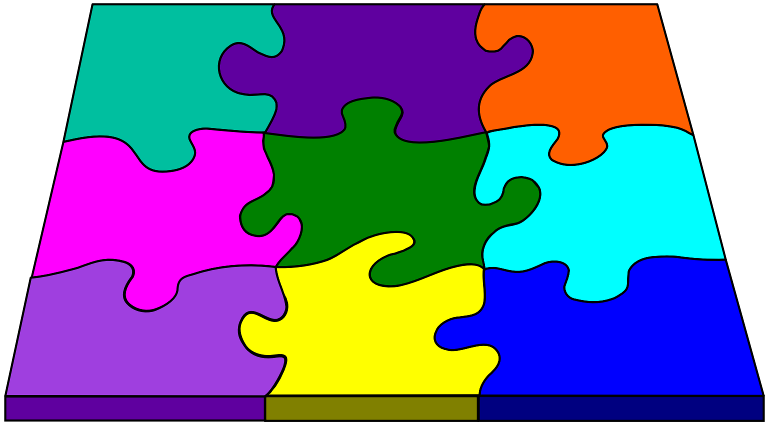


Traversal Strategies

Specification and Implementation

Idea of Traversal Strategies

- Defining high-level artifact in terms of a low-level artifact without committing to details of low-level artifact in definition of high-level artifact. Low-level artifact is parameter to definition of high-level artifact.
- Exploit structure of low-level artifact.

Also: Dynamic call graphs !

Applications of Traversal Strategies

- Application 1
  - High-level: Adaptive program, containing strategy.
  - Low-level: Class graph
- Application 2 (see paper by Dave Mandelin on Prospector and Jungloids PLDI 2005)
  - High-level: High-level API
  - Low-level: Low-level API

Similar to a function definition accessing parameter generically

- *High-level(Low-level)*
  - *High-level* does not refer to all information in *Low-level* but *High-level(Low-level)* contains details of *Low-level*.

Overview

- Use structure in graphs to express subgraphs and path sets in those graphs.
- Gain: writing programs in terms of strategies yields shorter and more flexible programs.
- Does not work well on dense graphs and graphs with self loops: use hierarchical approach in this case.

Graphs used

- object graphs
- class graphs
- strategy graphs
- traversal graphs
- propagation graphs = folded traversal graphs

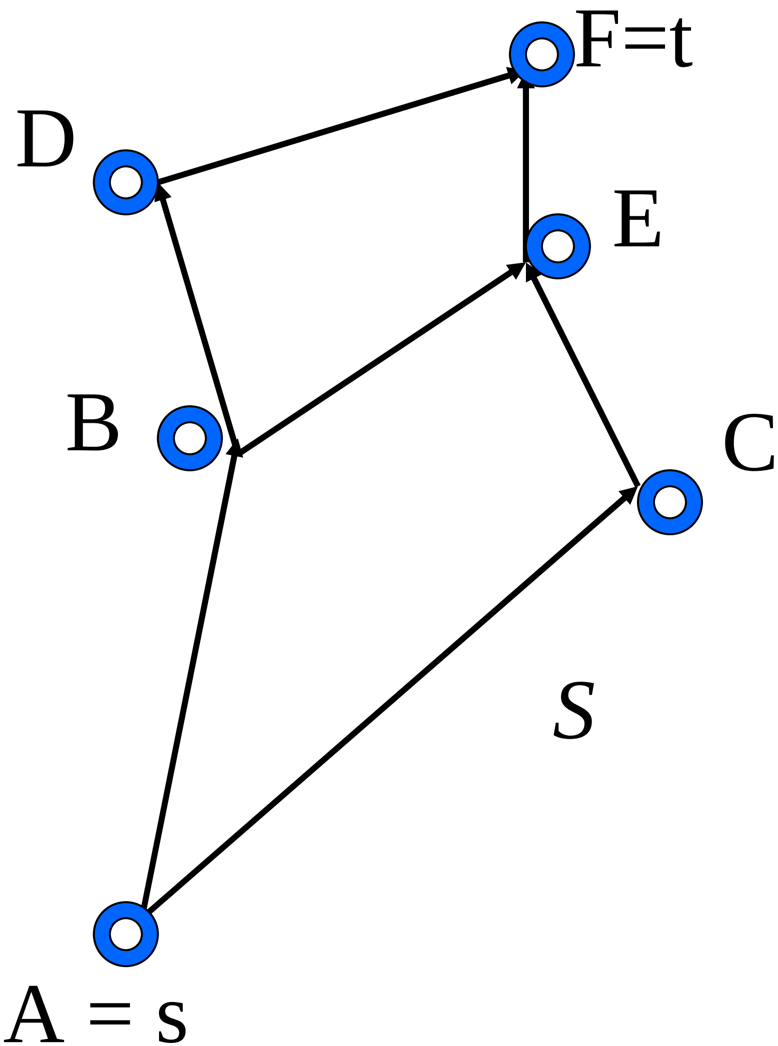
Simplified form of theory

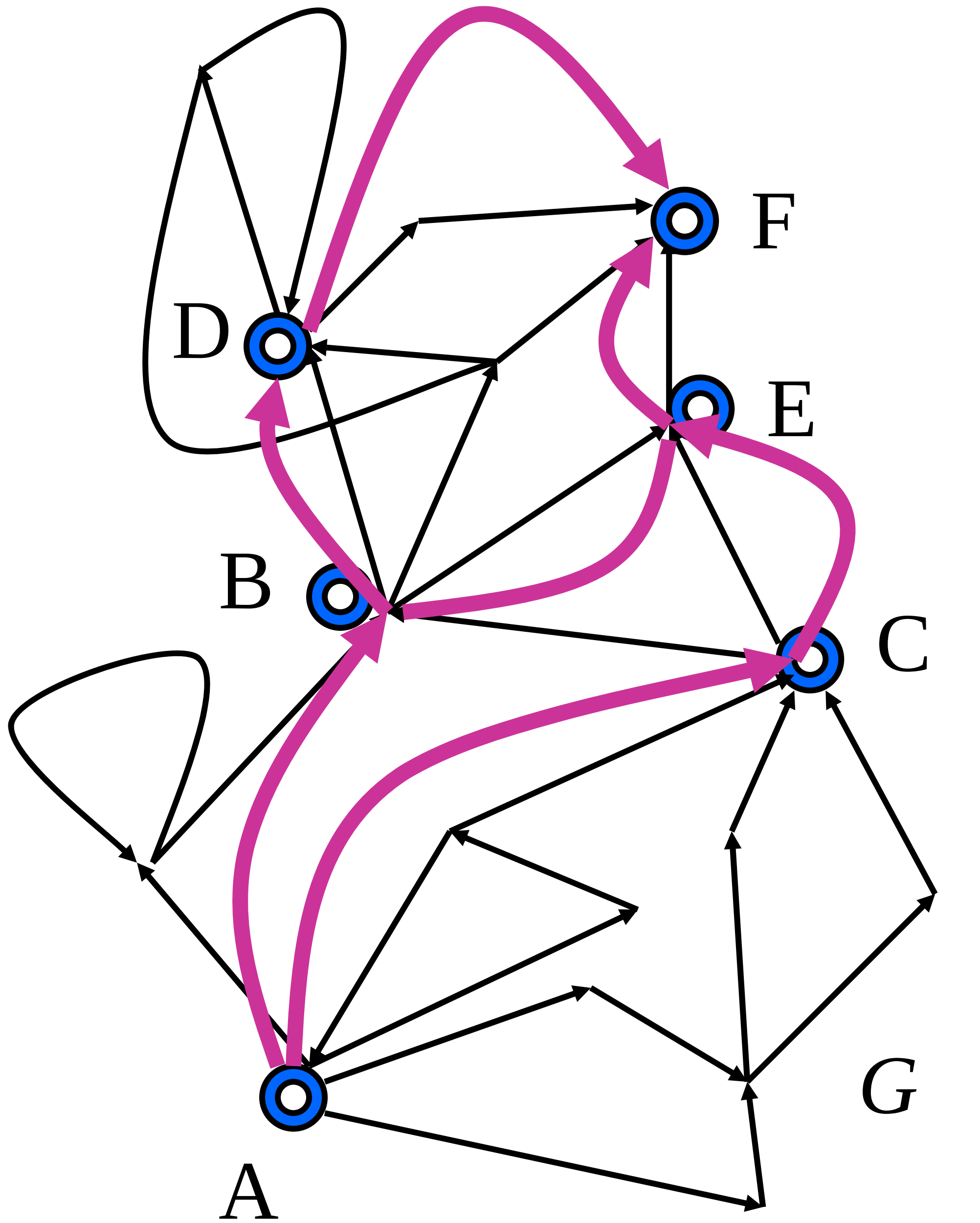
- Focus on class graphs with one kind of nodes and one kind of edges.

Strategy definition: embedded, positive strategies

- Given a graph G, a strategy graph S of G is any subgraph of the transitive closure of G with source s and target t.
- The transitive closure of $G=(V,E)$ is the graph $G^*=(V,E^*)$, where $E^*=\{(v,w)$: there is a path from vertex v to vertex w in $G\}$.

S is a strategy for G

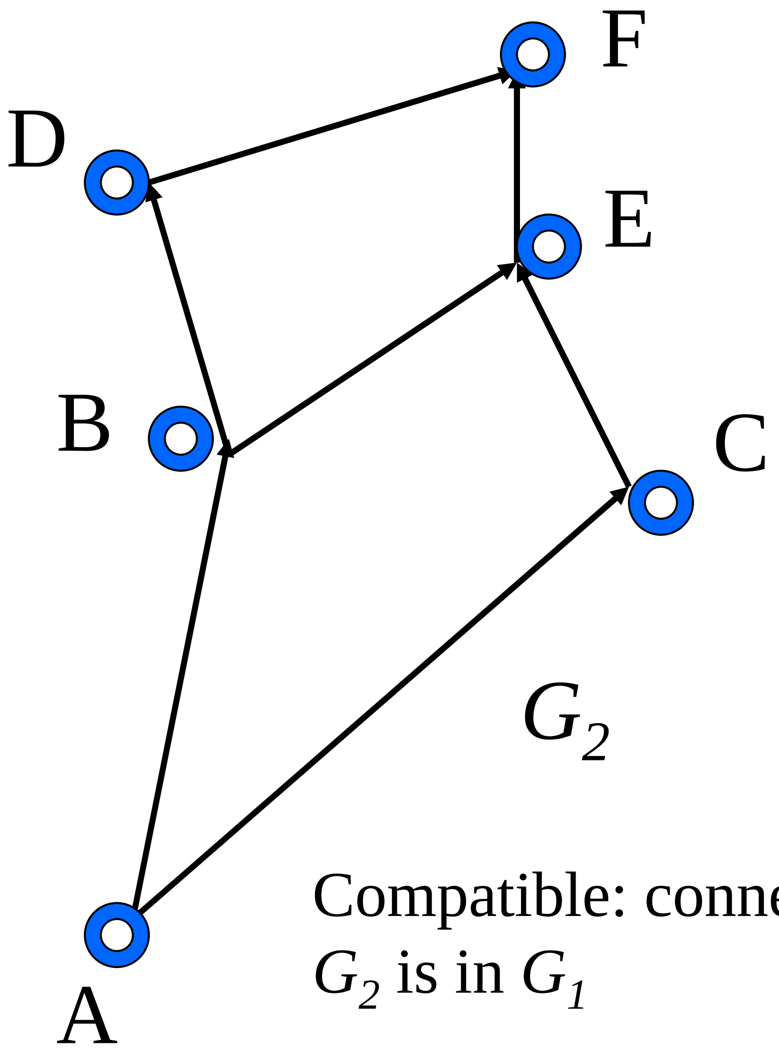




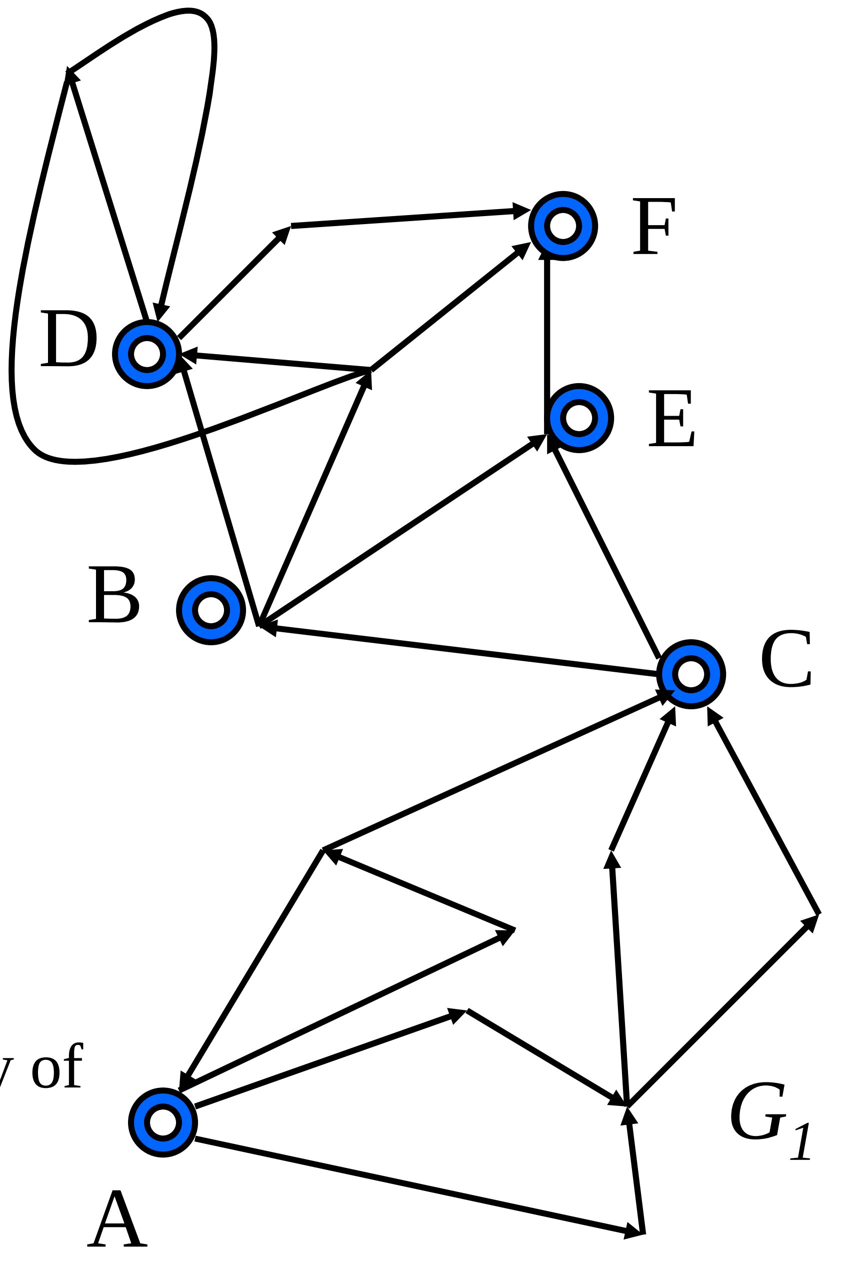
Discussion

- Seems strange: define a strategy for a graph but strategy is independent of graph.
- Many very different graphs can have the same strategy.
- Better: A graph G is an instance of a graph S, if S is a subgraph of the transitive closure of G. (call G: concrete graph, S: abstract graph).

G_1 compatible G_2



Compatible: connectivity of G_2 is in G_1



Theory of Strategy Graphs

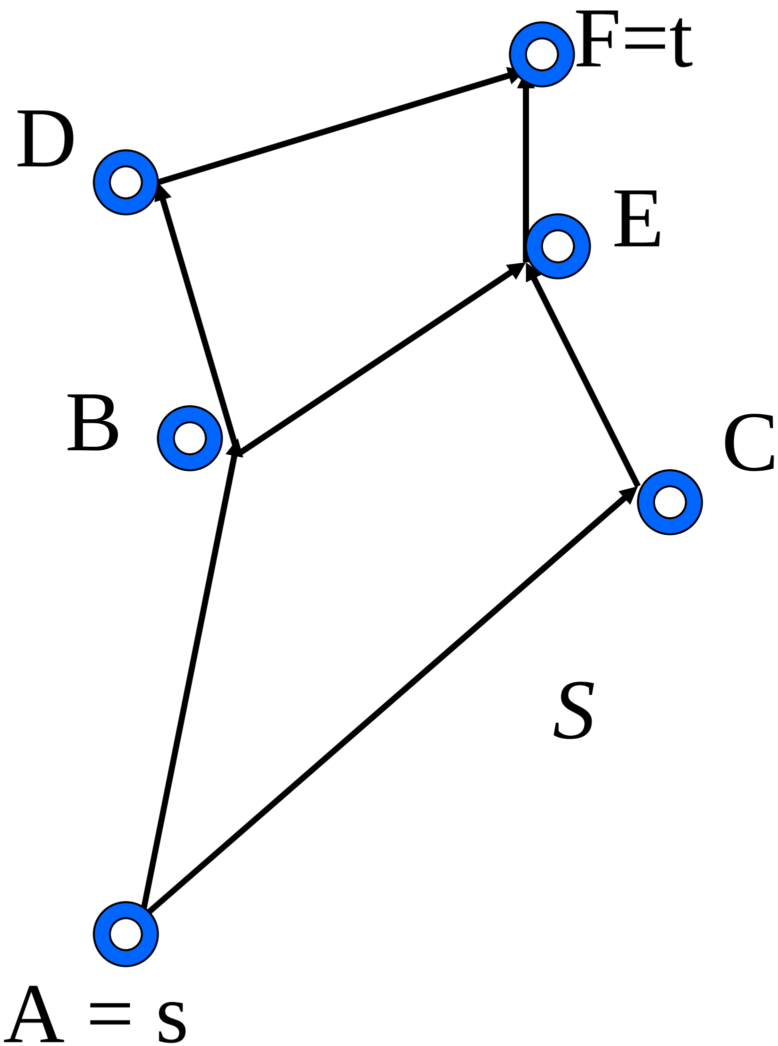
- Palsberg/Xiao/Lieberherr: TOPLAS ‘95
- Palsberg/Patt-Shamir/Lieberherr: Science of Computer Programming 1997
- Lieberherr/Patt-Shamir/Doug Orleans: Strategy graphs, 1997 NU TR, TOPLAS 2004
- Lieberherr/Patt-Shamir: Dagstuhl ‘98 Workshop on Generic Programming (LNCS)

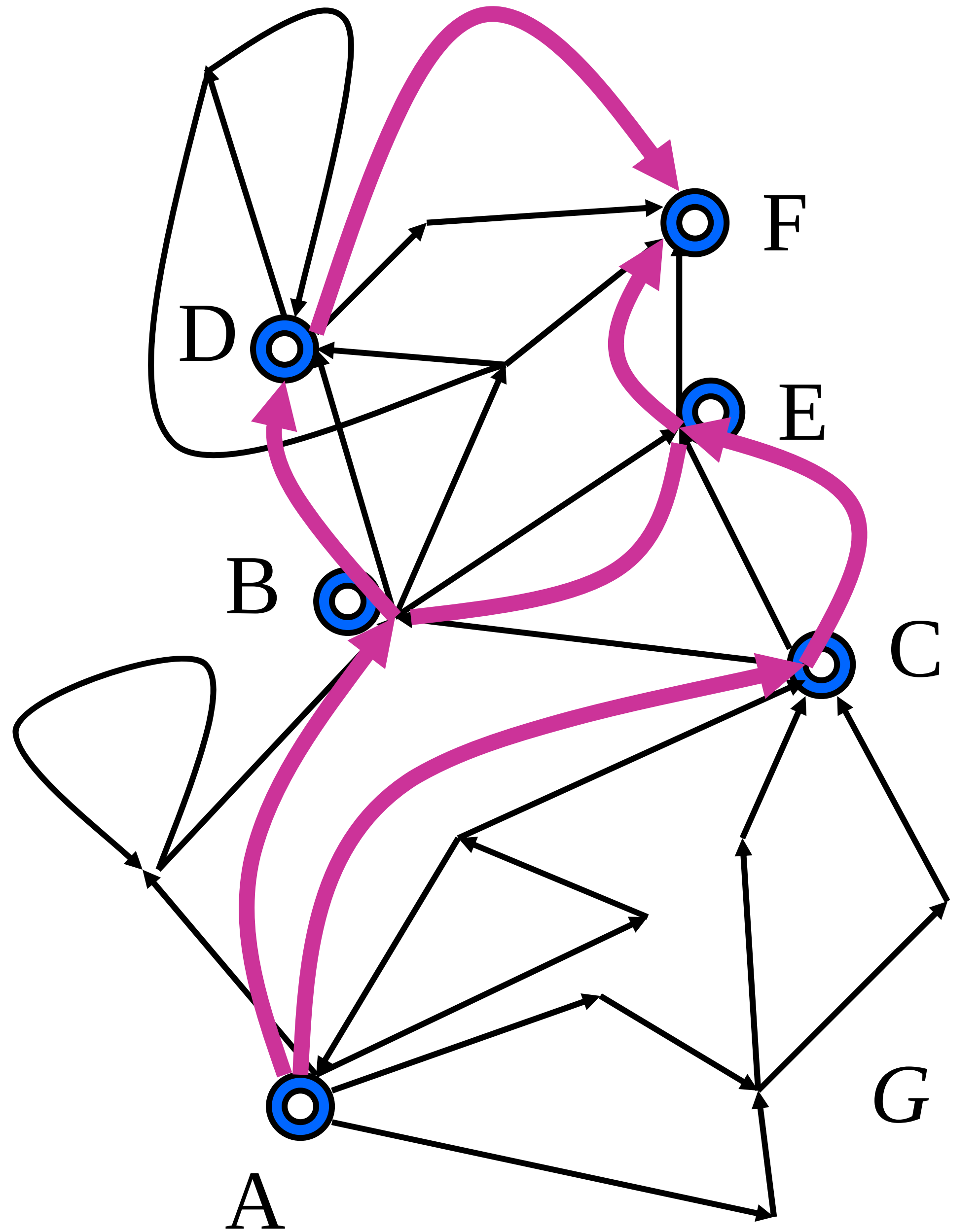
Strategy graph and base graph are directed graphs

Key concepts

- Strategy graph *S* with source *s* and target *t* of a base graph *G*. *Nodes(S)* subset *Nodes(G)* (Embedded strategy graph).
- A path *p* is an ***expansion*** of path *p'* if *p'* can be obtained by deleting some elements from *p*.
- *S* defines ***path set*** in *G* as follows: $PathSet_{st}(G,S)$ is the set of all *s*-*t* paths in *G* that are expansions of any *s*-*t* path in *S*.

PathSet(G , S)





Learning map

generalization

other relationships

numbers: order of coverage

correspondences
X:class path - concrete path
Y:object path - concrete path
traversal path - class path

1 graph paths labeled

8 FROM-TO computation

3 object graph

2 class graph

5 strategy graph

9 traversal graph

10 propagation graph

4 object traversal defined by concrete path set

6 name map constraint map

11 zig-zags short-cuts

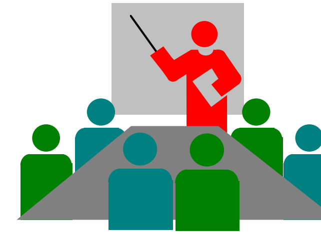
7 Algorithm 1
in: strategy + class graph
out: traversal graph

12 Algorithm 2
in: traversal + object graph
out: object traversal

generalization

other relationships

Learning map



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7 Algorithm 1
in: strategy + class graph
out: traversal graph

12 Algorithm 2
in: traversal + object graph
out: object traversal

Remarks about traversals

- If object graph is cyclic, traversal is not well defined.
- Traversals are opportunistic: As long as there is a possibility for success (i.e., getting to the target), the branch is taken.
- Traversals do not look ahead. Visitors must delay action appropriately.

Strategies: traversal specification

- Strategies select class-graph paths and then derive concrete paths by applying the natural correspondence.
- Traversals are defined in terms of sets of concrete paths.
- A strategy selects class graph paths by specifying a high-level topology which spans all selected paths.

Strategies

- A strategy *SS* is a triple $SS = (S,s,t)$, where $S = (C,D)$ is a directed unlabeled graph called the strategy graph, where *C* is the set of strategy-graph nodes and *D* is the set of strategy-graph edges, and $s,t \in C$ are the source and target of *SS*, respectively.

Strategies, constraint map

- Need negative constraints
- Given a class graph $G = (V,E,L)$, an element predicate EP for G is a predicate over $V \cup E$. Given a strategy SS, a function B mapping each edge of SS to an element predicate is called a constraint map for SS and G.

Strategies, constraint map

- Let S be a strategy graph, let G be a class graph, let N be a name map and let B be a constraint map for S and G. Given a strategy-graph path $p = <a_0\ a_1 \ldots a_n>$, we say that a class graph path p' is a satisfying expansion of p with respect to B under N if there exist paths $p_1, \ldots, p_n$ such that $p' = p_1 . p_2 \ldots p_n$ and:

Strategies, constraint map

- For all $0<i<n+1$, $Source(p_i)=N(a_{i-1})$ and $Target(p_i)= N(a_i)$.
- For all $0<i<n+1$, the interior elements of p_i satisfy the element predicate $B(a_{i-1},a_i)$.

Strategies

- Many ways to decompose a path.
- Element constraints never apply to the ends of the subpaths.
- `from A bypassing {A,B} to B`

Strategies, path sets

- Let $SS = (S,s,t)$ be a strategy, let $G = (V,E,L)$ be a class graph, and let N be a name map for SS and G and let B be a constraint map for S and G. The set of concrete paths $PathSet[SS,G,N,B]$ is $\{X(p') \mid p' \in P_G(N(s),N(t))$ and there exists $p \in P_S(s,t)$ such that p' is an expansion of $N(p)$ *w.r.t.* $B\}$.

Strategies

- *PathSet[SS,G,N] = PathSet[SS,G,N,B_{TRUE}]* for the constraint map B_{TRUE} which maps all strategy graph edges to the trivial element predicate that is always TRUE.

Strategies

- Are used in adaptive programs.
- Adaptive programs are expressed in terms of class-valued and relation-valued variables. Class graph not known when program is written.

Learning map

generalization (thick line)

other relationships (thin line)

numbers: order of coverage

1 graph paths labeled

8 FROM-TO computation

correspondences
X:class path - concrete path
Y:object path - concrete path
traversal path - class path

3 object graph

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7 Algorithm 1
in: strategy + class graph
out: traversal graph

12 Algorithm 2
in: traversal + object graph
out: object traversal

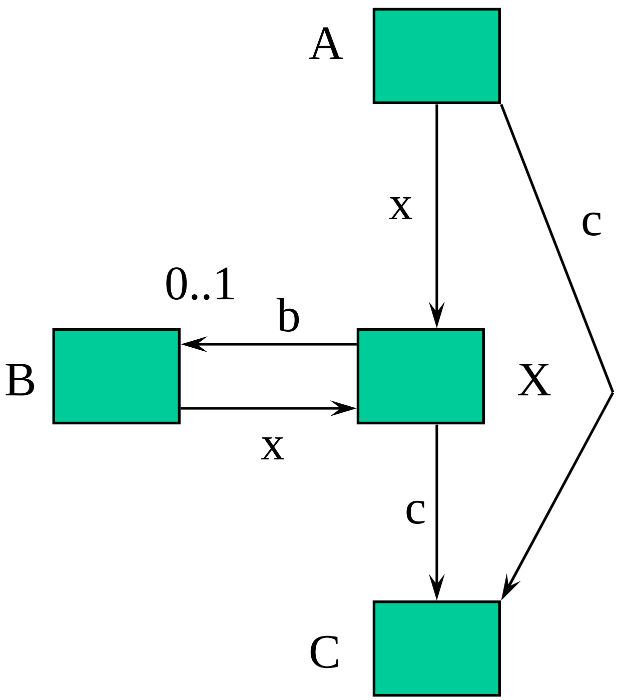
What we tried.

- Path set is represented by subgraph of class graph, called propagation graph. Propagation graph is translated into a set of methods. Works in many cases. Two important cases which do not work:
  - short-cuts
  - zig-zags

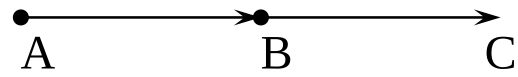
Short-cut

```
strategy:
{A -> B
 B -> C}
```

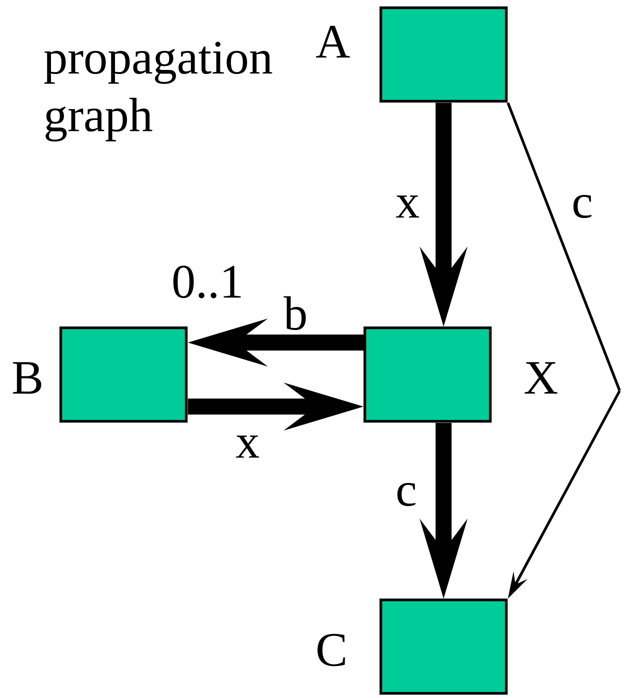
class graph



strategy graph with name map



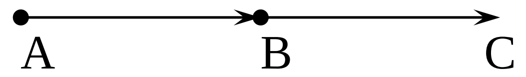
propagation graph



1+1=3 Short-cut

```
strategy:
{A -> B
 B -> C}
```

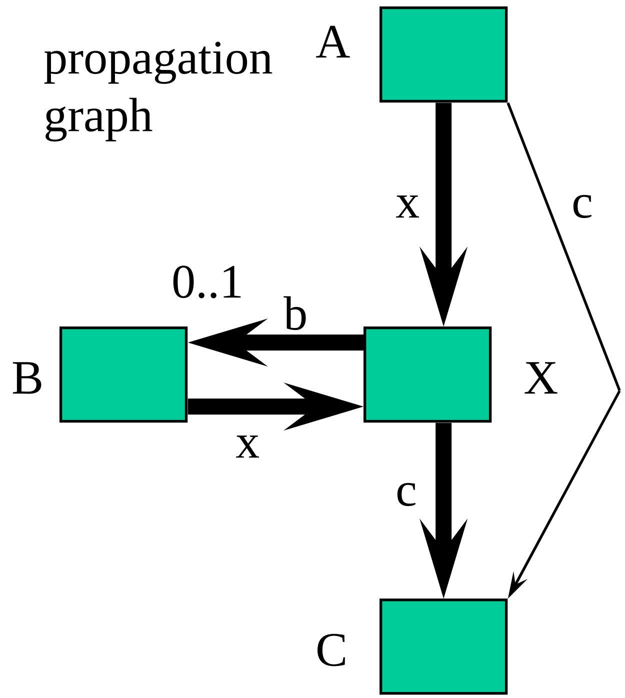
strategy graph with name map



Incorrect traversal code:

```
class A {void t(){x.t();}}
class X {void t(){if (b!==null)b.t();c.t();}}
class B {void t(){x.t();}}
class C {void t(){}}
```

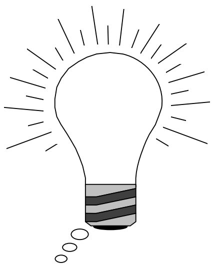
propagation graph



Correct traversal code:

```
class A {void t(){x.t();}}
class X {void t(){if (b!==null)b.t2();}
          void t2(){if (b!==null)b.t2();c.t2();}
}
class B {void t2(){x.t2();}}
class C {void t2(){}}
```

abstract representation
of traversal code

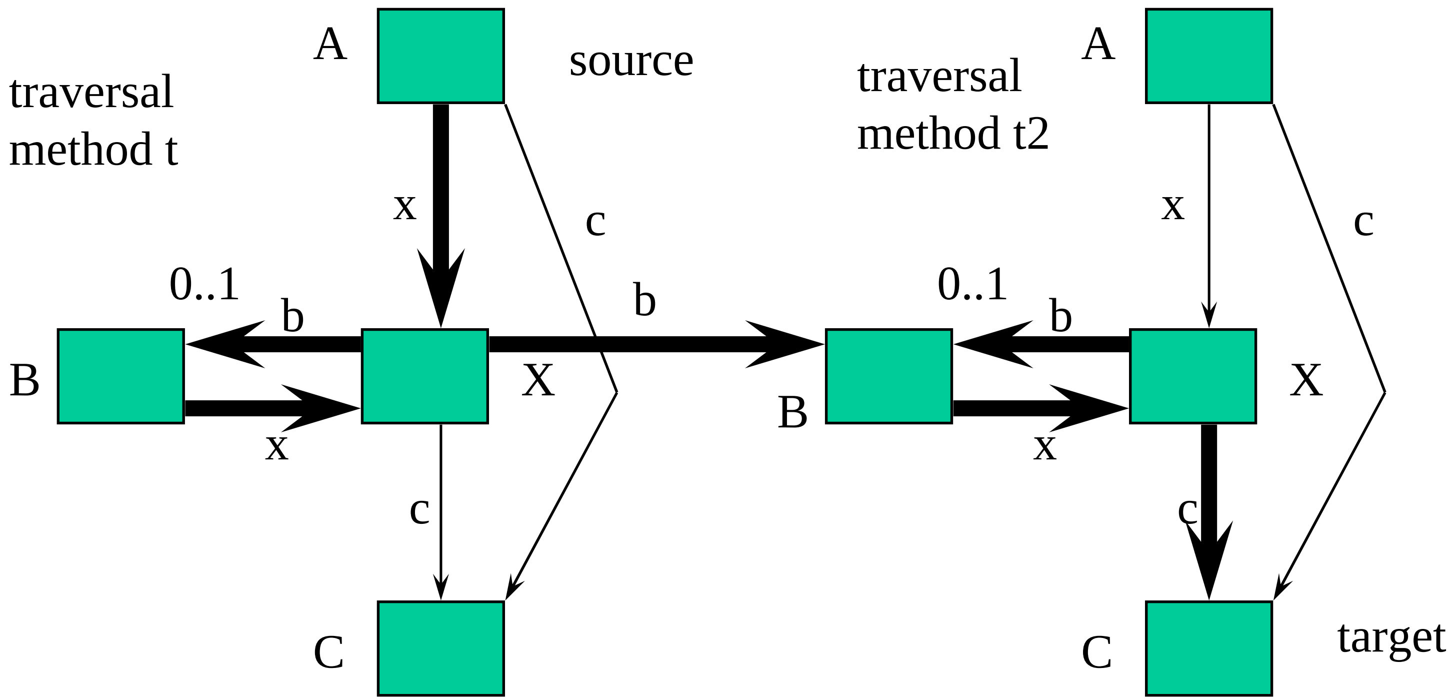


Short-cut

```
strategy:
{A -> B
 B -> C}
```

class graph

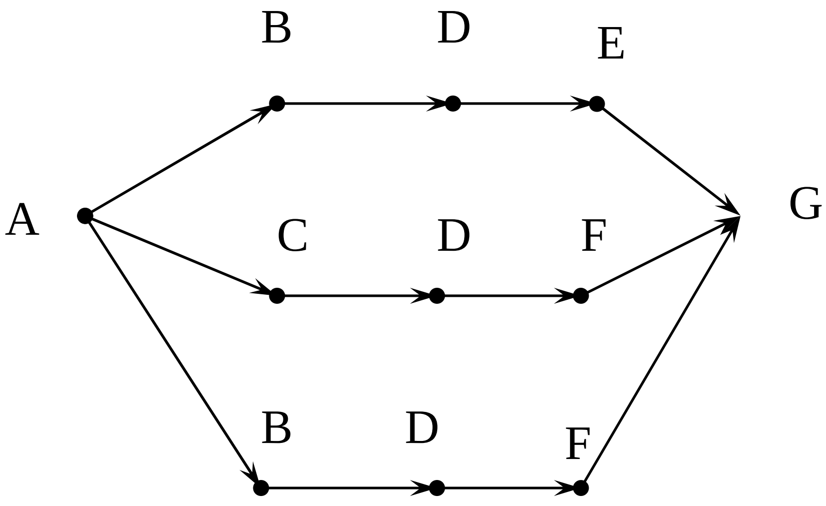
class graph



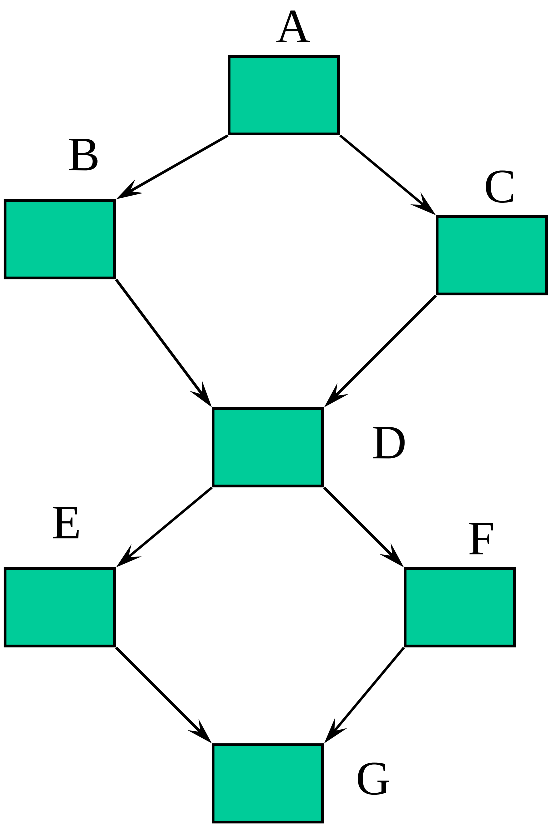
thick edges with incident nodes: traversal graph

Zig-zags

strategy graph
with name map



class graph



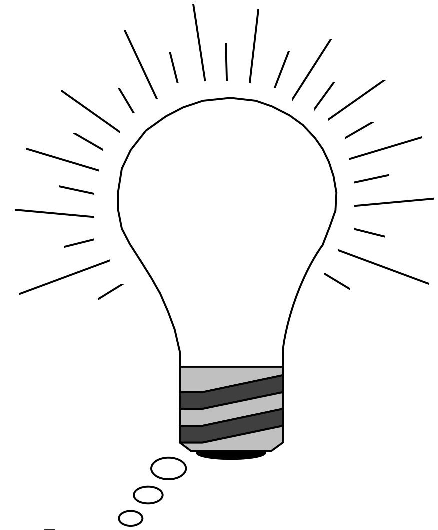
<A C D E G> is excluded

At a D-object need to remember how we got there. Need argument for traversal methods. Represent traversal by tokens in traversal graph.

Compilation of strategies

- Two parts
  - construct graph which expresses the traversal *PathSet[SS,G,N,B]* in a more convenient way: traversal graph *TG(SS,G,N,B)*. Represents allowed traversals as a “big” graph.
  - Generate code for traversal methods by using *TG(SS,G,N,B)*.

Compilation of strategies



- Idea of traversal graph:
  - Paths defined by `from A to B` can be represented by a subgraph of the class graph. Compute all edges reachable from A and from which B can be reached. Edges in intersection form graph which represents traversal.
  - Generalize to any strategies: Need to use *big* graph but above `from A to B` approach will work.

Compilation of strategies

- Idea of traversal graph:
  - traversal graph is “big brother” of propagation graph
  - is used to control traversal
  - FROM-TO computation: Find subgraph consisting of all paths from A to B in a directed graph: Fundamental algorithm for traversals
  - Traversal graph computation is FROM-TO computation.

Strategy behind Strategy

- Instead of developing a specialized algorithm to solve a specific problem, modify the data until a standard algorithm can do the work. May have implications on efficiency.
- In our case: use FROM-TO computation.

FROM-TO computation

- Problem: Find subgraph consisting of all paths from A to B in a directed graph.
  - Forward depth-first traversal from A
    - colored in red
  - Backward depth-first traversal from B
    - colored in blue
  - Select nodes and edges which are colored in both red and blue.

Traversal graph computation Algorithm 1

- Let the strategy graph $S = (C,D)$ and let the strategy graph edges be $D = \{e_1, e_2, \ldots ,e_k\}$.
- 1. Create a graph $G'=(V',E')$ by taking k copies of G, one for each strategy graph edge. Denote the ith copy as $G^i = (V^i,E^i)$.
- The nodes in V^i and edges in E^i are denoted with superscript i, as in v^i, e^i, etc.

Why *k* copies?

- Mimics using *k* distinct traversal method names.
- Run-time traversals need enough state information.

Traversal graph computation

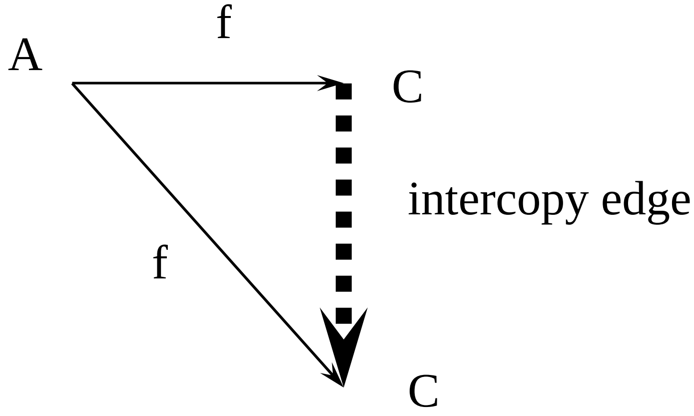
- Each class-graph node *v* corresponds to *k* nodes in *V'*, denoted $v^1, \ldots, v^k$.
- Extend *Class* mapping to apply to nodes of G' by setting $Class(v^i) = v$, where $v^i \in V$ and $v \in V$.

Preview of step 2

- Link the copied class graphs through temporary use of intercopy edges.
- Each strategy graph node is responsible for additional edges in the traversal graph.
- If strategy graph node has one incoming and one outgoing edge, one edge is added.

Preview of step 2

- Addition of edges from one copy to the next:



f may be ◊

Traversal graph computation

- 2.a For each strategy-graph node $a \in C$: Let $I = \{ei_1, \dots, ei_n\}$ be the strategy-graph edges incoming into a, and let $O=\{eo_1, \dots, eo_m\}$ be the set of strategy graph edges outgoing from a. Let $N(a)=v \in V$. Add n times m edges v^j to v^l for $j=1, \dots, n$ and $l = 1, \dots, m$. Call these edges intercopy edges.

Traversal graph computation

- 2.b For each node $v^i \in G'$ with an outgoing intercopy edge: Add edges (u^i,f,v^j) for all u^i such that $(u^i,f,v^i) \in E^i$, and for all v^j which are reachable from v^i through intercopy edges only.
- 2.c Remove all intercopy edges added in step 2.a.

Note: there is a bug lurking here!

- It took a while to find it. Doug Orleans found it in April 99.
  - We used traversal strategies for over two years
  - Paper was reviewed by reviewers of a top journal (Journal of the ACM)
- Solution: switch steps two and three. Why?

Preview of step 3

- Delete edges and nodes which we do not want to traverse.

Traversal graph computation

- 3. For each strategy-graph edge e_i = *from a to b*: Let $N(a) = u$ and $N(b) = v$. Remove from the subgraph G^i all elements which do not satisfy the predicate $B(e_i)$, with the exception of u^i and v^i.
  - $V^{\,i} = \{v^i,u^i\} \cup \{w^i \mid B(e_i)(w)=TRUE\}$, and
  - $E^{\,i} = \{(w^i,l,y^i) \mid B(e_i)(w,l,y)= B(e_i)(w)= B(e_i)(y)=TRUE\}$.

Preview of step 4

- Get ready for the FROM-TO computation in the traversal graph: need a single source and target.

Traversal graph computation

- 4.a Add a node s^* and an edge $(s^*,N(s)^i)$ for each edge e_i outgoing from s in the strategy graph, where s is the source of the strategy.
- 4.b Add a node t^* and an edge $(N(t)^i,t^*)$ for each edge e_i incoming into t in the strategy graph, where t is the target of the strategy.

Traversal graph computation

- 4.c Mark all nodes and edges in *G'* which are both reachable from *s** and from which *t** is reachable, and remove unmarked nodes and edges from *G'*. Call the resulting graph *G''=(V'',E'')*.
- The above is an application of the FROM-TO computation.

Traversal graph computation

- 5. Return the following objects:
  - The graph obtained from *G''* after removing *s** and *t** and all their incident edges. This is the traversal graph *TG(SS,G,N,B)*.
  - The set of all nodes *v* such that *(s*,v)* is an edge in *G''*. This is the start set, denotes T_s.
  - The set of all nodes *v* such that *(v,t*)* is an edge in *G''*. This is the finish set, denoted T_f.

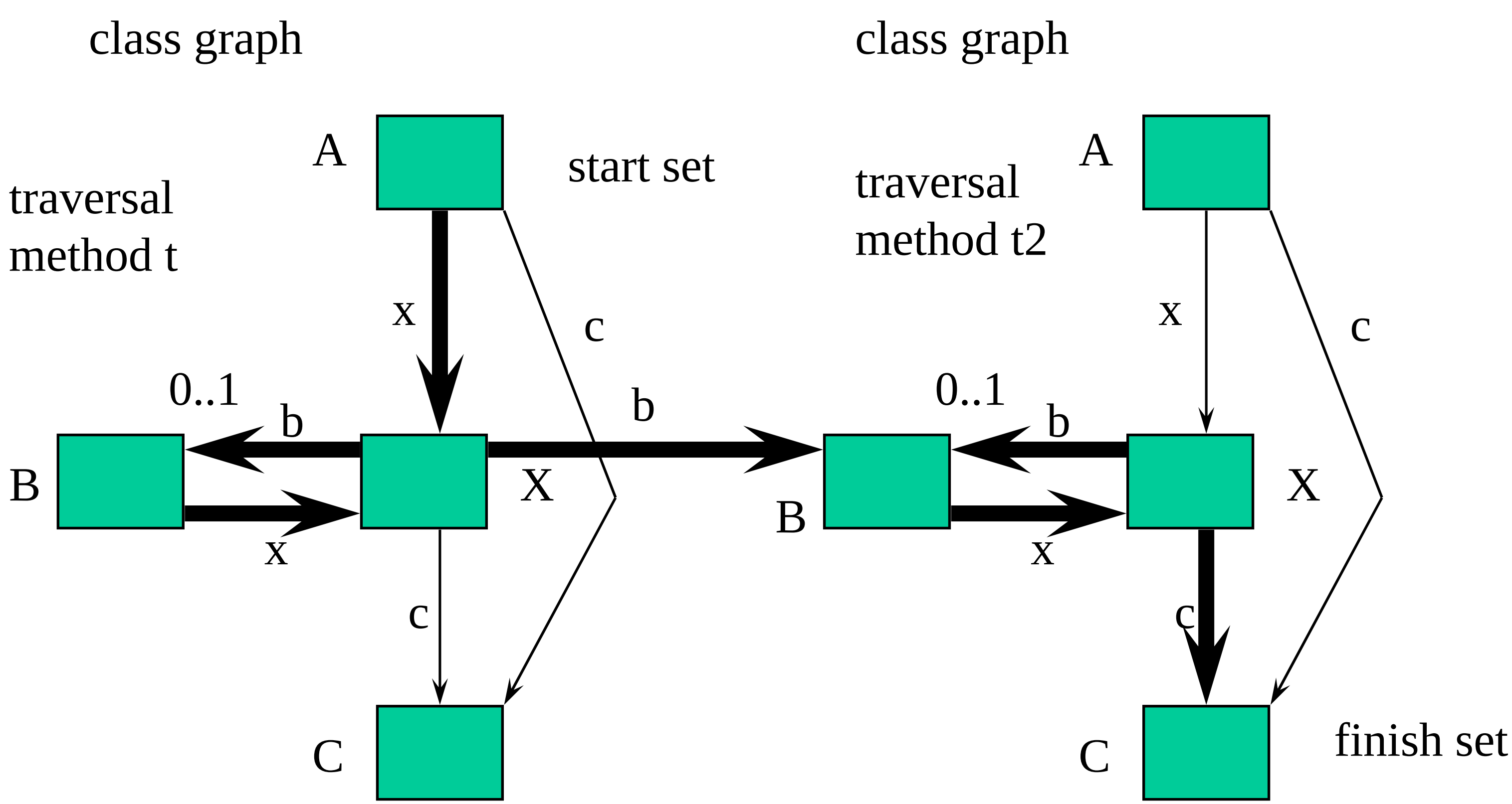
Traversal graph properties

- If *p* is a path in the traversal graph, then under the extended *Class* mapping, *p* is a path in the class graph. (Roughly: traversal graph paths are class graph paths.)

abstract representation
of traversal code

Short-cut

```
strategy:
{A -> B
 B -> C}
```



thick edges with incident nodes: traversal graph

Can now think in terms of a graph and need no longer path sets. But graph may be bigger.

Traversal graph properties

- Let *SS* be a strategy, *G* a class graph, *N* a name map, and let *B* be a constraint map. Let *TG=TG(SS,G,N,B)* be the traversal graph and let T_s be the start set and T_f the finish set generated by algorithm 1. Then $X(Class(P_{TG}(T_s, T_f)))=PathSet[SS,G,N,B]$. (Roughly: Paths from start to finish in traversal graph are the paths selected by strategy.)

abstract representation
of traversal code

Short-cut

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strategy:
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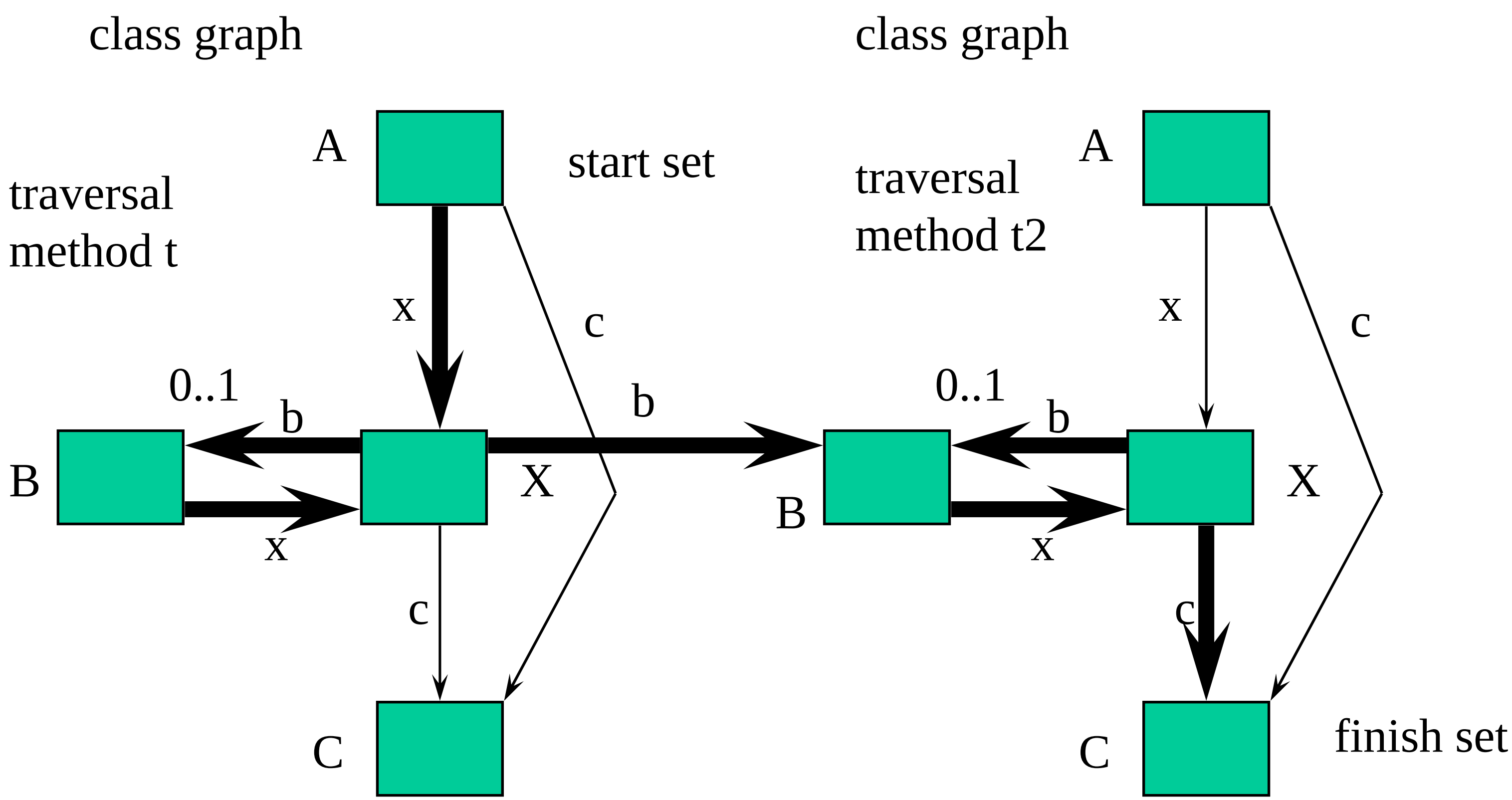
 B -> C}
```



thick edges with incident nodes: traversal graph

generalization

other relationships

Learning map

numbers: order of coverage

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8 FROM-TO computation

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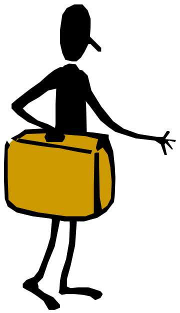
out: object traversal

Traversal methods algorithm Algorithm 2

- Idea is to traverse an object graph while using the traversal graph as a road map.
- Maintain set of “tokens” placed on the traversal graph.
- May have several tokens: path leading to an object may be a prefix of several distinct paths in *PathSet[SS*,*G*,*N*,*B]*.

Traversal method algorithm

- Traversal method *Traverse(T)*, where *T* a set of tokens, i.e., a set of nodes in the traversal graph.
- When *Traverse(T)* invokes visit at an object, that object is added to traversal history.

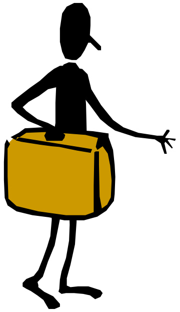


Traversal method algorithm

- *Traversal(T)* is generic: same method for all classes.
- *Traversal(T)* is initially called with the start set T_s computed by algorithm 1.

Traversal methods algorithm

- *Traverse(T)*, guided by traversal graph *TG*.
  - 1. define a set of traversal graph nodes *T'* by *T'={v | Class(v)=Class(*`this`*)* and there exists $u \in T$ such that $u=v$ or $(u,\Diamond,v)$ is an edge in *TG*}.
  - 2. If *T'* is empty, return.
  - 3. Call `this`.visit().



Traversal methods algorithm

– 4. Let Q be the set of labels which appear both on edges outgoing from a node in $T' \in TG$ and on edges outgoing from `this` in the object graph. For each field name $l \in Q$, let

$$T_l = \{v | (u,l,v) \in TG \text{ for some } u \in T'\}.$$

– 5. Call `this`.$l.Traverse(T_l)$ for all $l \in Q$, ordered by "<", the field ordering.

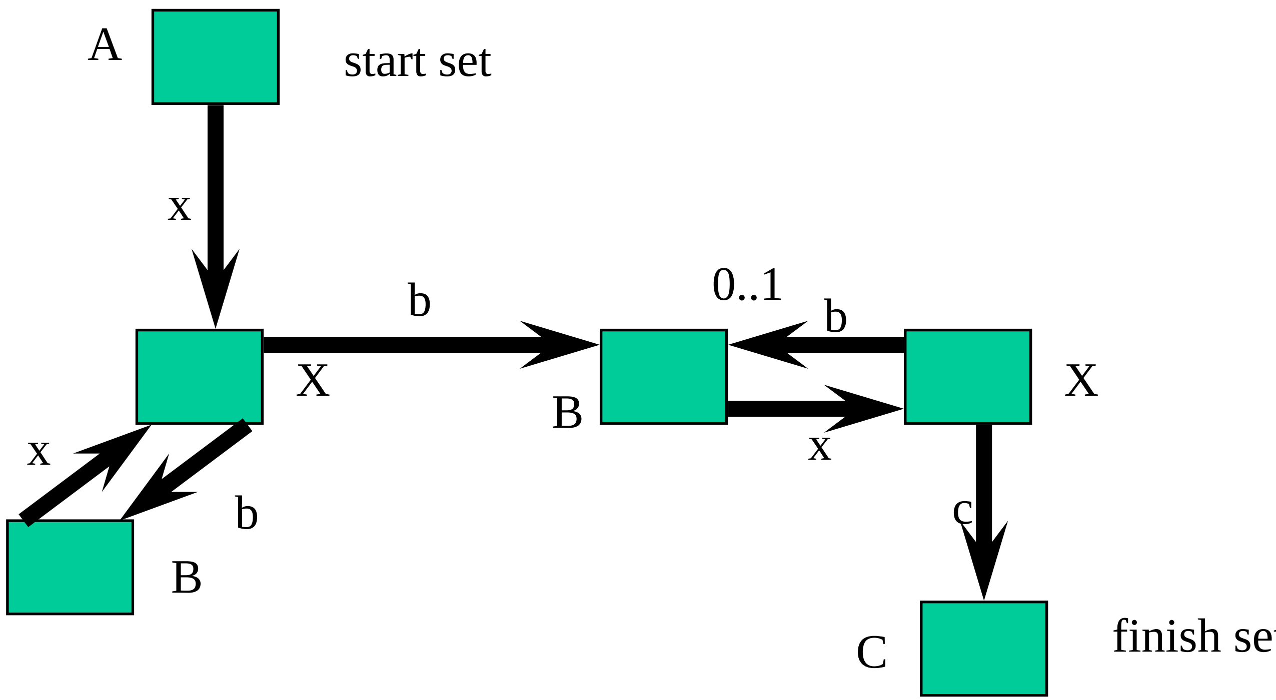
Short-cut

```
strategy:
{A -> B
 B -> C}
```

Object graph

A(
<x> X(
<b> B(
<x> X(
<c> C()))
<c> C()))

Traversal graph



Short-cut

strategy:
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Object graph

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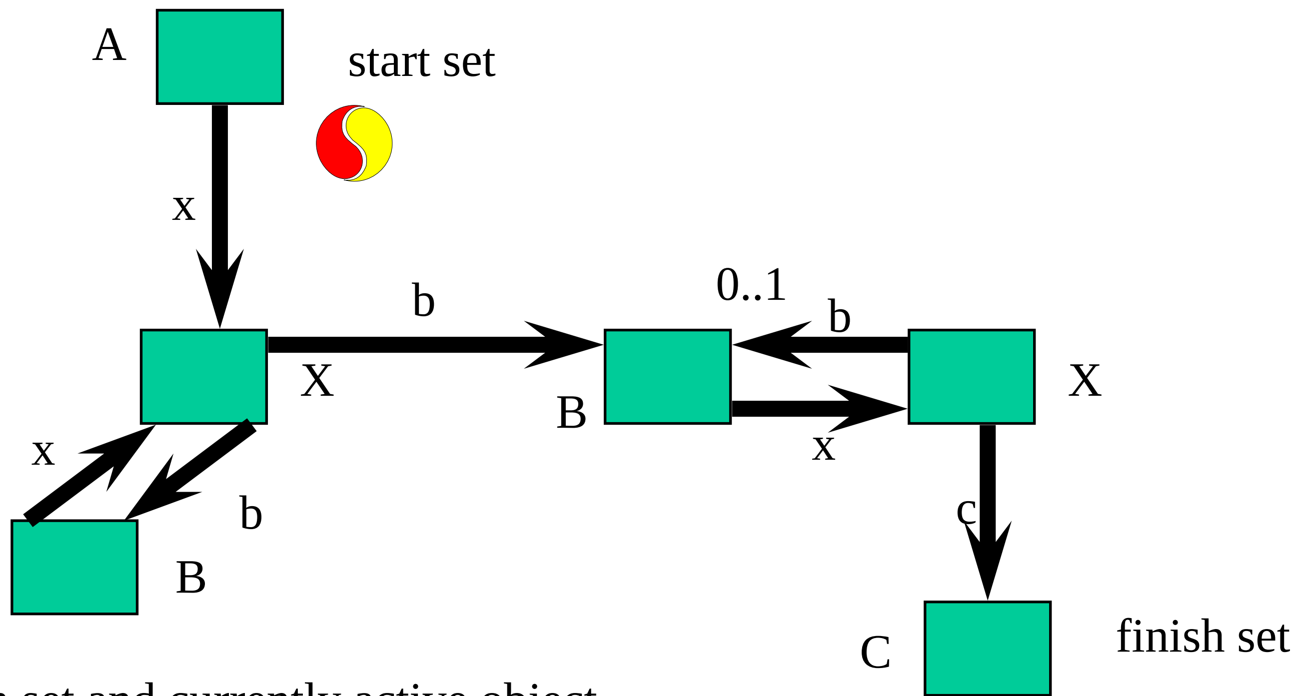
Traversal graph



Used for token set and currently active object

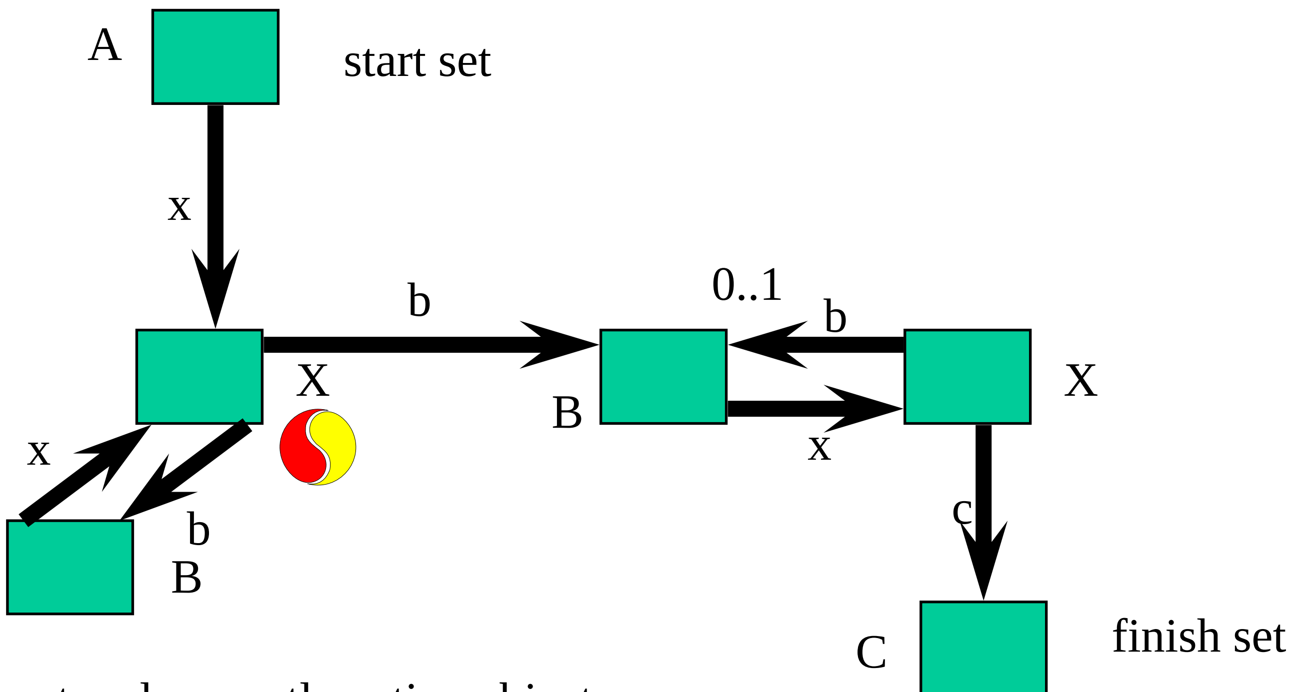
Short-cut

```
strategy:
{A -> B
 B -> C}
```

Object graph

A(
 <x> X(
  <b> B(
   <x> X(
    <c> C()))
  <c> C()))

Traversal graph



Used for token set and currently active object

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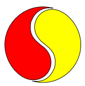
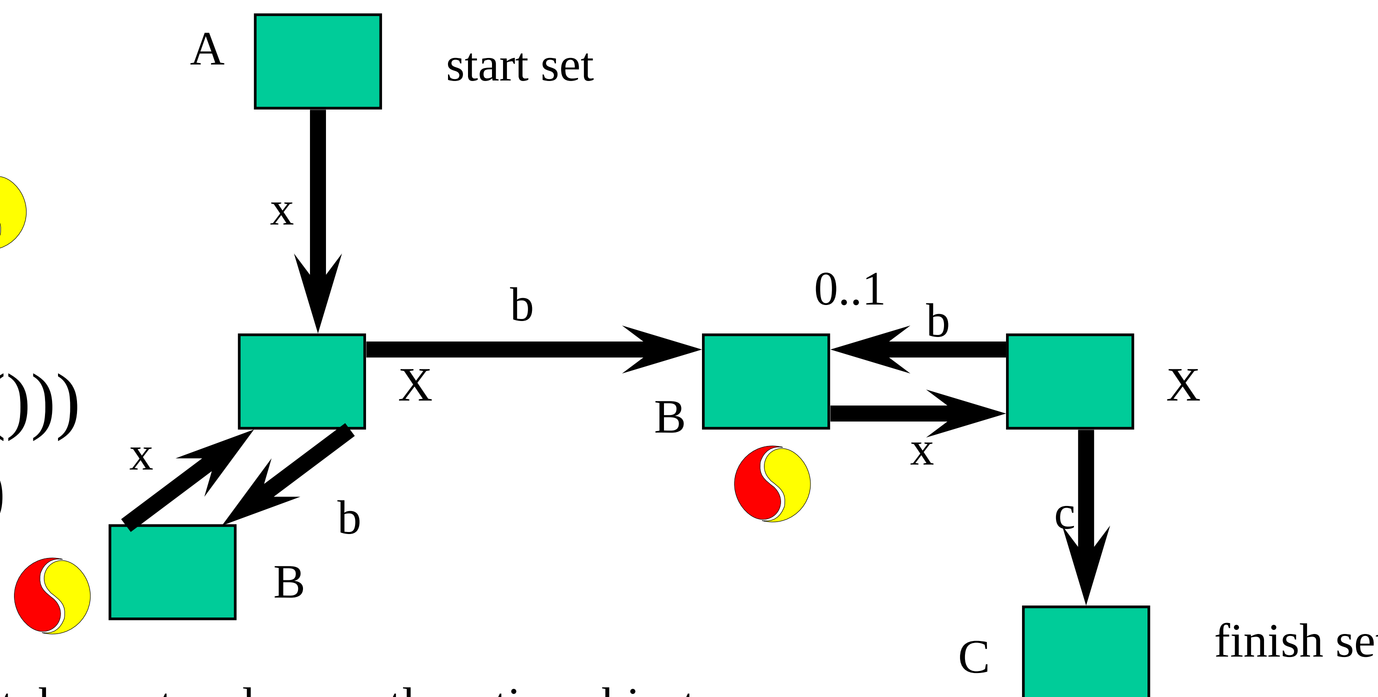
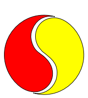
A(
<x> X(
<b> B(
<x> X(
<c> C()))
<c> C()))

Traversal graph



 Used for token set and currently active object

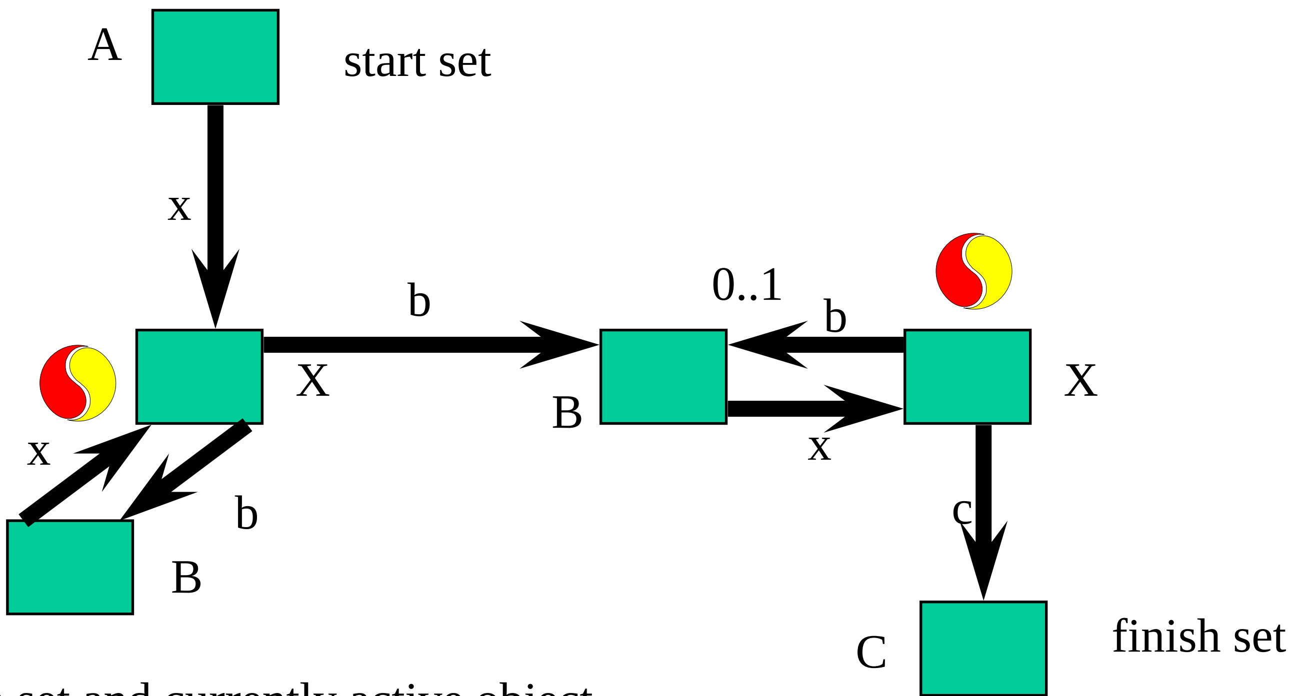
Short-cut

```
strategy:
{A -> B
 B -> C}
```

Object graph

A(
<x> X(
<b> B(
<x> X(
<c> C()))
<c> C()))

Traversal graph



Used for token set and currently active object

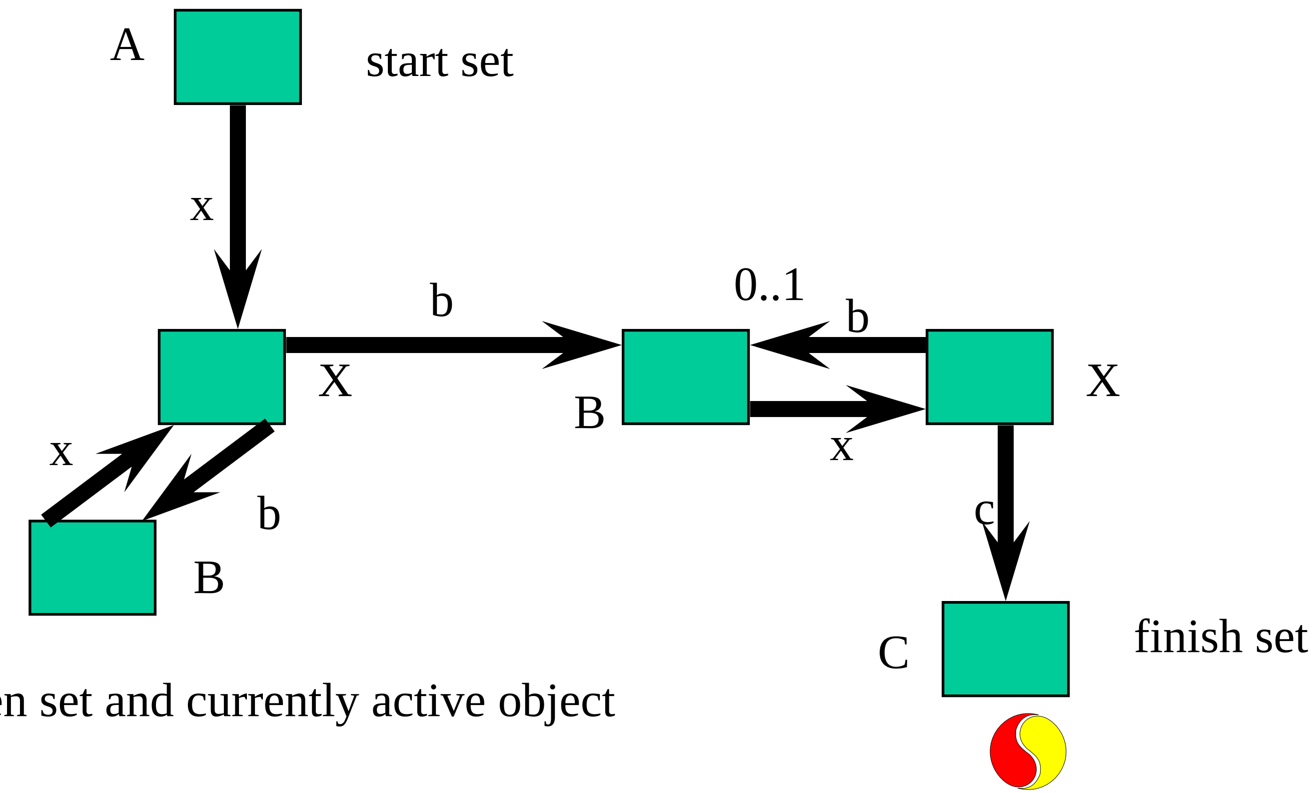
Short-cut

```
strategy:
{A -> B
 B -> C}
```

Object graph

A(
<x> X(
<b> B(
<x> X(
<c> C()))
<c> C()))

Traversal graph



Used for token set and currently active object

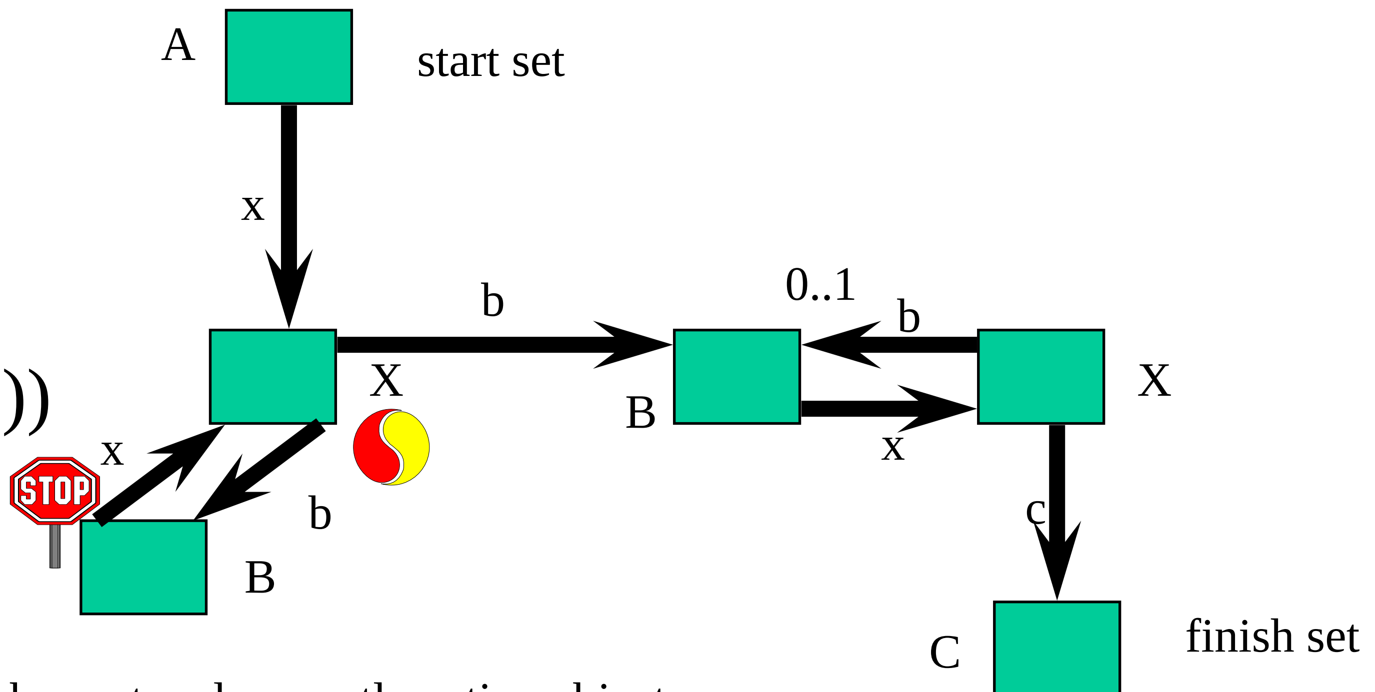
Short-cut

```
strategy:
{A -> B
 B -> C}
```

Object graph

Traversal graph

A(
<x> X(
<b> B(
<x> X(
<c> C()))
<c> C()))



Used for token set and currently active object

After going back to X

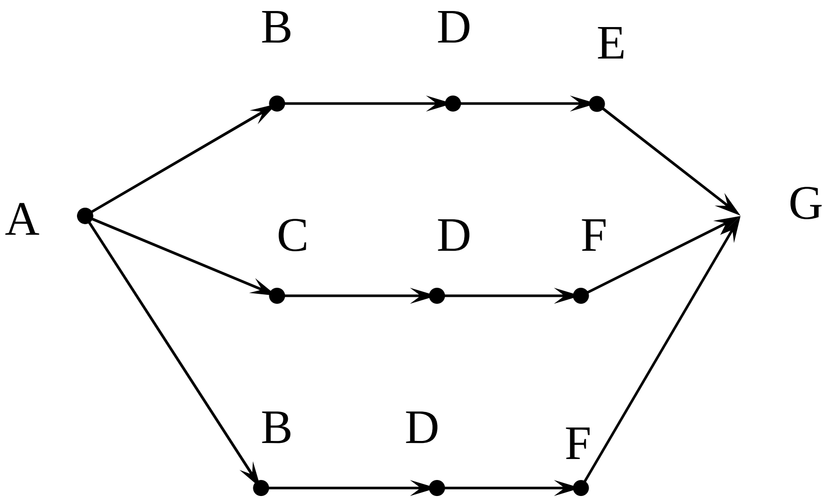
Traversal algorithm property

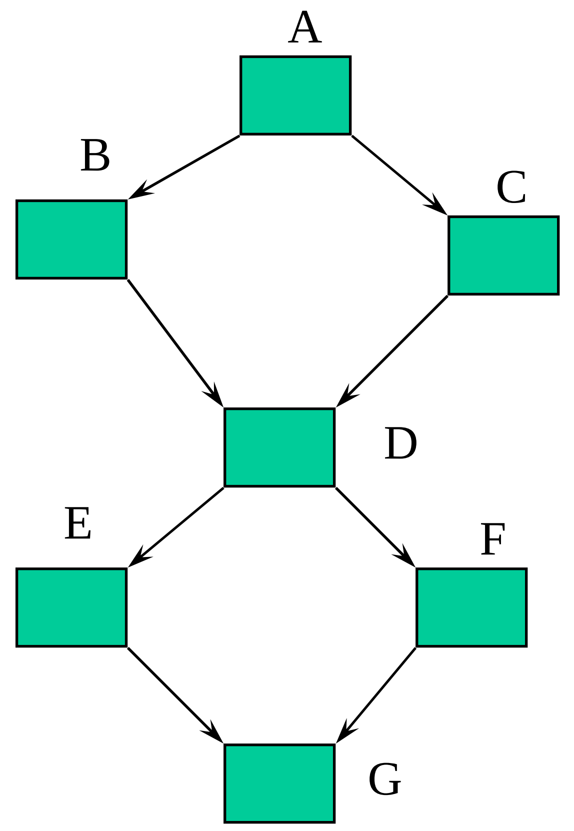
- Let *O* be an object tree and let *o* be an object in *O*. Suppose that the *Traverse* methods are guided by a traversal graph *TG* with finish set T_f. Let *H(o,T)* be the sequence of objects which invoke visit while *o.Traverse(T)* is active, where *T* is a set of nodes in *TG*. Then ***traversing*** *O* ***from*** *o* ***guided by*** $X(P_{TG}(T,T_f))$ ***produces*** *H(o,T)*.

strategy graph
with name map

Zig-zags

class graph





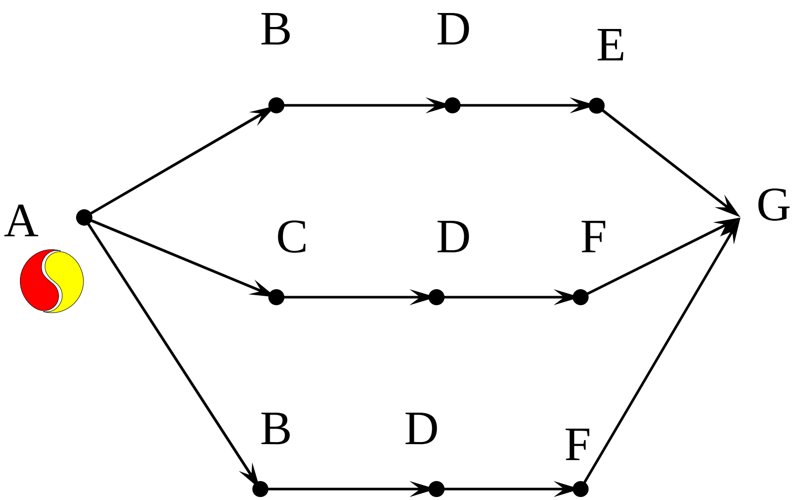
<A C D E G> is excluded

traversal graph = strategy graph
(essentially)

`shorter: {A->D D->F F->G A->B B->E E->G}`

Zig-zags

strategy graph
with name map



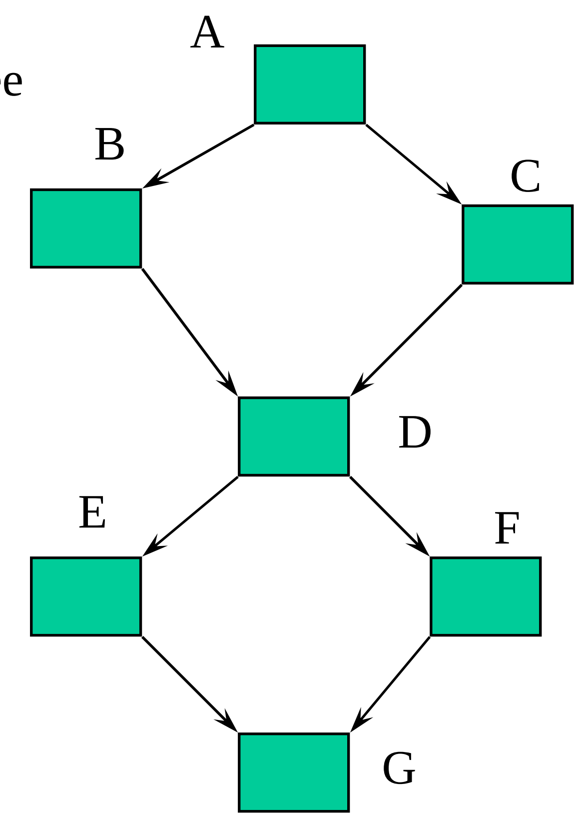
<A C D E G> is excluded

traversal graph = strategy graph
(essentially)

A(
 B(
  D(
   E(
    G())
   F(
    G()))))
 C(
  D(
   E(
    G())
   F(
    G())))))

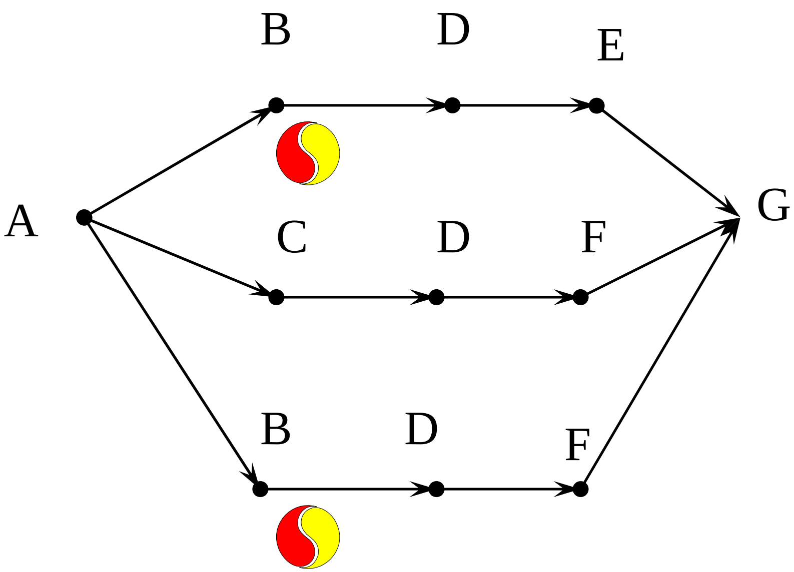
object tree

class graph



Zig-zags

strategy graph
with name map



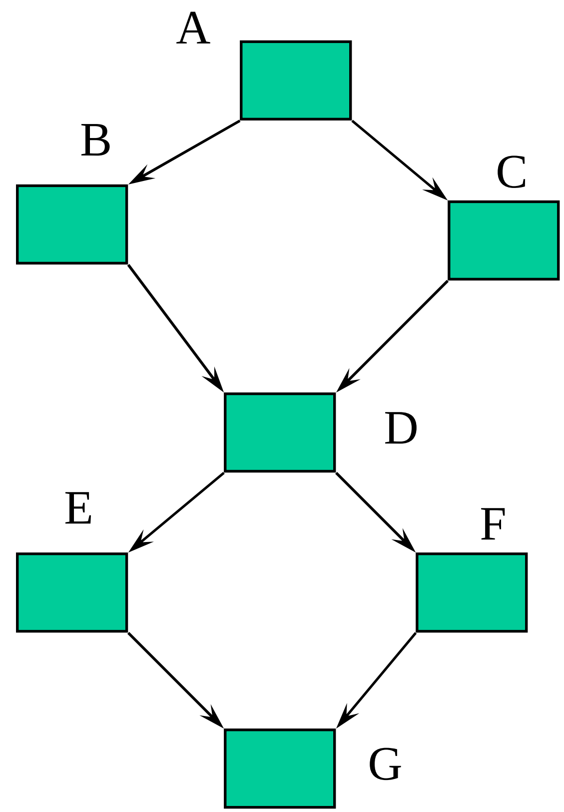
<A C D E G> is excluded

traversal graph = strategy graph
(essentially)

object tree

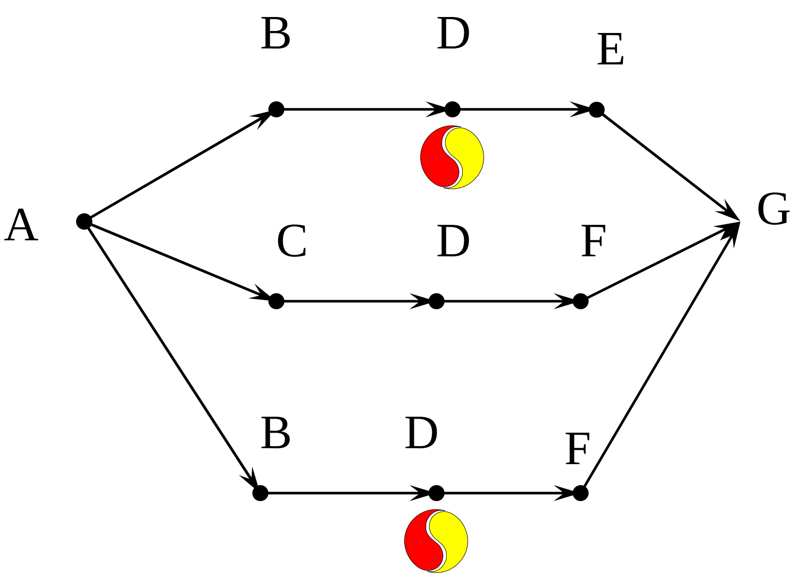
A(
  B(
    D(
      E(
        G())
      F(
        G())))
  C(
    D(
      E(
        G())
      F(
        G())))))

class graph



Zig-zags

strategy graph
with name map



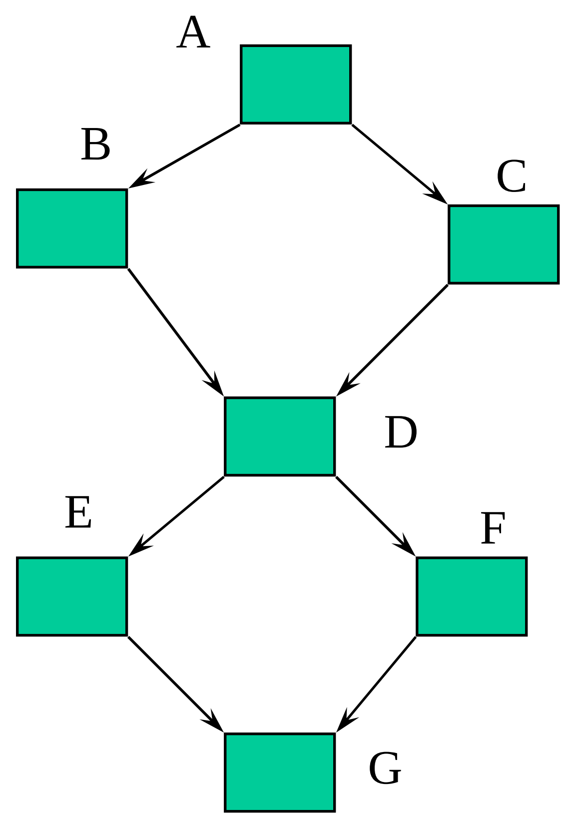
<A C D E G> is excluded

traversal graph = strategy graph
(essentially)

object tree

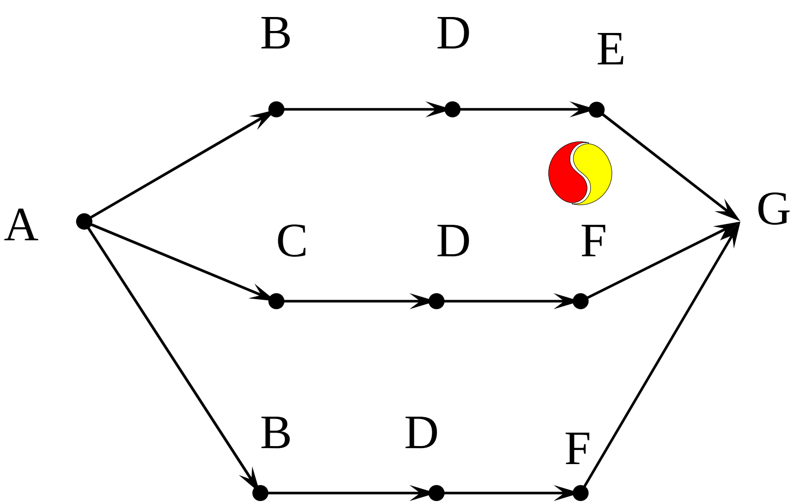
A(
 B(
  D(
   E(
    G())
   F(
    G()))))
 C(
  D(
   E(
    G())
   F(
    G()))))

class graph



Zig-zags

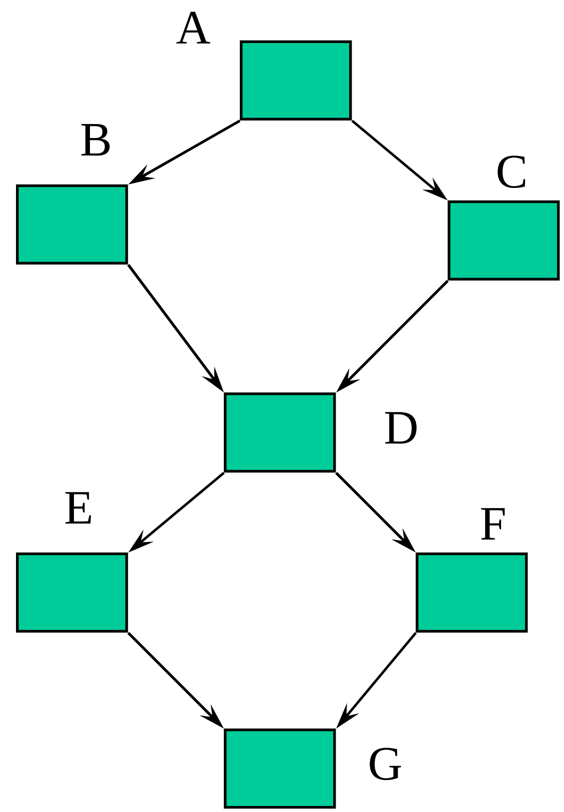
strategy graph
with name map



object tree

```
A(
  B(
    D(
      E(
        G())
      F(
        G()))))
  C(
    D(
      E(
        G())
      F(
        G())))))
```

class graph

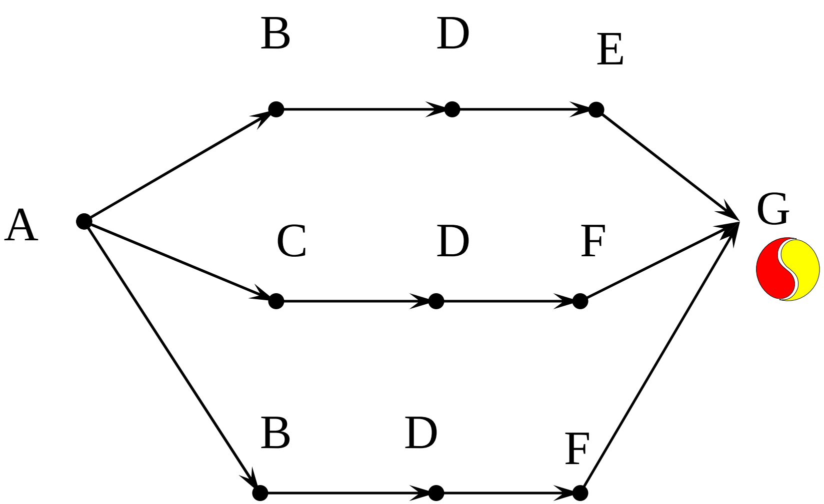


<A C D E G> is excluded

traversal graph = strategy graph
(essentially)

Zig-zags

strategy graph
with name map

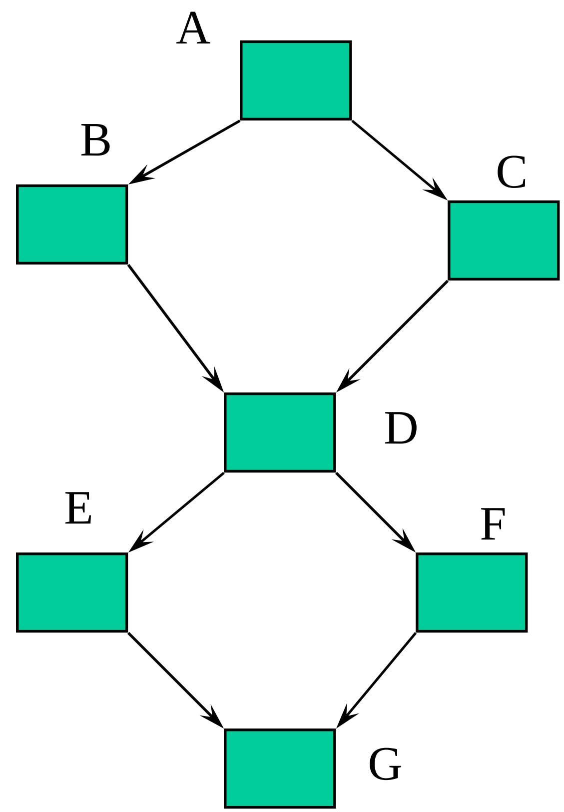


<A C D E G> is excluded

traversal graph = strategy graph
(essentially)

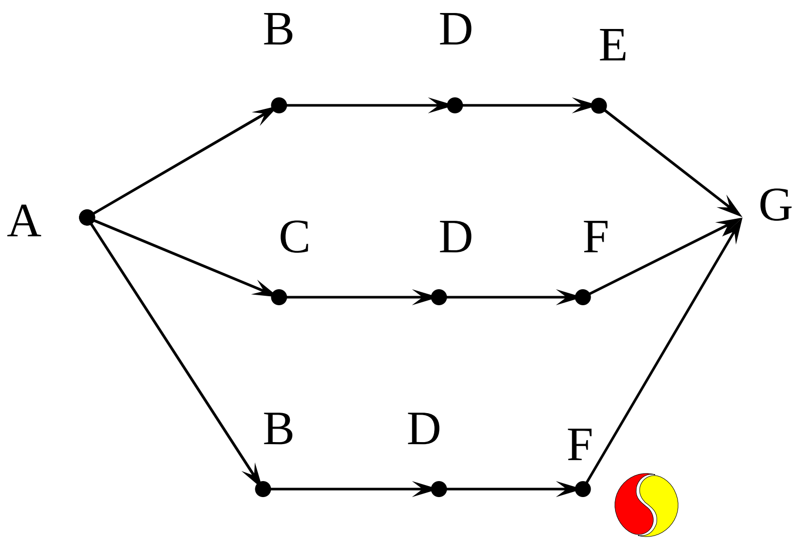
A(object tree
B(
D(
E(
G())
F(
G())))
C(
D(
E(
G())
F(
G()))))

class graph



Zig-zags

strategy graph
with name map

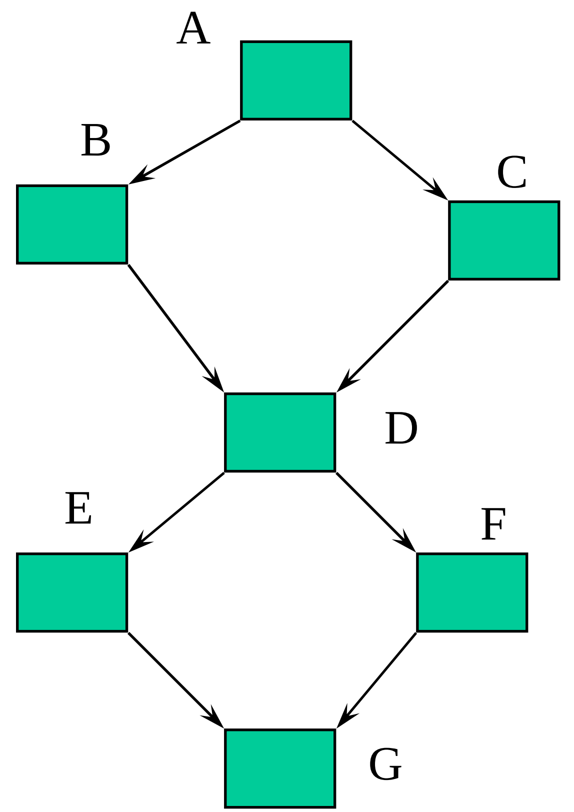


<A C D E G> is excluded

traversal graph = strategy graph
(essentially)

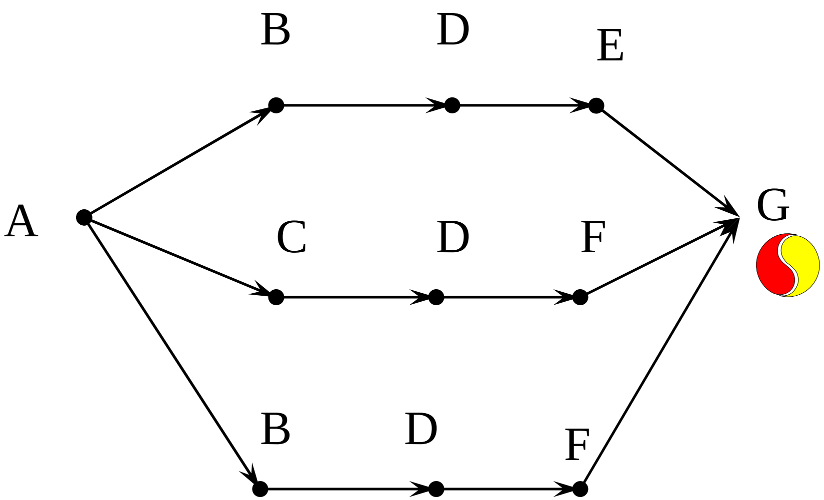
A(object tree
  B(
    D(
      E(
        G())
      F(
        G())))
  C(
    D(
      E(
        G())
      F(
        G()))))

class graph



Zig-zags

strategy graph
with name map



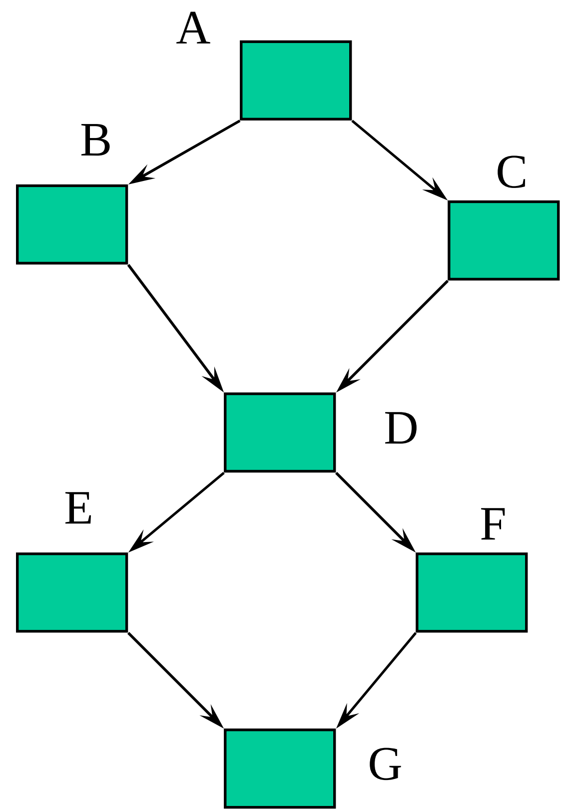
<A C D E G> is excluded

traversal graph = strategy graph
(essentially)

object tree

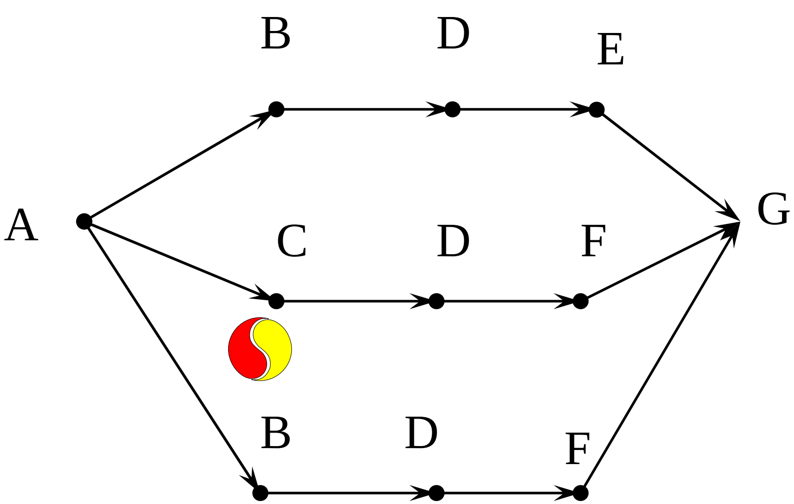
A(
 B(
  D(
   E(
    G())
   F(
    G()))))
 C(
  D(
   E(
    G())
   F(
    G()))))

class graph



Zig-zags

strategy graph
with name map



<A C D E G> is excluded

traversal graph = strategy graph
(essentially)

object tree

```
A(
 B(
  D(
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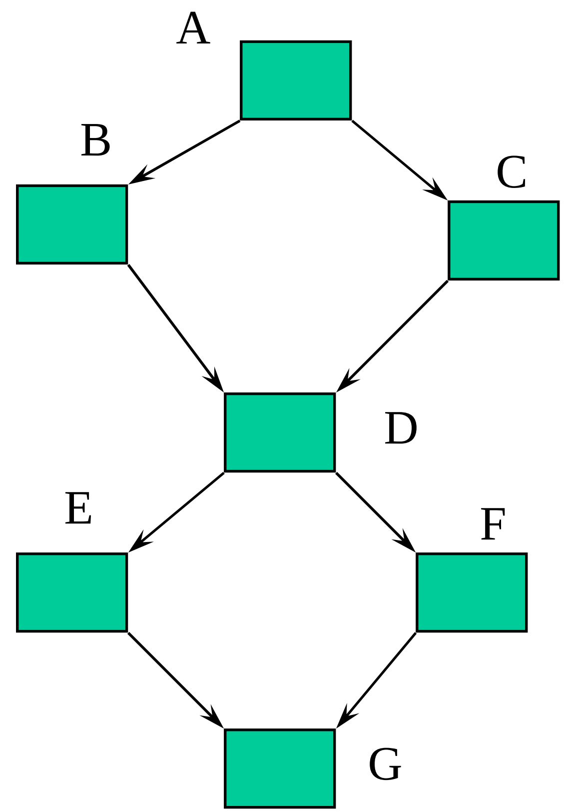
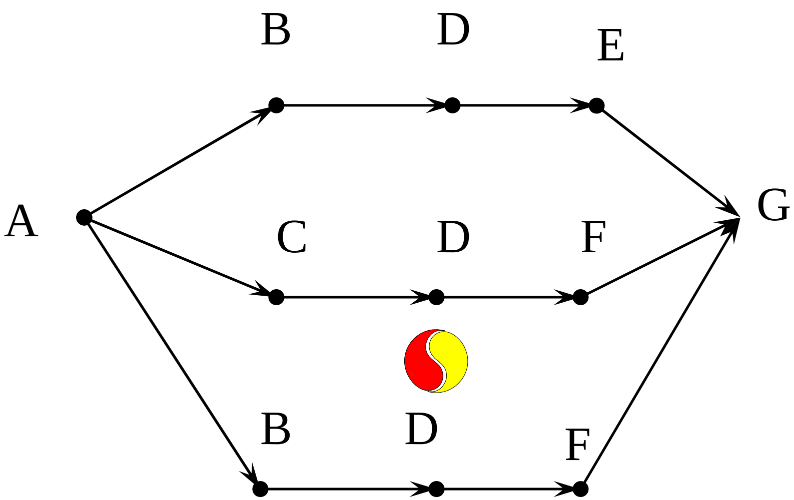
    G())
   F(
    G())))
 C(
  D(
   E(
    G())
   F(
    G())))))
```

class graph



Zig-zags

strategy graph
with name map



<A C D E G> is excluded

traversal graph = strategy graph
(essentially)

A(object tree
B(
D(
E(
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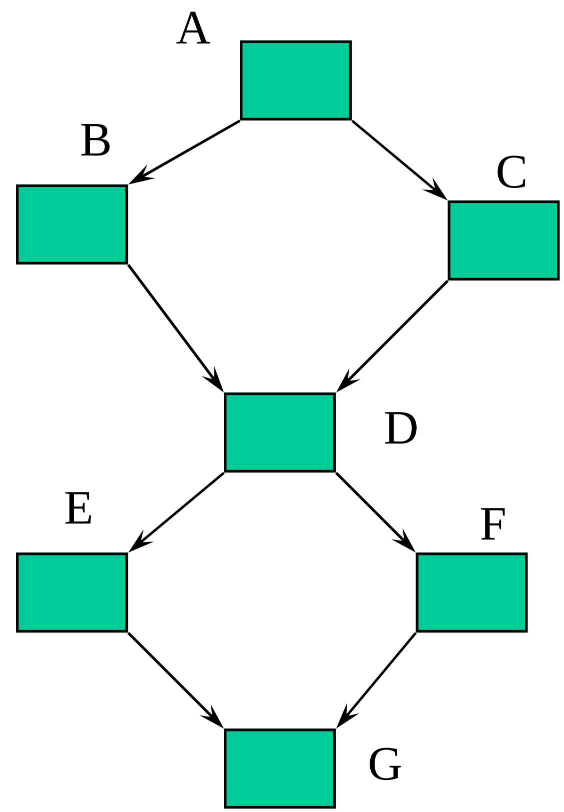
F(
G()))))
C(
D(
E(
G())
F(
G())))))

class graph



Main Theorem

- Let *SS* be a strategy, let *G* be a class graph, let *N* be a name map, and let *B* be a constraint map. Let *TG* be the traversal graph generated by Algorithm 1, and let T_s and T_f be the start and finish sets, respectively.

Main Theorem (cont.)

- Let *O* be an object tree and let *o* be an object in *O*. Let *H* be the sequence of nodes visited when *o.Traverse* is called with argument T_s , guided by *TG*. Then ***traversing*** *O* ***from*** *o* ***guided by*** *PathSet[SS,G,N,B]* ***produces*** *H*.

Complexity of algorithm

- Algorithm 1: All steps run in time linear in the size of their input and output. Size of traversal graph: $O(|S|^2 \, |G| \, d_0)$ where d_0 is the maximal number of edges outgoing from a node in the class graph.
- Algorithm 2: How many tokens? Size of argument T is bounded by the number of edges in strategy graph.

Simplifications of algorithm

- If no short-cuts and zig-zags, can use propagation graph. No need for traversal graph. Faster traversal at run-time.
- Presence of short-cuts and zig-zags can be checked efficiently (compositional consistency).
- See chapter 15 of AP book.

Extensions

- Multiple sources
- Multiple targets
- Intersection of traversals

Summary

- Abstract model behind strategy graphs.
- How to implement strategy graphs.
- How to apply: Precise meaning of strategies; how to write traversals manually (watch for short-cuts and zig-zags).

Where to get more information

- Paper with Boaz-Patt Shamir (strategies.ps in my FTP directory)
- Implementation of Demeter/Java and AP Library shows you how algorithms are implemented in Demeter/Java (and Java). See Demeter/Java resources page.
- Chapter 15 of AP book.

Feedback

- Send email to lieber@ccs.neu.edu.