The CLOSER: Automating Resource Management in Java

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    - Operating system resources: Files, sockets, ...
    - Window system resources: Fonts, colors, ...
    - Application specific resources: Listeners, model view control pattern, ...

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Application Specific Resources

```
public class SomeView {
    private SomeListener l;
    private WorkbenchWindow w;

    public void createPartControl(Composite parent) {
        l = new Listener(this);
        w.addPerspectiveListener(l);
    }

    public void dispose(){
        w.removePerspectiveListener(l);
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We call m the **obligating** method and m' the **fulfilling** method.

Existing Approaches and Their Drawbacks

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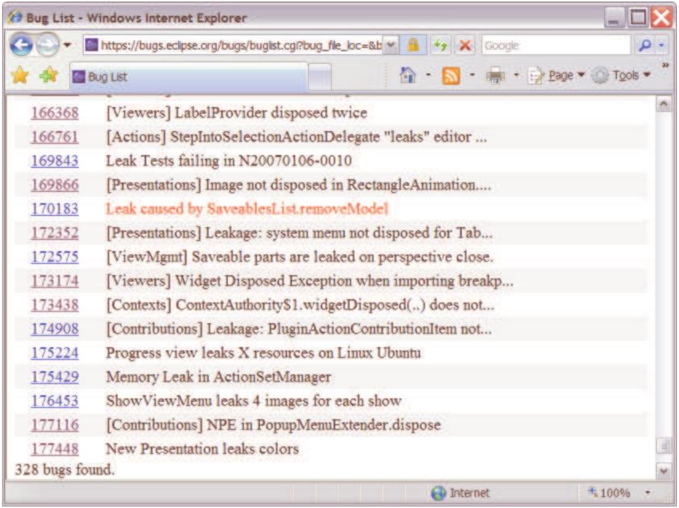

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- Finalization
  - In current JVM implementations, program might run out of non-memory resources before finalizers are called
  - Asynchronous with respect to last use point
  - And therefore almost never used in practice

What is Ideal Resource Management?

- **Dispose resource after its last use (read or write).**

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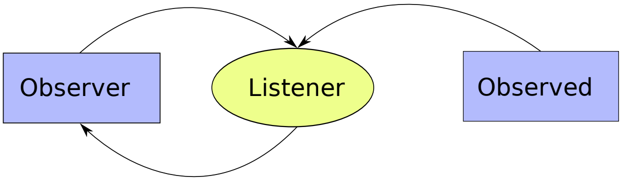

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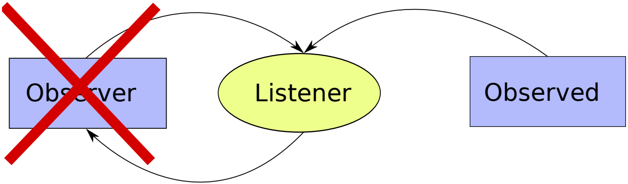

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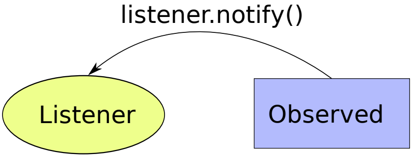

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- **Solution:** Just as last use is approximated by traditional notion of reachability, we approximate last relevant use by **interest reachability**.

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  - If A references B through a non-interest link, then the relevant behavior of A does not depend on the existence of B.
  - Non-interest links must be annotated by the programmer since "relevant" behavior defines application semantics.

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- Advantages:
  - Resource drag is much shorter compared to asynchronous approaches.
  - Works even if disposing the resource has visible side effect (e.g, disposal removes button from a window).

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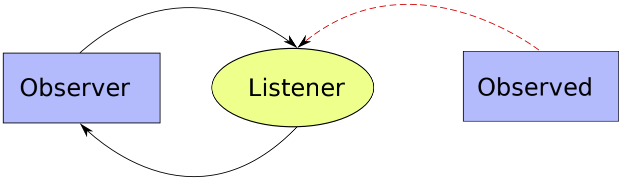

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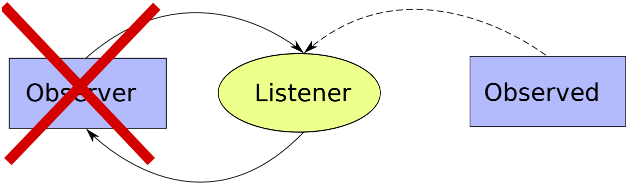

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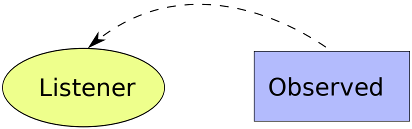

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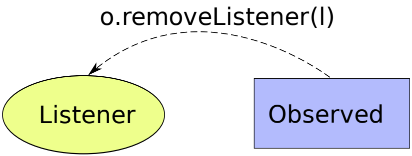

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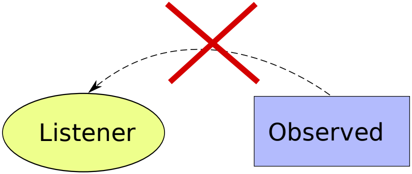

How to Achieve this Goal

Recall:

We want to guarantee that a resource is disposed as soon as it becomes unreachable through interest links.

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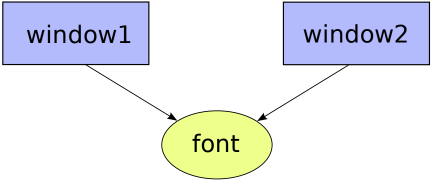
- Whenever possible, statically identify the first program point where resource becomes unreachable through interest links
- When this is not possible, identify the correct dispose point using a variation of reference counting.

Problem: Resource Sharing

A Font object is shared between two Window objects and should be disposed when last window is closed by the user:



Overview of Our Approach

- The user annotates:
  - the set of **primitive resources**

Overview of Our Approach

```
class WorkbenchWindow {

  private Listener l;

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- CLOSER statically analyzes resource lifetimes to identify how and where each resource should be disposed.

- CLOSER automatically inserts any appropriate resource dispose calls into source code.

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- σ_E is a mapping from edges to a boolean value identifying whether that edge is an interest or non-interest edge

Example RIG

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public class BufferPrinter {
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  public BufferPrinter(Buffer buf) {
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    this.listener =
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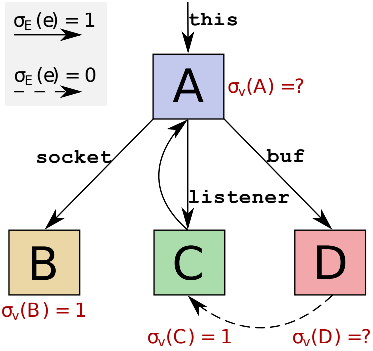

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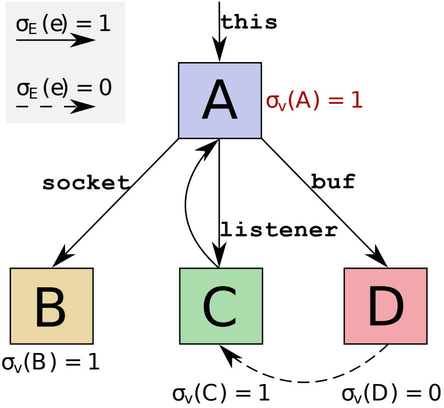
- and the `dispose` method synthesized by CLOSER becomes the corresponding fulfilling method.

Higher-Level Resource Example



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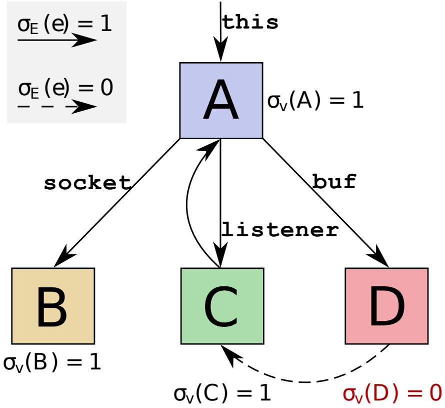

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- Dynamic dispose
  - Requires keeping a run-time "interest-count"
  - Needed whenever CLOSER infers that resource may be shared.

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  - Then by doing data flow analysis to ensure that the inferred solicitor candidates “agree” at every program point.

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- If such a unique path exists, then $l.f_1 ... f_n$ is designated as a solicitor candidate for r
- If the inferred solicior candidates for r are consistent, then r is disposed through the cascading series of dispose calls initiated by l`.dispose()`, invoked after the last use point of l

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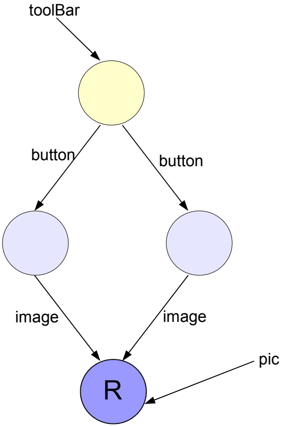

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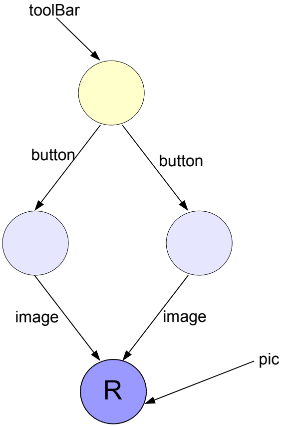

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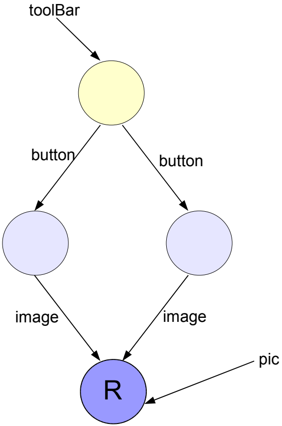

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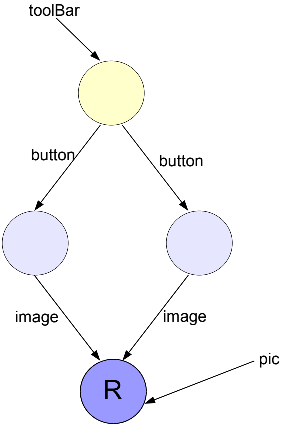

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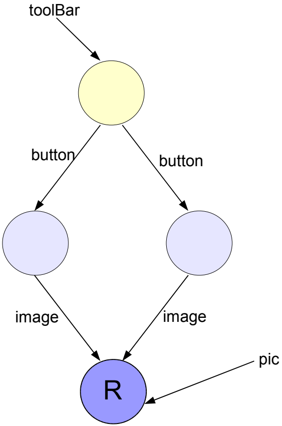

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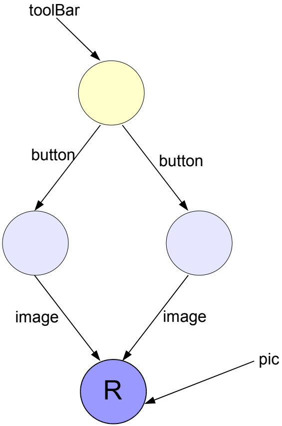

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- Dynamic Instrumentation:
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  - A `Manager` class keeps dynamic interest counts
  - The modified source code calls static methods of the `Manager`
- CLOSER appears transparent to the programmer
  - The programmer can inspect and understand the code instrumented by CLOSER

Case Study

- We applied CLOSER to automate resource management of an SWT Showcase Graphics Application

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Case Study

- We applied CLOSER to automate resource management of an SWT Showcase Graphics Application
- $\sim$ 7500 lines of code
- Uses 67 different resources
- Reasonably complex resource management logic
- Manually removed all resource management code

Case Study, Continued

	Original	Instrumented
# Resources	67	67
# Strong Static Dispose	116	117
# Weak Static Dispose	14	63
# Dynamic Dispose	0	0
# Number of Resource Bugs	1	0
# Lines of Resource Mgmt Code	316	356
Resource Mgmt Code to Application Size Ratio	4.2%	4.9%

Case Study, Continued

	Original	Instrumented
# Resources	67	67
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# Number of Resource Bugs	1	0
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Resource Mgmt Code to Application Size Ratio	4.2%	4.9%

- User annotates only 5 resources.
- CLOSER infers all the remaining 62 resources.

Case Study, Continued

	Original	Instrumented
# Resources	67	67
# Strong Static Dispose	116	117
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	Original	Instrumented
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- Missing dispose call in the original code was a resource leak.
- Programmer forgot to dispose a `Transpose` (resource in SWT).

Case Study, Continued

	Original	Instrumented
# Resources	67	67
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Resource Mgmt Code to Application Size Ratio	4.2%	4.9%

- More weak dispose calls because CLOSER is path-insensitive.
- Inserts redundant null-checks even though one already exists.

Case Study, Continued

```
private void paint() {
    if(image == null) {
        if(image!=null){
            image.dispose();
        }
        image = new Image(...);
    }
}
```

Case Study, Continued

	Original	Instrumented
# Resources	67	67
# Strong Static Dispose	116	117
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- No shared resources in the application.
- CLOSER successfully identified all resources as unshared.

Case Study, Continued

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# Number of Resource Bugs	1	0
# Lines of Resource Mgmt Code	316	356
Resource Mgmt Code to Application Size Ratio	4.2%	4.9%

- CLOSER doesn't cause code bloat or substantial runtime overhead.
- And it is correct by construction.

Related Work

DeLine, R., and Fahndrich, M.
Enforcing high-level protocols in low-level software.
In *PLDI '01: Proceedings of the ACM SIGPLAN 2001 conference on Programming language design and implementation* (New York, NY, USA, 2001), ACM Press, pp. 59–69.

Guyer, S., McKinley, K., and Frampton, D.
Free-Me: a static analysis for automatic individual object reclamation.
Proceedings of the 2006 ACM SIGPLAN conference on Programming language design and implementation (2006), 364–375.

Heine, D. L., and Lam, M. S.
A practical flow-sensitive and context-sensitive c and c++ memory leak detector.
In *PLDI '03: Proceedings of the ACM SIGPLAN 2003 conference on Programming language design and implementation* (New York, NY, USA, 2003), ACM, pp. 168–181.

Blanchet, B.
Escape analysis for object oriented languages. application to Java^{tm}.
In *OOPSLA* (Denver, 1998).

Boehm, H.
Destructors, finalizers, and synchronization.
ACM SIGPLAN Notices 38, 1 (2003), 262–272.