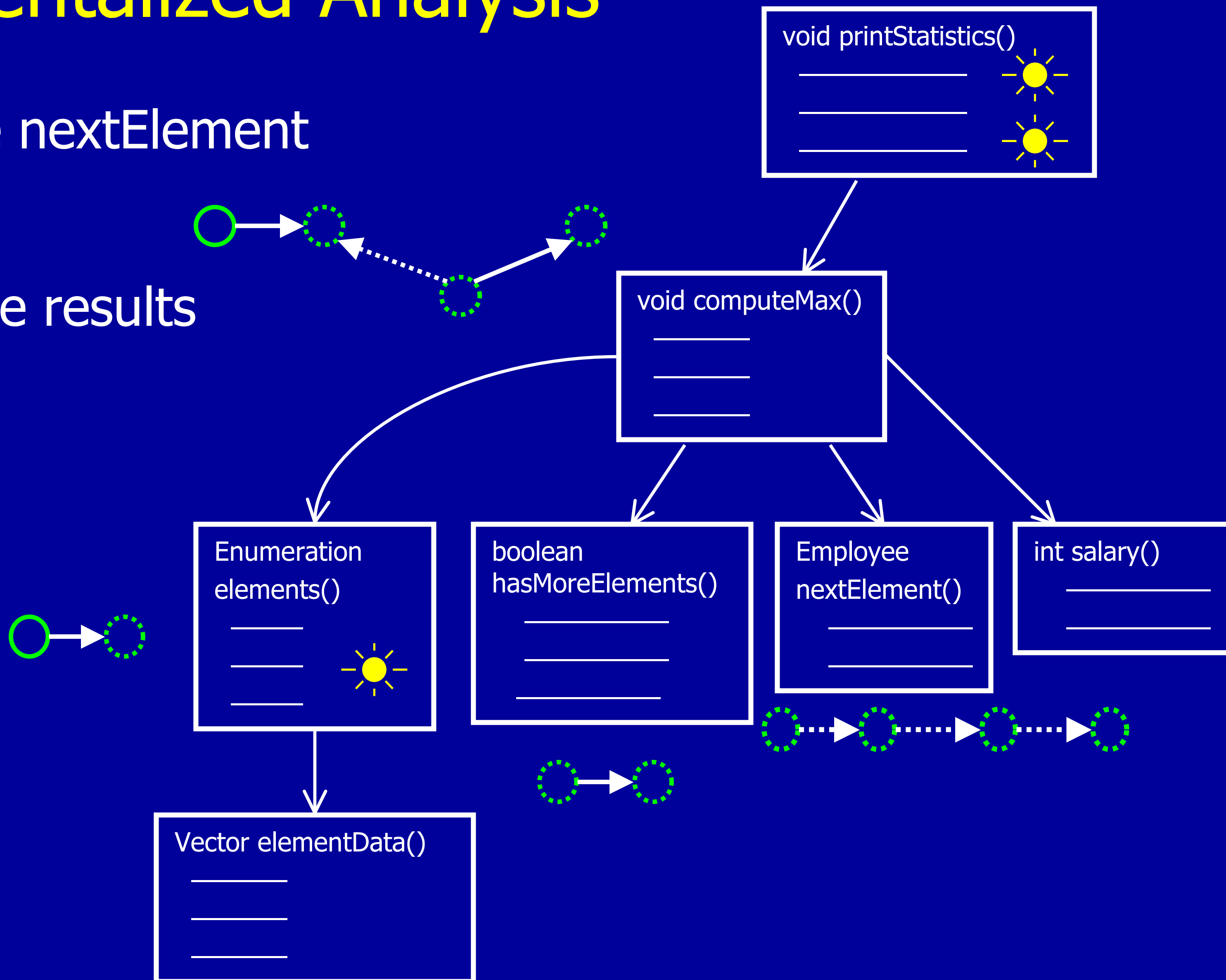
Analyze nextElement



Incrementalized Analysis

Analyze nextElement

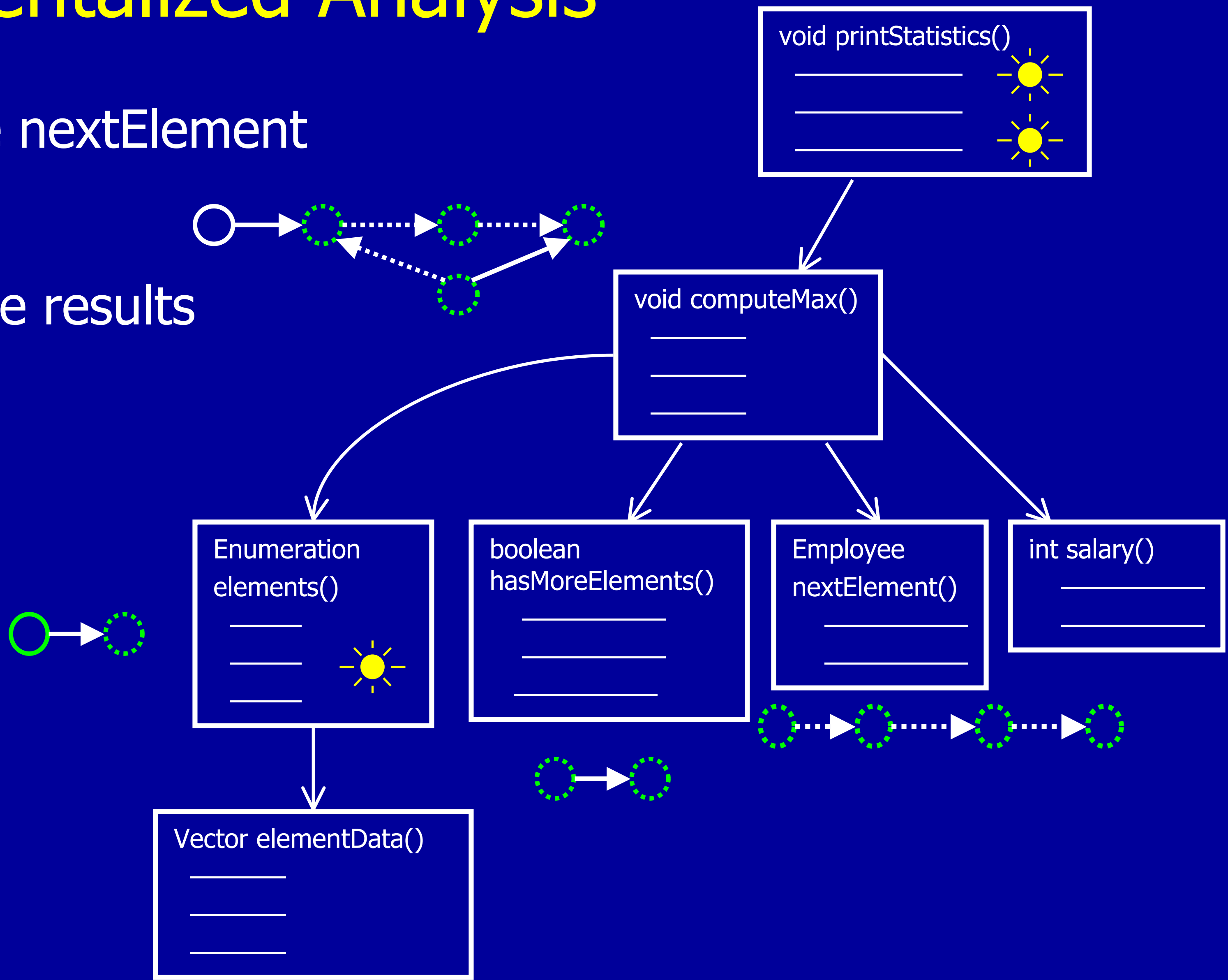
Combine results



Incrementalized Analysis

Analyze nextElement

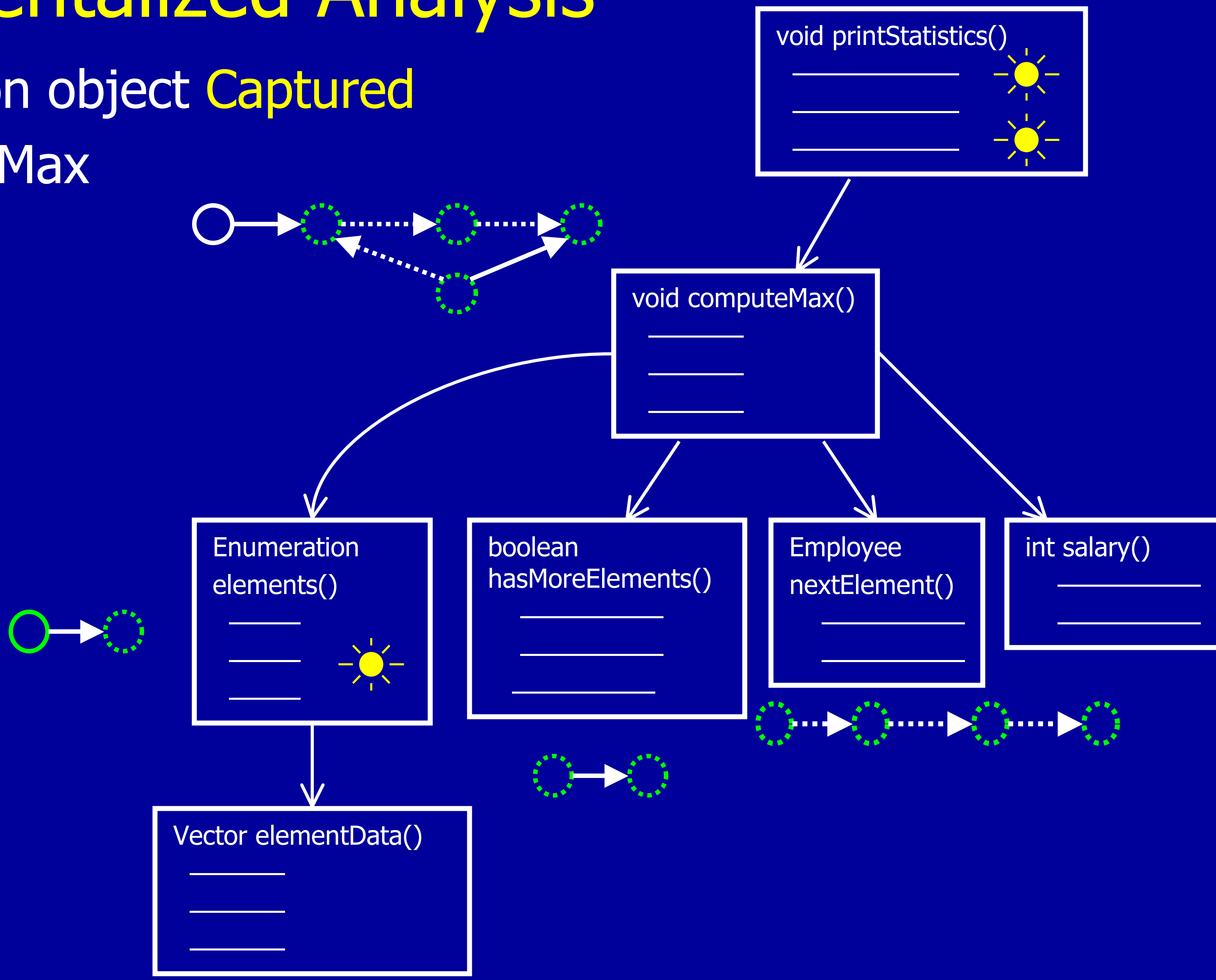
Combine results



Incrementalized Analysis

Enumeration object Captured

in computeMax



Incrementalized Analysis

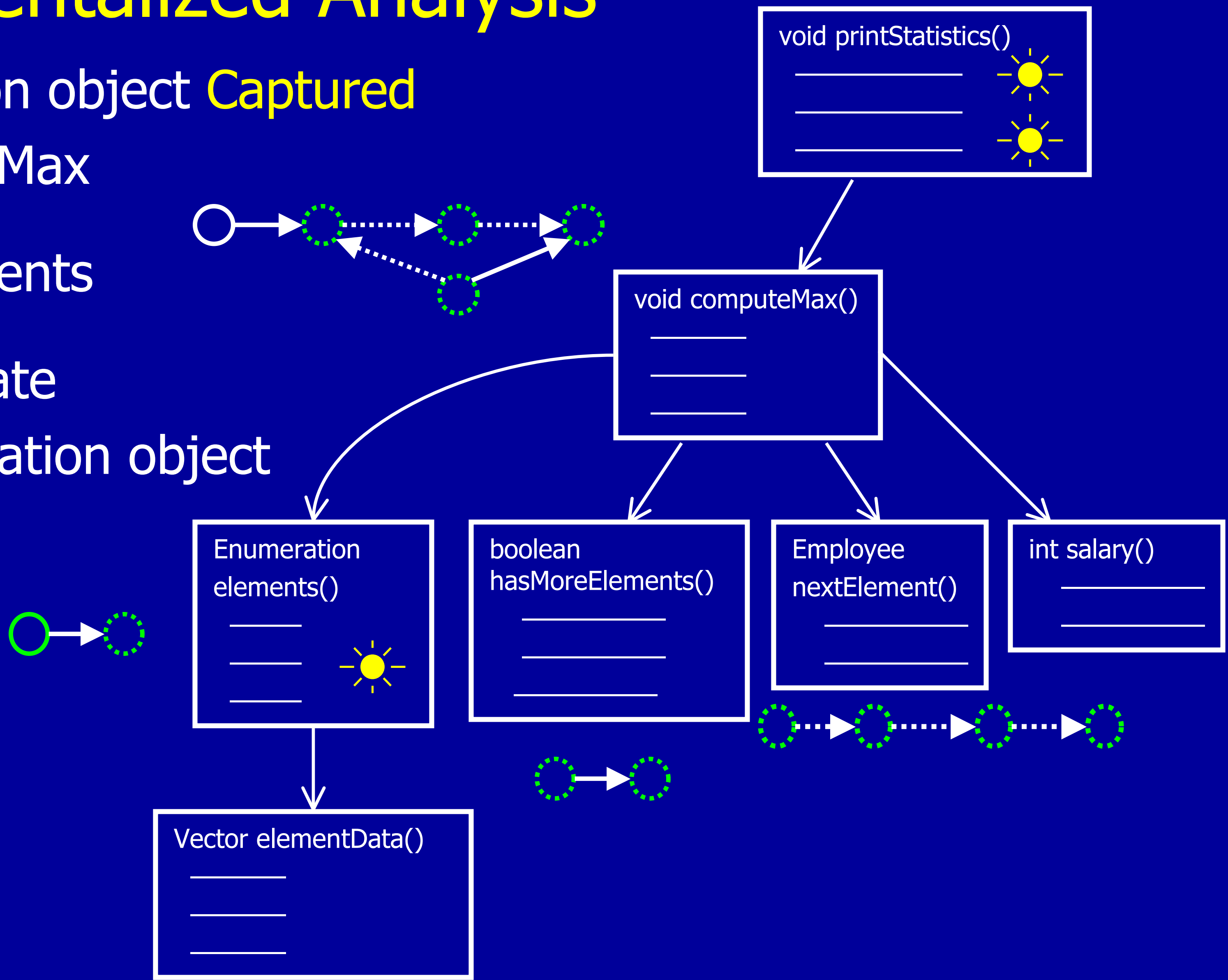
Enumeration object Captured

in computeMax

Inline elements

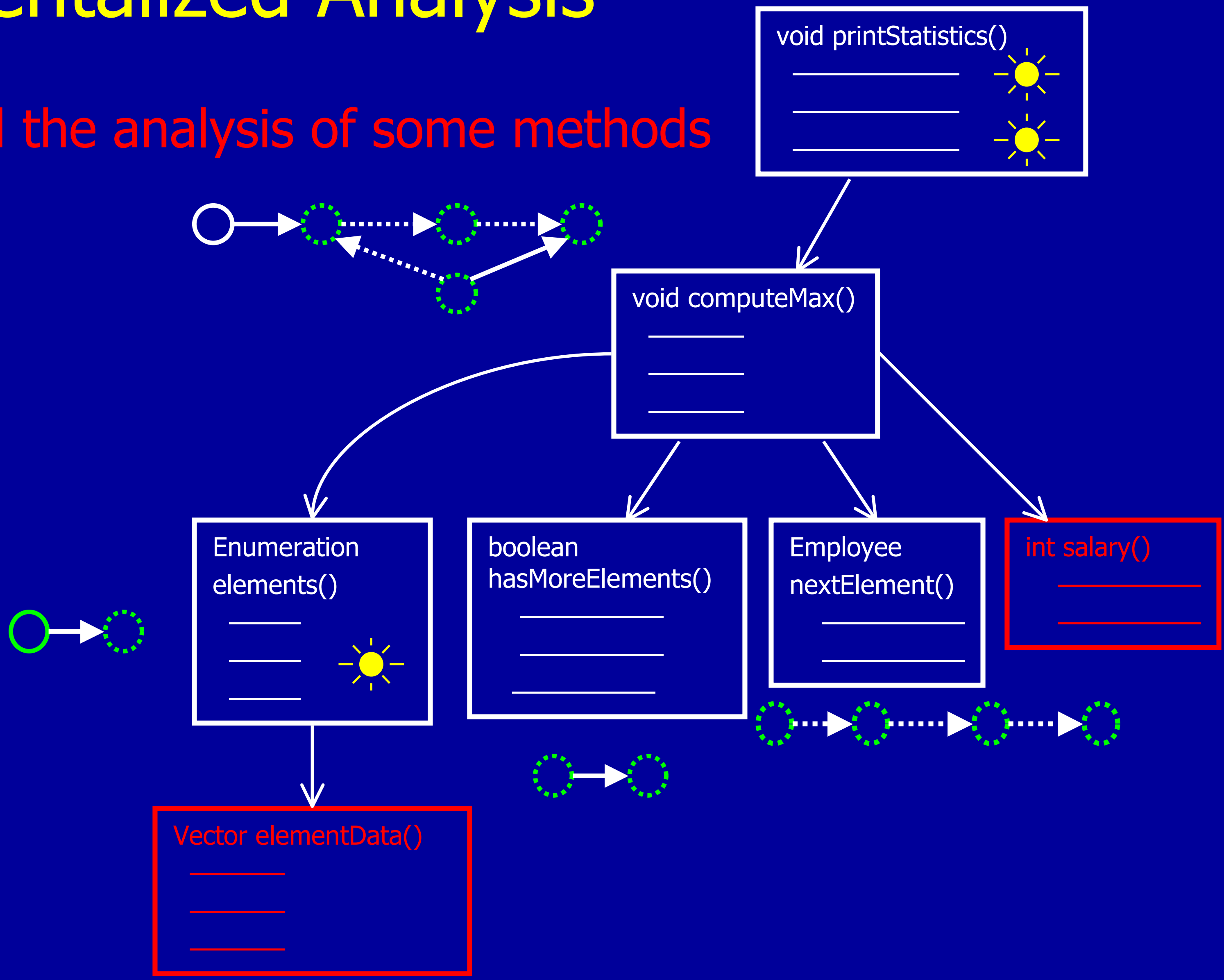
Stack allocate

enumeration object



Incrementalized Analysis

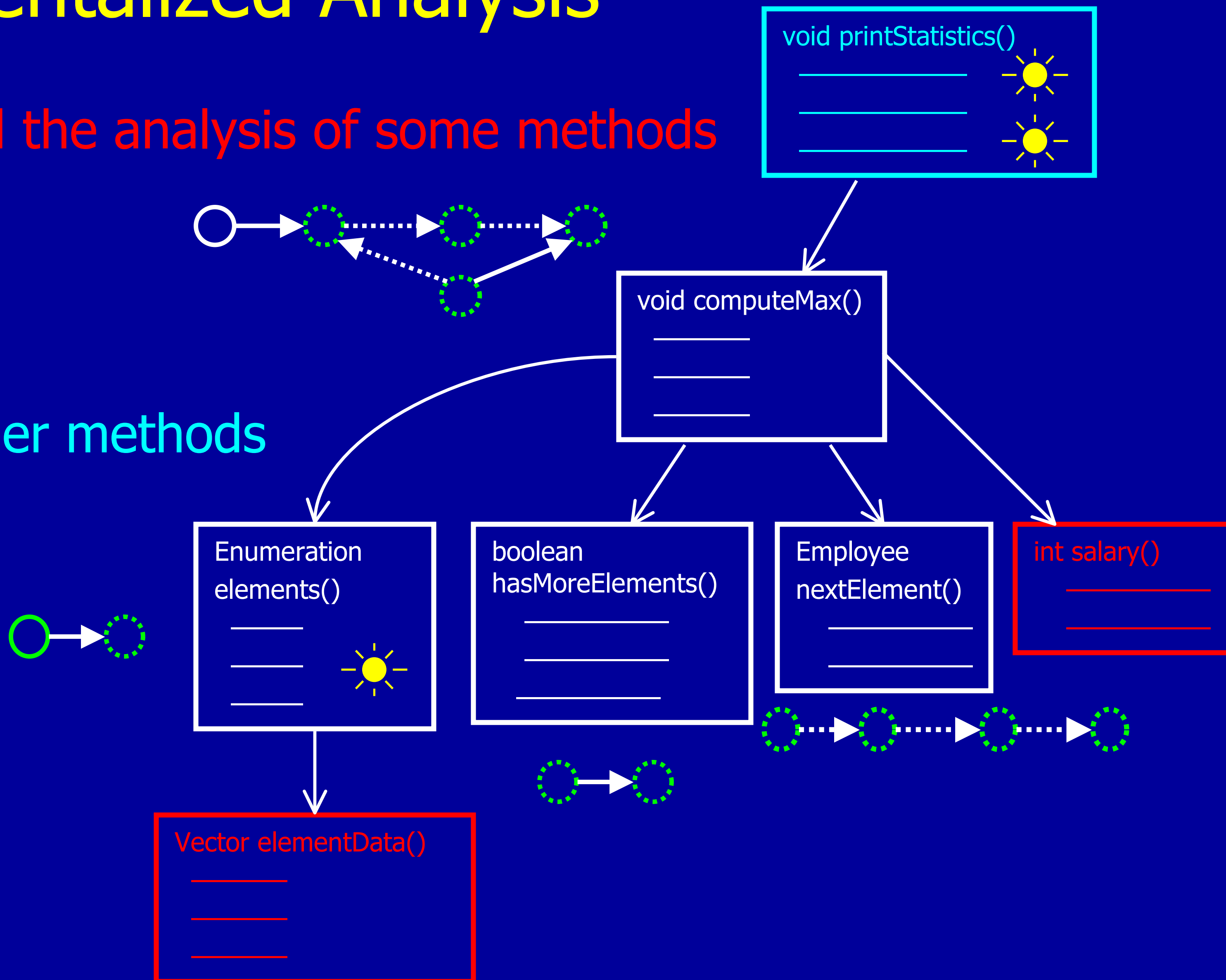
We skipped the analysis of some methods



Incrementalized Analysis

We skipped the analysis of some methods

We ignored
some other methods



Result

- We can incrementally analyze
  - Only what is needed
  - For whatever allocation site we want
  - And even temporarily suspend analysis part of the way through!

New Issue

- We can incrementally analyze
  - Only what is needed
  - For whatever allocation site we want
  - And even temporarily suspend analysis part of the way through!

But…

- Lots of analysis opportunities
  - Not all opportunities are profitable
  - Where to invest analysis resources?
  - How much resources to invest?

Analysis Policy

Formulate policy as solution to an investment problem

Goal

Maximize optimization payoff from invested analysis resources

Analysis Policy Implementation

- For each allocation site, estimate marginal return on invested analysis resources
- Loop
  - Invest a unit of analysis resources (time) in site that offers best return

    Expand analyzed region surrounding site
  - When unit expires, recompute marginal returns (best site may change)

Marginal Return Estimate

$$\frac{N \cdot P(d)}{C \cdot T}$$

N = Number of objects allocated at the site

P(d) = Probability of capturing the site, knowing we explored a region of call depth d

C = Number of skipped call sites the allocation site escapes through

T = Average time needed to analyze a call site

Marginal Return Estimate

$$\frac{N \cdot P(d)}{C \cdot T}$$

As invest analysis resources

- explore larger regions around allocation sites
- get more information about sites
- marginal return estimates improve
- analysis makes better investment decisions!

Usage Scenarios

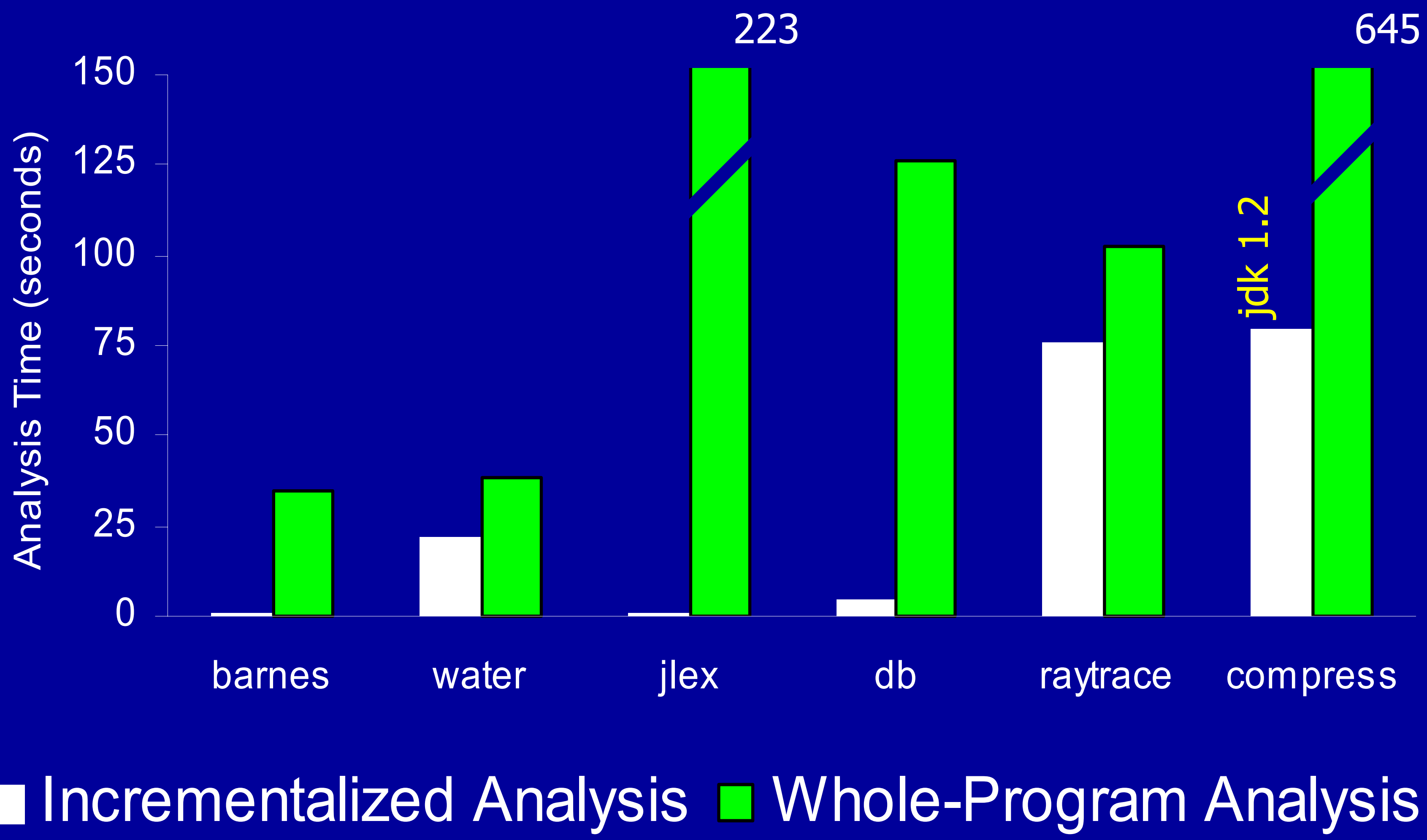
- Ahead of time compiler
  - Give algorithm an analysis budget
  - Algorithm spends budget
  - Takes whatever optimizations it uncovered
- Dynamic compiler
  - Algorithm acquires analysis budget as a percentage of run time
  - Periodically spends budget, delivers additional optimizations
  - Longer program runs, more optimizations

Experimental Results

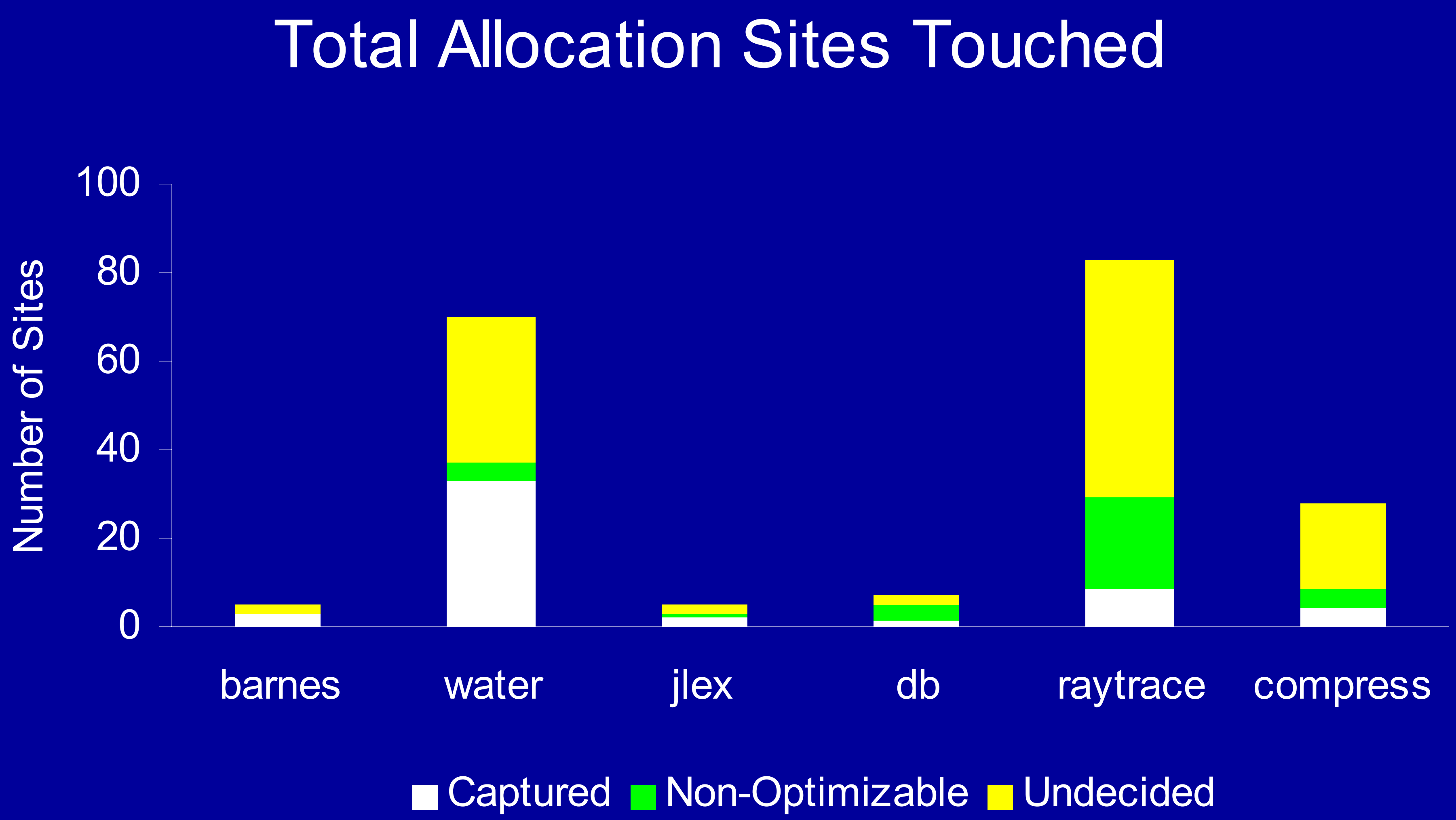
Methodology

- Implemented analysis in MIT Flex System
- Obtained several benchmarks
  - Scientific computations: barnes, water
  - Our lexical analyzer: jlex
  - Spec benchmarks: db, raytrace, compress

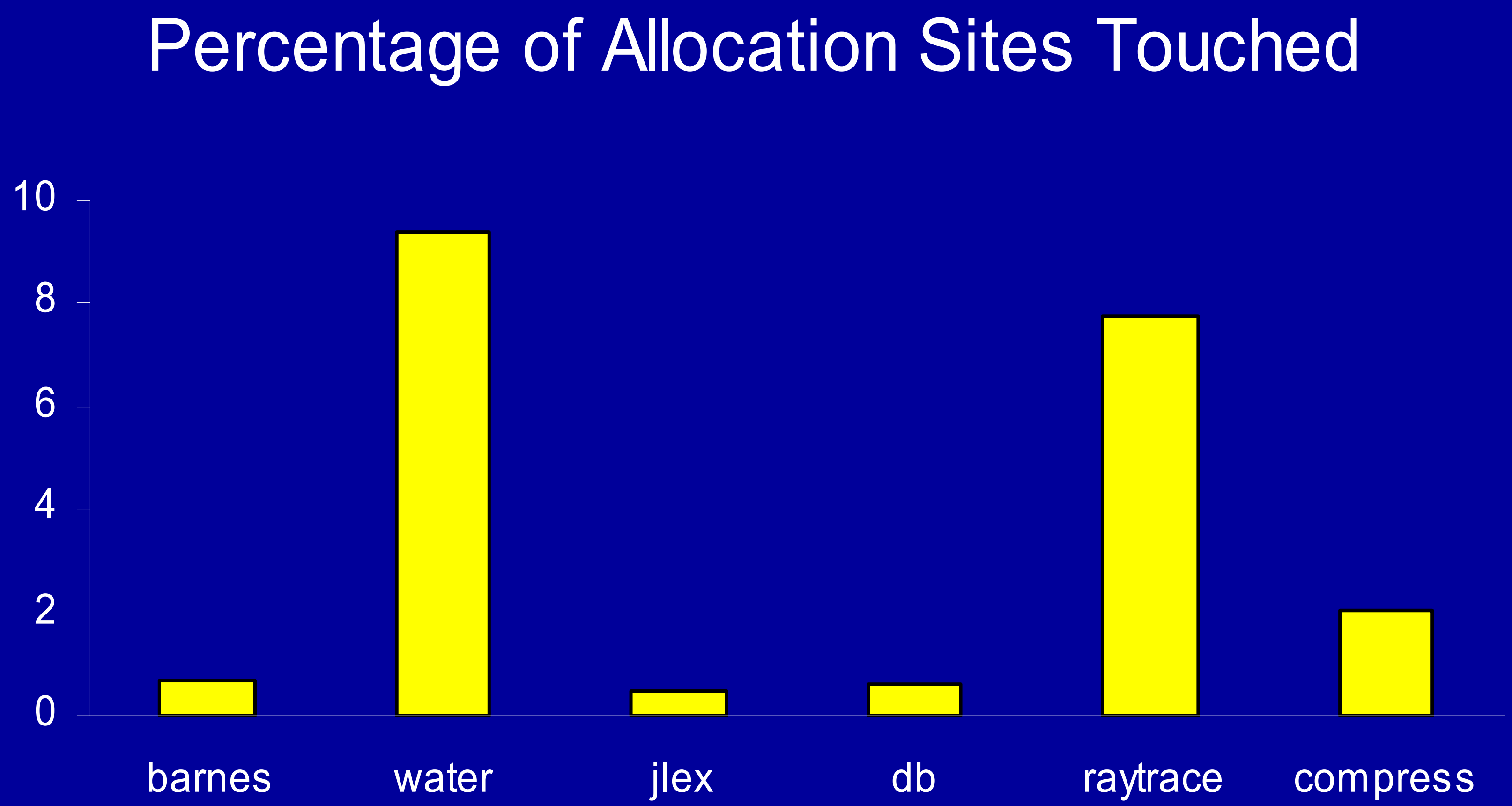
Analysis Times



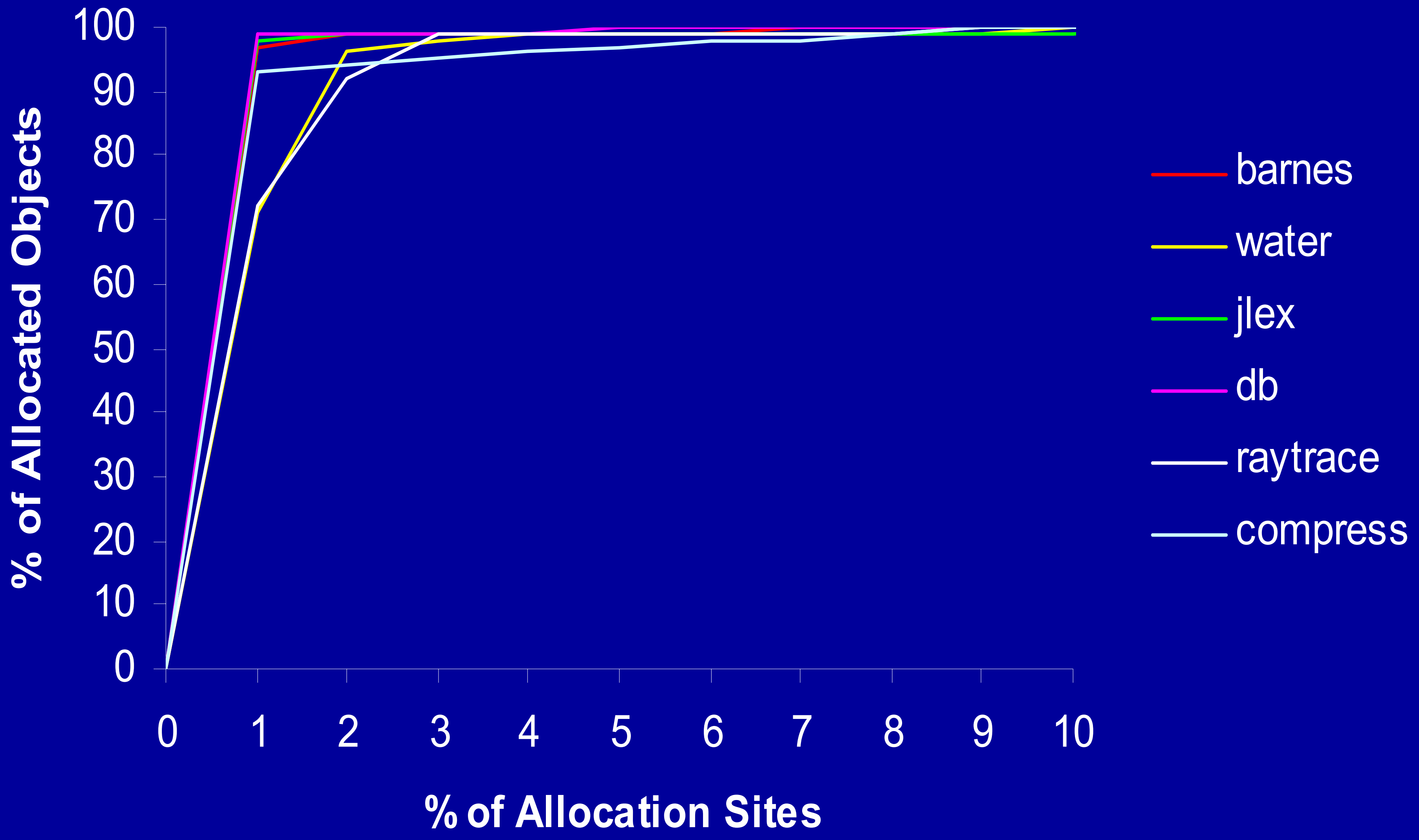
Allocation Sites Analyzed



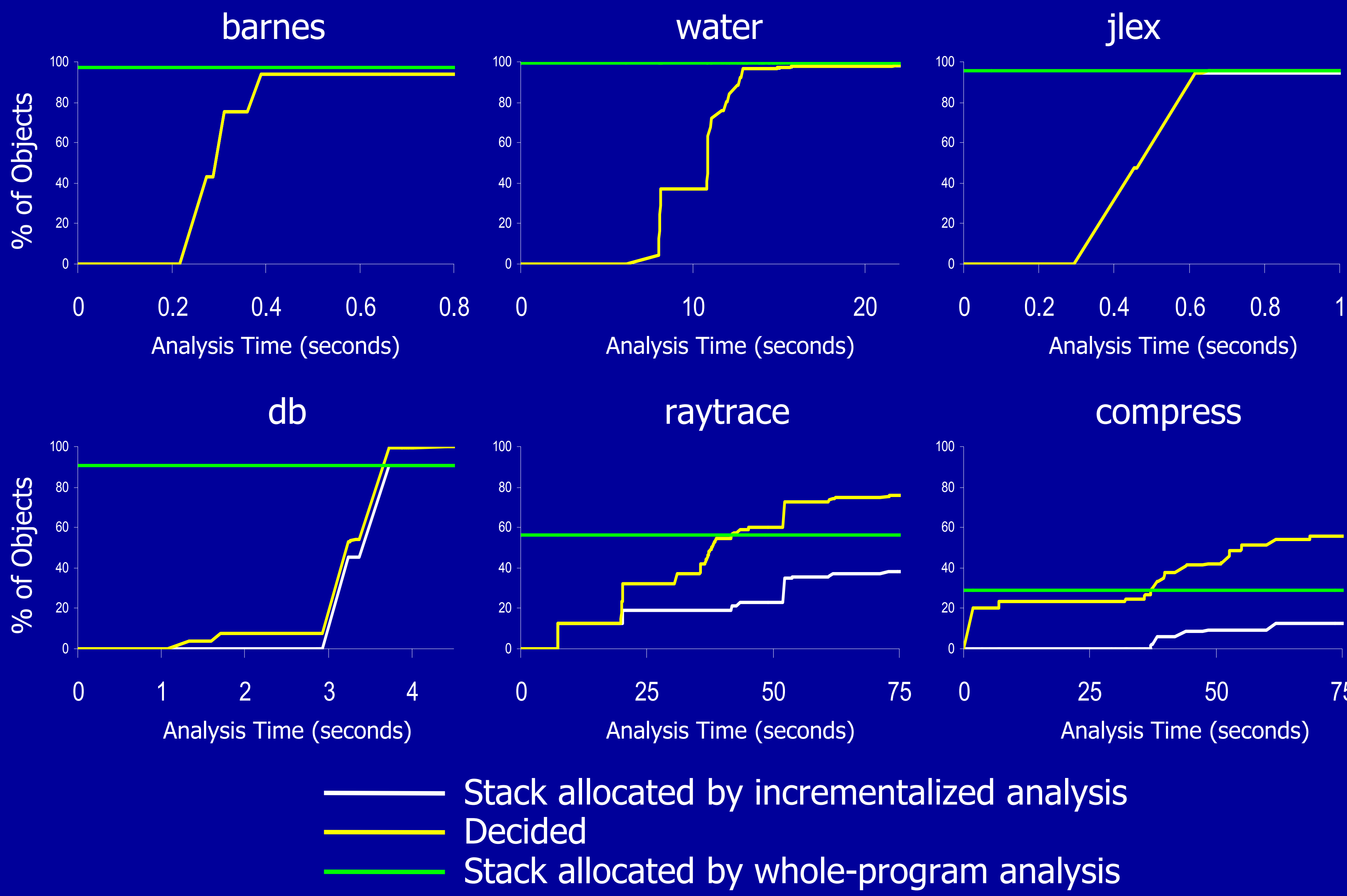
Allocation Sites Analyzed



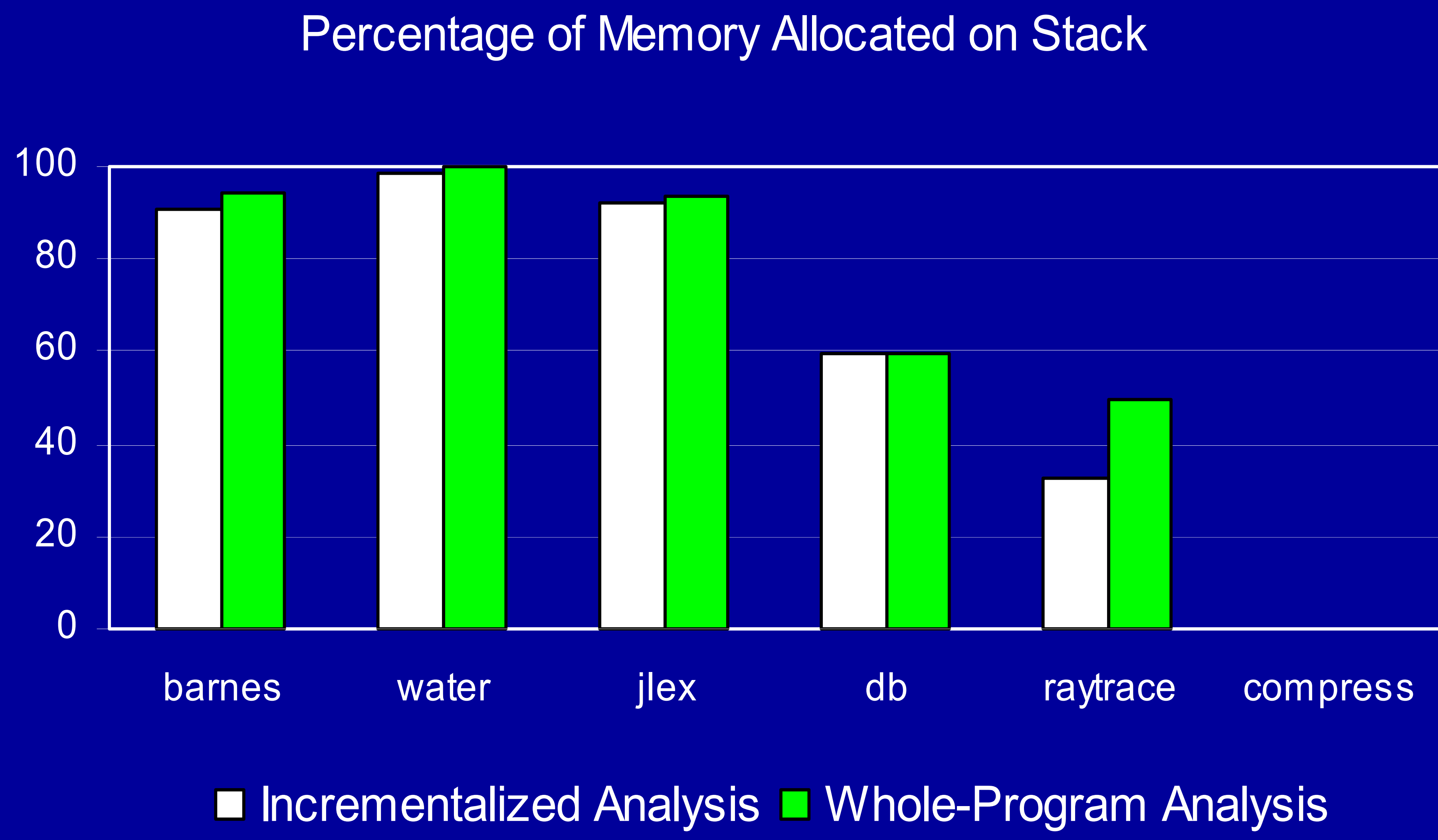
Distribution of Allocated Objects



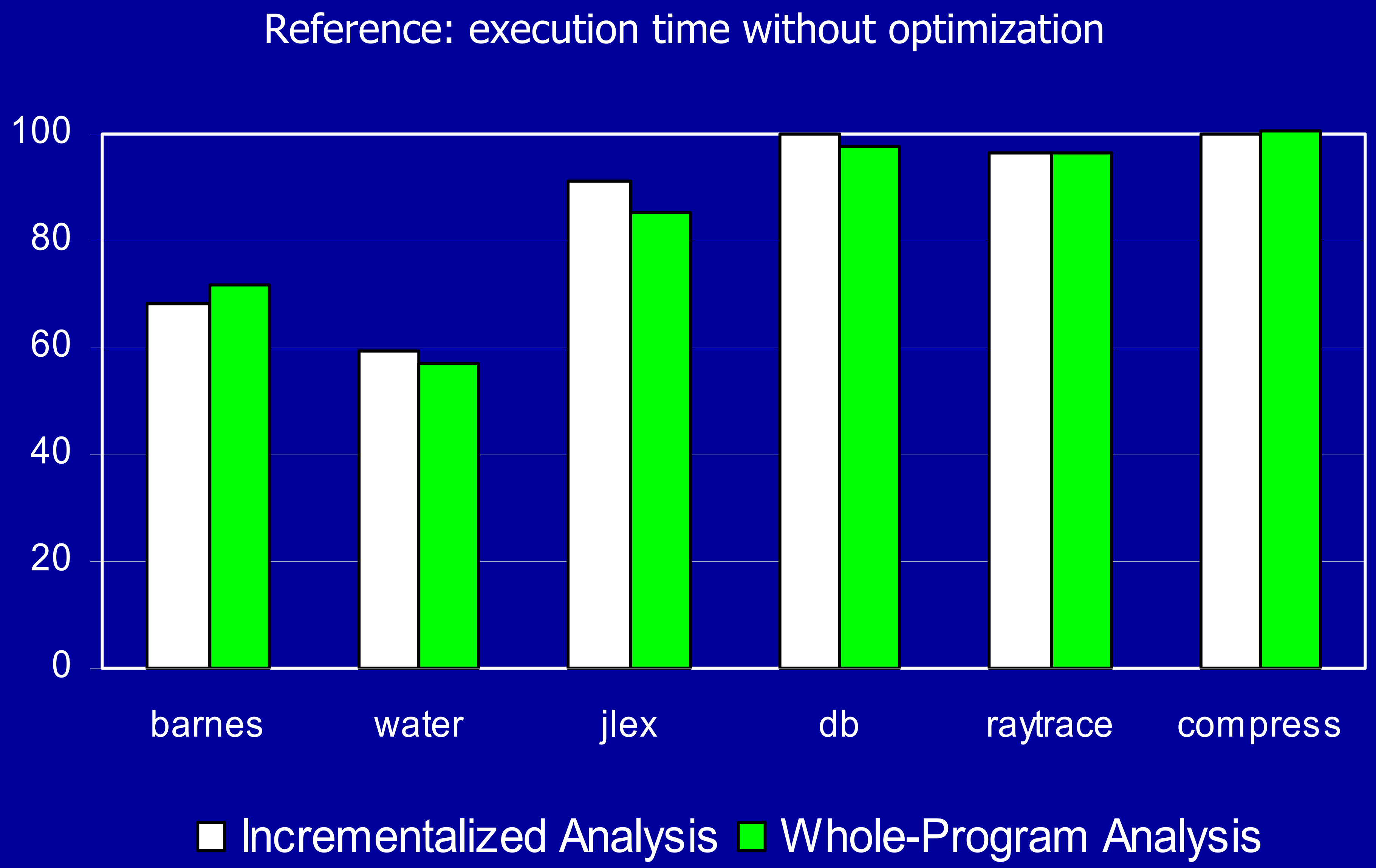
Analysis Time Payoff



Stack Allocation



Normalized Execution Times



Experimental Summary

Key Application Properties

Most objects allocated at very few allocation sites

Can capture objects with an incremental analysis of region surrounding allocation sites

Consequence

Most of the benefits of whole-program analysis

Fraction of the cost of whole-program analysis

Related Work

Demand-driven Analyses

- Horwitz, Reps, Sagiv (FSE 1995)
- Duesterwald, Soffa, Gupta (TOPLAS 1997)
- Heintze, Tardieu (PLDI 2001)

Key differences

- Integration of escape information enables incrementalized algorithms to suspend partially completed analyses
- Maintain accurate marginal payoff estimates
- Avoid overly costly analyses

Related Work

Previous Escape Analyses

- Blanchet (OOPSLA 1999)
- Bogda, Hoelzle (OOPSLA 1999)
- Choi, Gupta, Serrano, Sreedhar, Midkiff (OOPSLA 1999)
- Whaley, Rinard (OOPSLA 1999)
- Ruf (PLDI 2000)

Key Differences

- Previous algorithms analyze whole program
- But could incrementalize other analyses
- Get a range of algorithms with varying analysis time/precision tradeoffs

Conclusion

Whole-Program Analysis → Incrementalized Analysis

Properties

- Uses escape information to incrementally analyze relevant regions of program
- Analysis policy driven by estimates of optimization benefits and costs

Results

- Most of benefits of whole program analysis
- Fraction of the cost