Query-Directed Adaptive Heap Cloning for Optimizing Compilers

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April 3, 2013

Heap cloning

Statically distinguishing heap objects by call paths

Heap cloning

Statically distinguishing heap objects by call paths

```
int main(){
  int* buffer1 = getMem();
  int* buffer2 = getMem();
}
```

```
int* getMem(){
  return malloc(10);
}
```

Heap cloning

Statically distinguishing heap objects by call paths

```
int main(){
  int* buffer1 = getMem();
  int* buffer2 = getMem();
}
```

```
int* getMem(){
  return malloc(10);
}
```

main

Program execution

Heap cloning

Statically distinguishing heap objects by call paths

```
int main(){
  int* buffer1 = getMem();
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}

int* getMem(){
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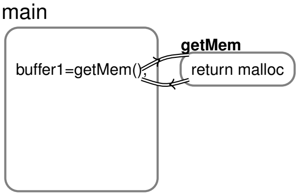
}
```



Program execution

@ Yulei Sui, CGO 2013, 25/02/2013
PLC, UNSW

Heap cloning

Statically distinguishing heap objects by call paths

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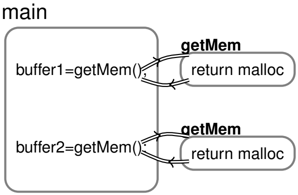
int main(){
  int* buffer1 = getMem();
  int* buffer2 = getMem();
}

int* getMem(){
  return malloc(10);
}
```



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Heap cloning

Statically distinguishing heap objects by call paths

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}
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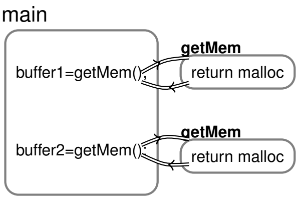
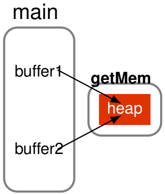
```
int* getMem(){
  return malloc(10);
}
```



Program execution



Points-to relations without heap cloning

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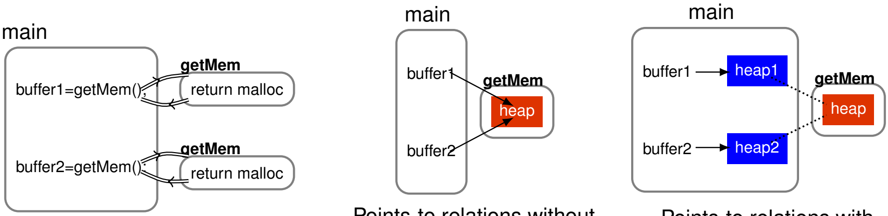
Heap cloning

Statically distinguishing heap objects by call paths

```
int main(){
  int* buffer1 = getMem();
  int* buffer2 = getMem();
}
```

```
int* getMem(){
  return malloc(10);
}
```

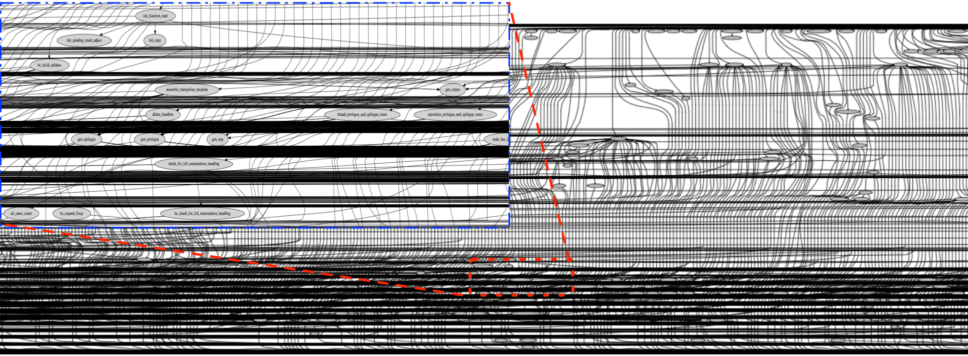


Program execution

Points-to relations without heap cloning

Points-to relations with heap cloning

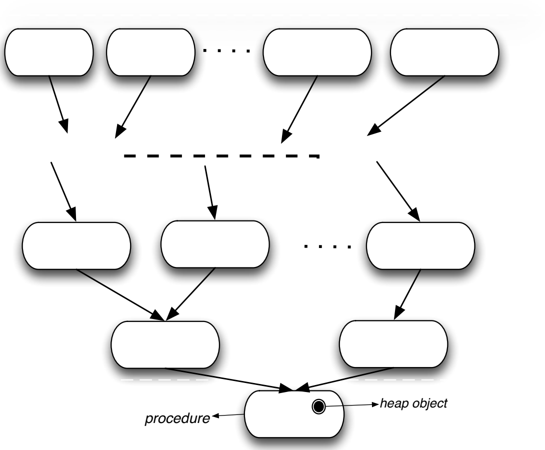
Call graph of 176.gcc (230.4KLOC)



#Procedures: 2256 #Pointers: 134380 #Calling Contexts: $1.2*10^5$

Context-sensitive heap cloning can be costly!

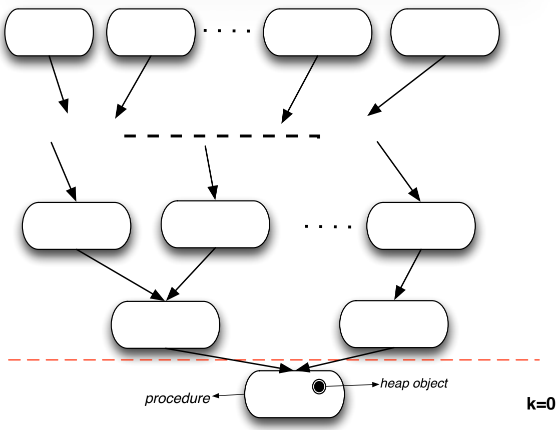
K-callsite-sensitive heap cloning



Call Graph with K-callsite-sensitive heap cloning

[Nystrom-SAS'04, Nystrom-PASTE'04, Lhotak-CC'06, Xu-ISSTA'08]

K-callsite-sensitive heap cloning



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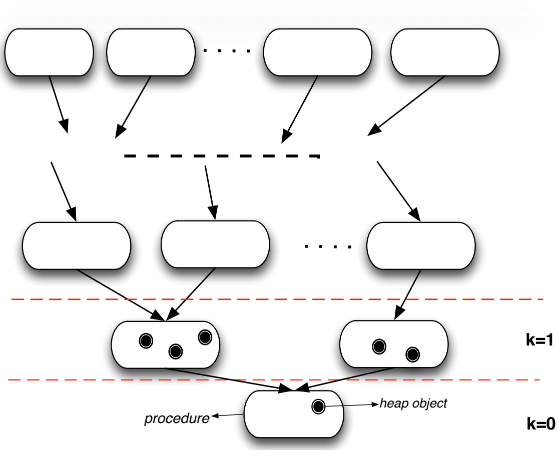

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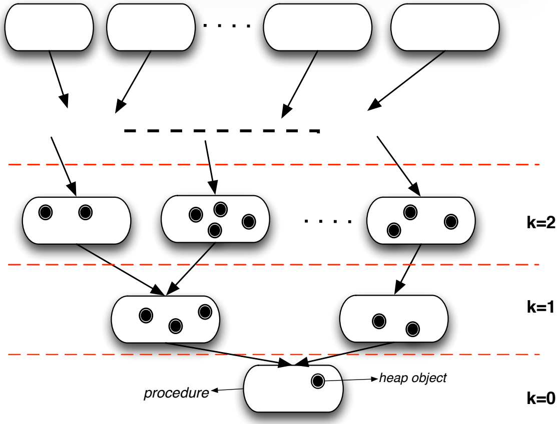

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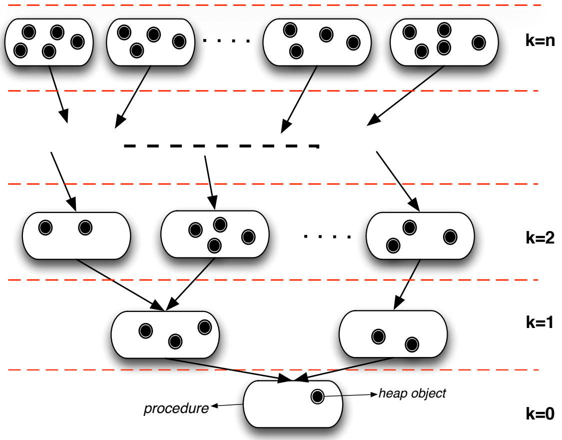

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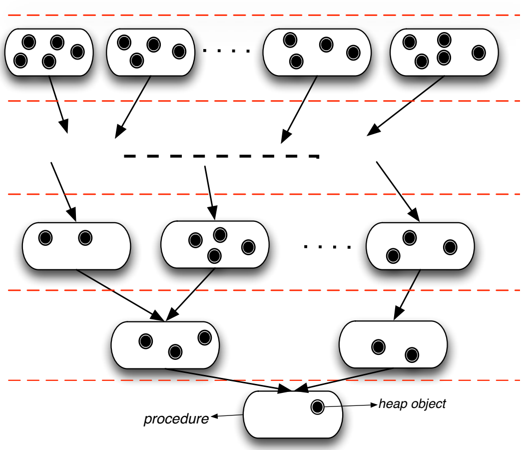

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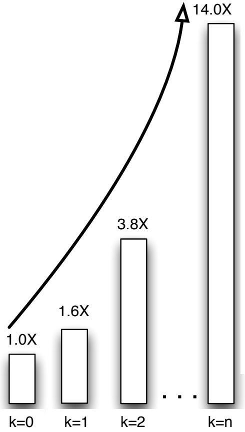

Analysis time of 176.gcc with Andersen-style context sensitive heap cloning

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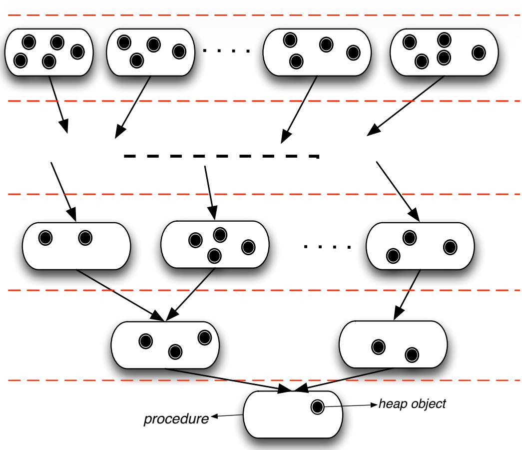
K-callsite-sensitive heap cloning



Call Graph with K-callsite-sensitive heap cloning

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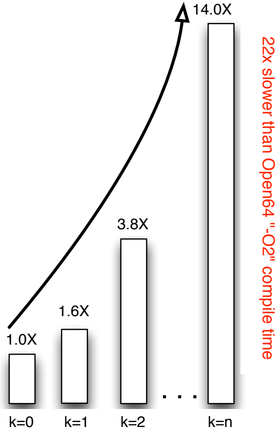

Analysis time of 176.gcc with Andersen-style context sensitive heap cloning

- Is *full heap cloning* overkill (relative to a client's needs)?

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- Is *k-callsite sensitive cloning* the best solution?

Alias Query

- Whether two expressions may represent the same memory location.

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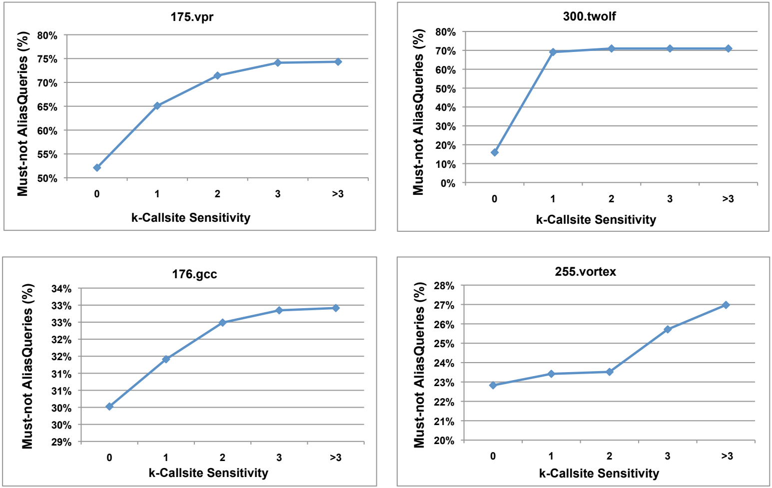
- For example: ⟨*buffer1,*buffer2⟩
  - Alias   Without Heap Cloning

Alias Query

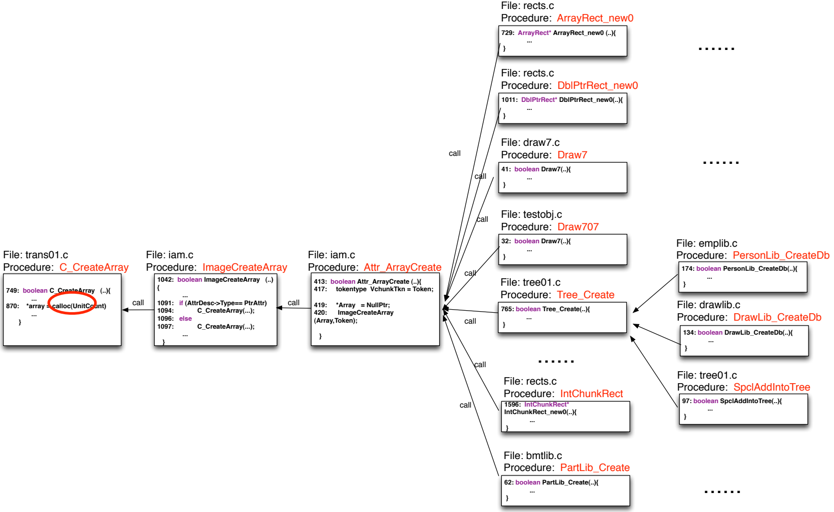
- Whether two expressions may represent the same memory location.
- For example: ⟨*buffer1,*buffer2⟩
  - Alias Without Heap Cloning
  - Not-Alias Heap Cloning

Analysis precision for answering alias queries



Percentage of must-not aliases disambiguated among the queries issued by WOPT with k-callsite-sensitive heap cloning

A close look at 255.vortex's call graph



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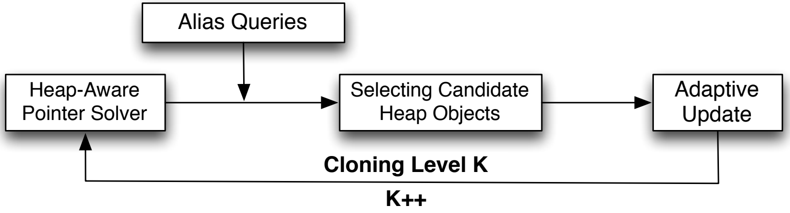
Goal

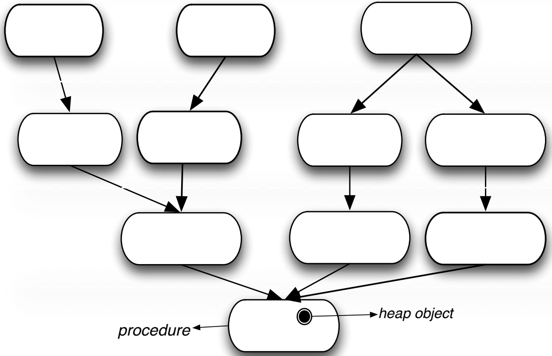
- Can we enable heap cloning only where it is necessary?
- Can we achieve the same precision as full heap cloning according to a client's needs?

Our QUDA framework

QUery-Directed Adaptive heap cloning



Query-directed adaptive heap cloning



Query-Directed Adaptive Heap Cloning

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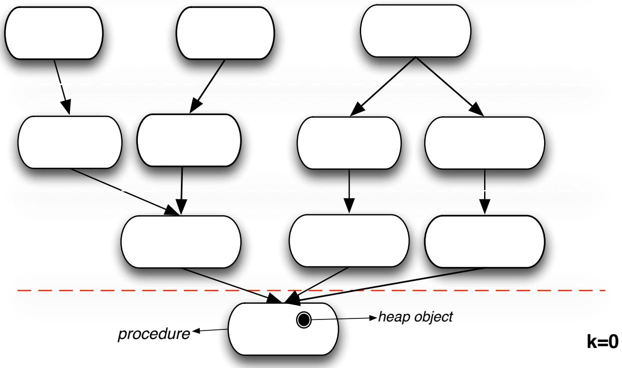

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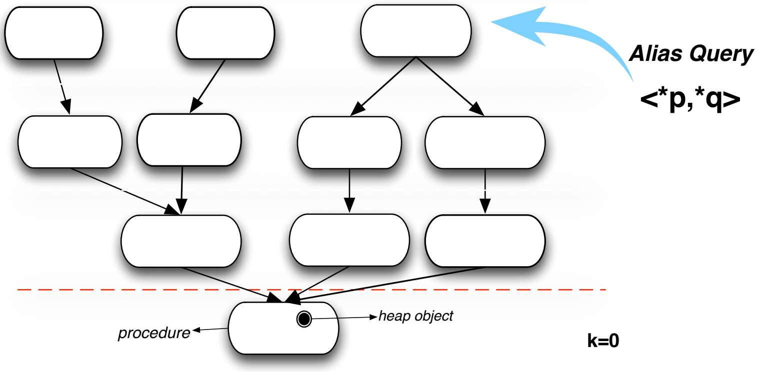

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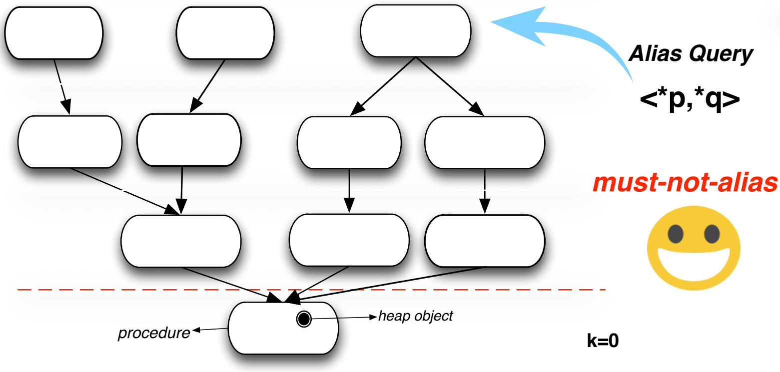

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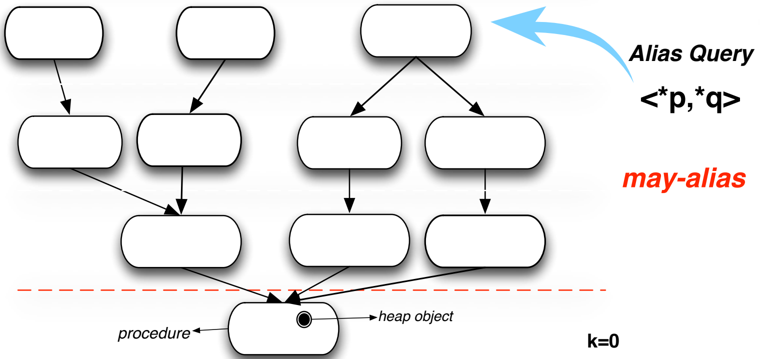

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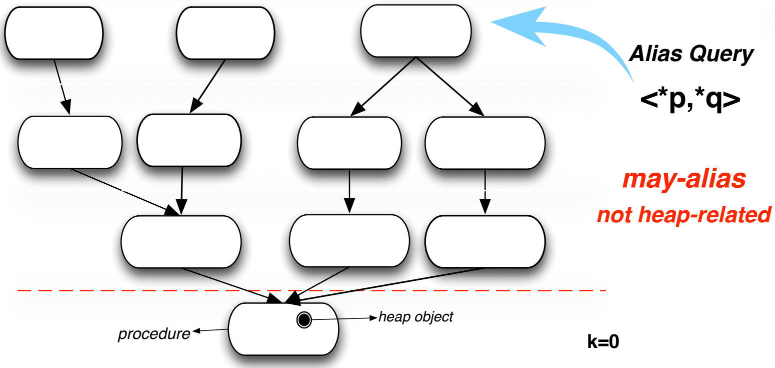

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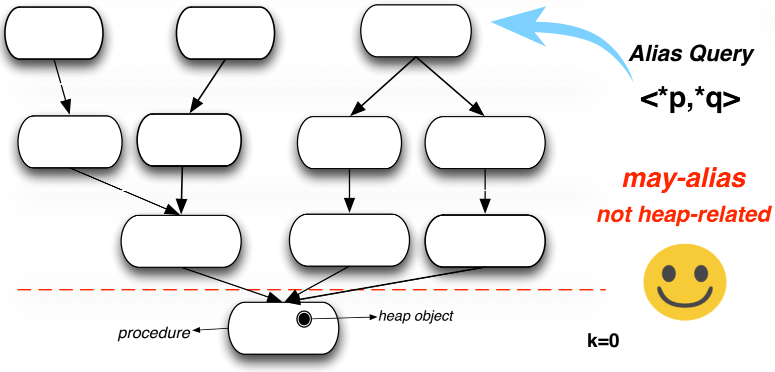

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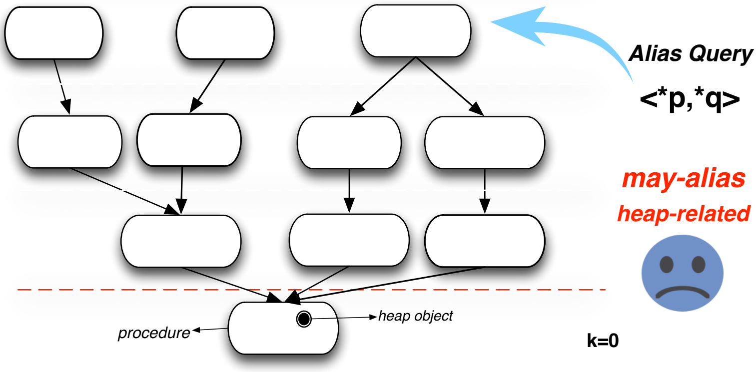

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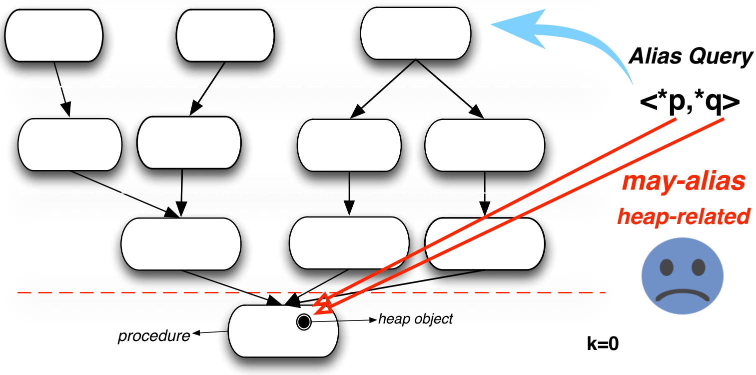

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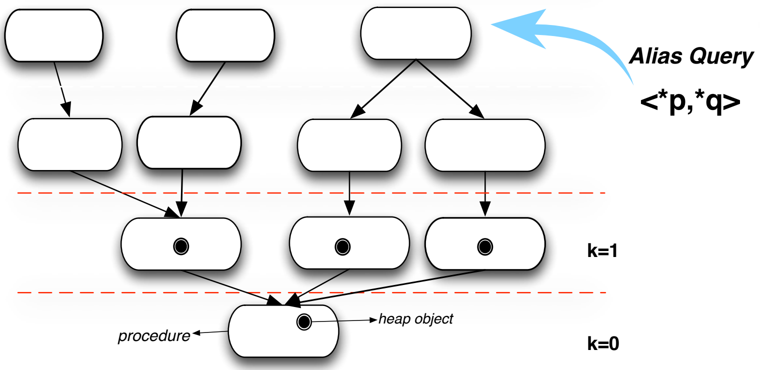

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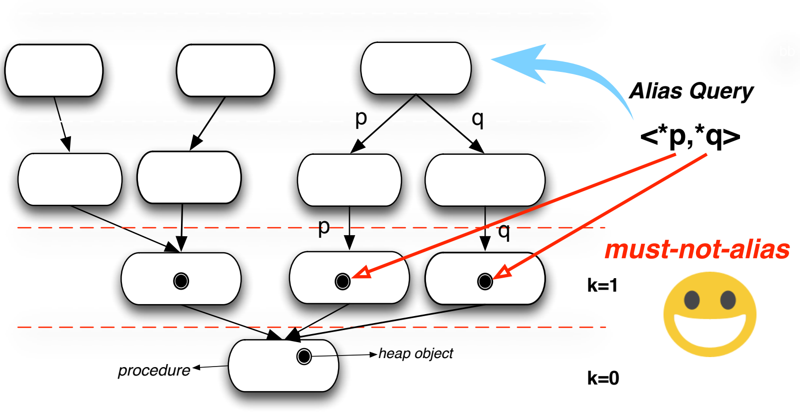

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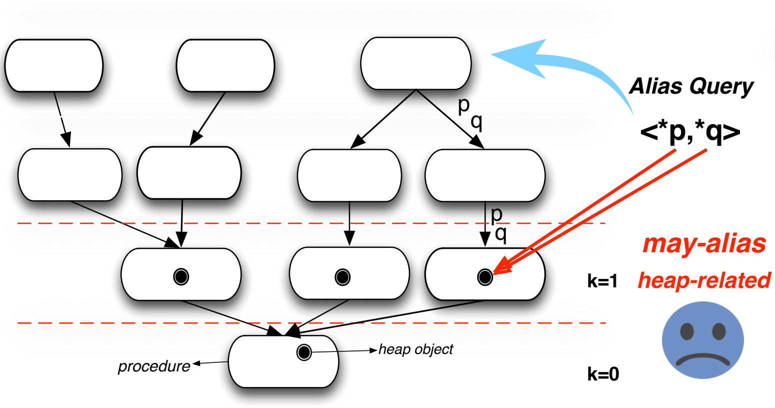

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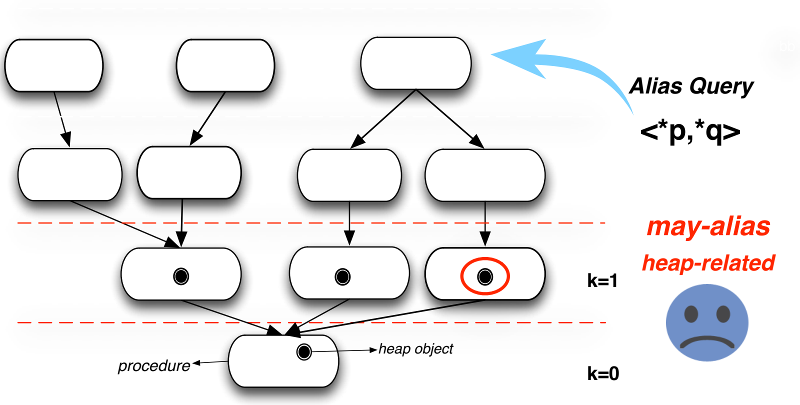

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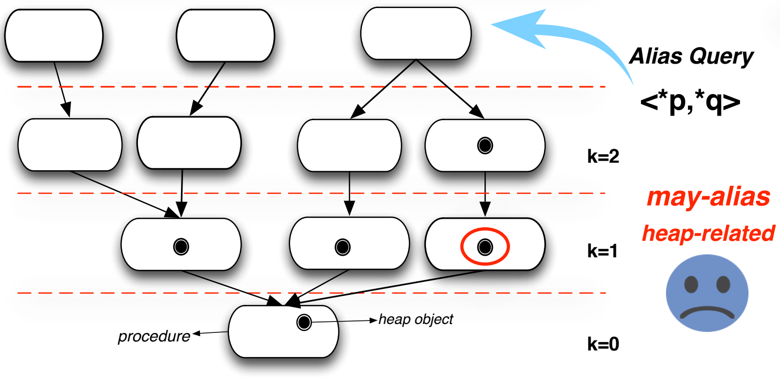

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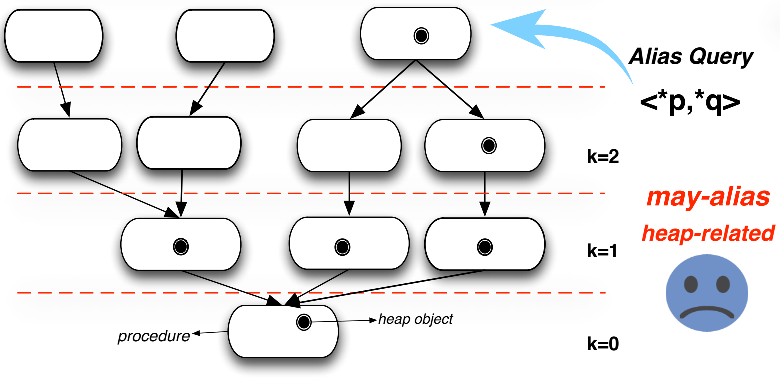

Query-Directed Adaptive Heap Cloning

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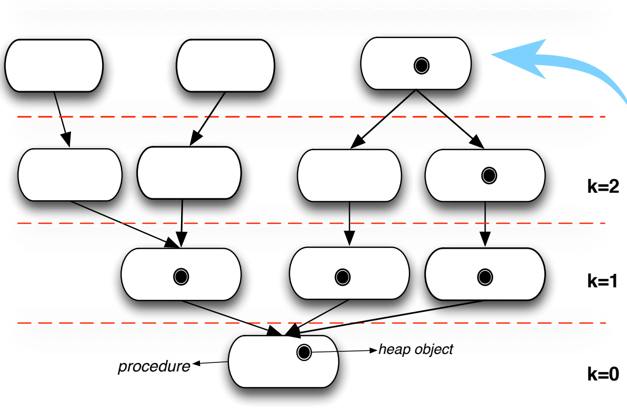
Query-directed adaptive heap cloning



Query-Directed Adaptive Heap Cloning

Alias Query

<*p,*q>

All done

Can't clone further

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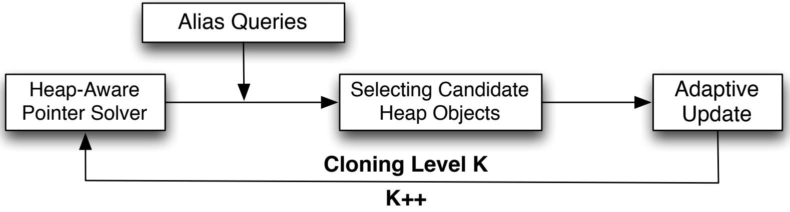
QUDA:QUery-Directed Adaptive heap cloning



Heap-aware pointer analysis

$x \rightarrow g$
$p \rightarrow o$

Heap-aware pointer analysis

$$\begin{array}{l} \mathrm{x} \rightarrow (\mathrm{true},\ g) \\ \mathrm{p} \rightarrow (h_o,\ \ \ o) \end{array}$$

Heap-aware pointer analysis

$$\begin{aligned} x &\rightarrow (\text{true}, \; g) \\ p &\rightarrow (h_o, \; o) \\ q &\rightarrow (h_o, \; o) \end{aligned}$$

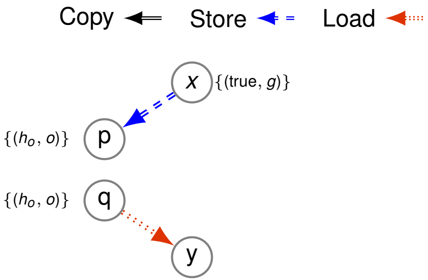
```
*p  =  x;
y   =  *q;
```

Heap-aware pointer analysis

$$x \to (\text{true}, g)$$
$$p \to (h_o, o)$$
$$q \to (h_o, o)$$

$$*p = x;$$
$$y = *q;$$

Constraint Graph:



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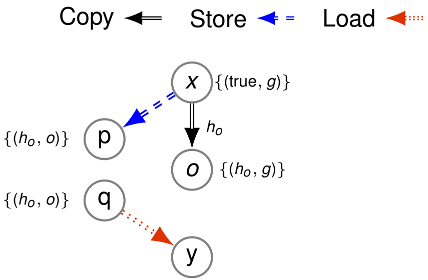

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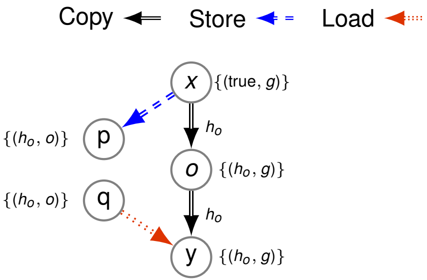


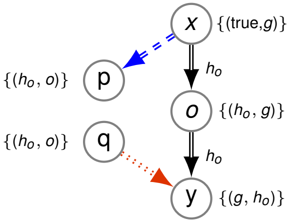
Candidate heap objects selection

Constraint Graph:

Copy ⟸ Store ⟸ Load ⟸

Alias Query

$\langle *x, *y \rangle$



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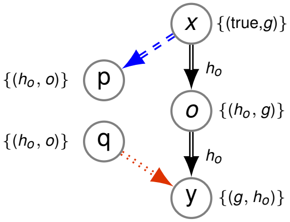


Alias Query

$\langle *x, *y \rangle$

pts(x)={true,g}

pts(y)={h_o,g}

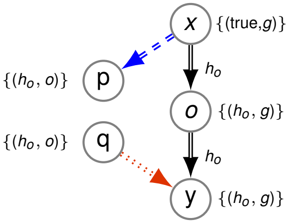
Candidate Heap Object $\{o\}$

Adaptive update

Constraint Graph:

Copy Store Load

Candidate Heap Object $\{o\}$



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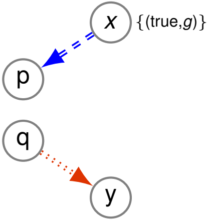

Next round resolution

Constraint Graph:

Copy Store Load

Alias Query

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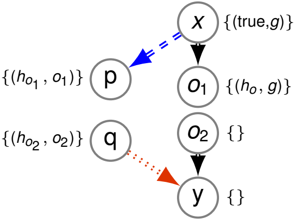
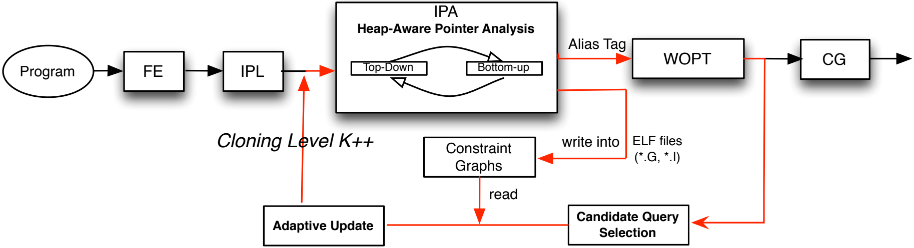
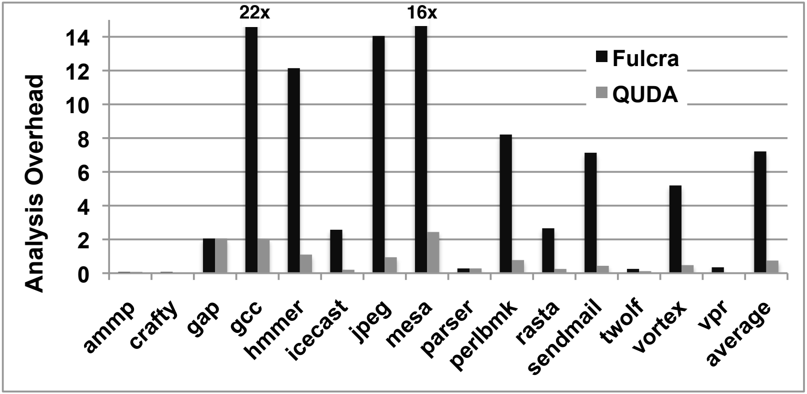
Not-alias!



QUDA framework in Open64

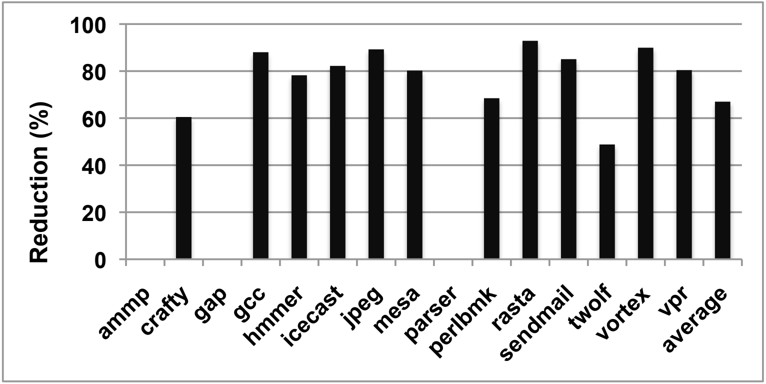


Analysis times of FULCRA and QUDA



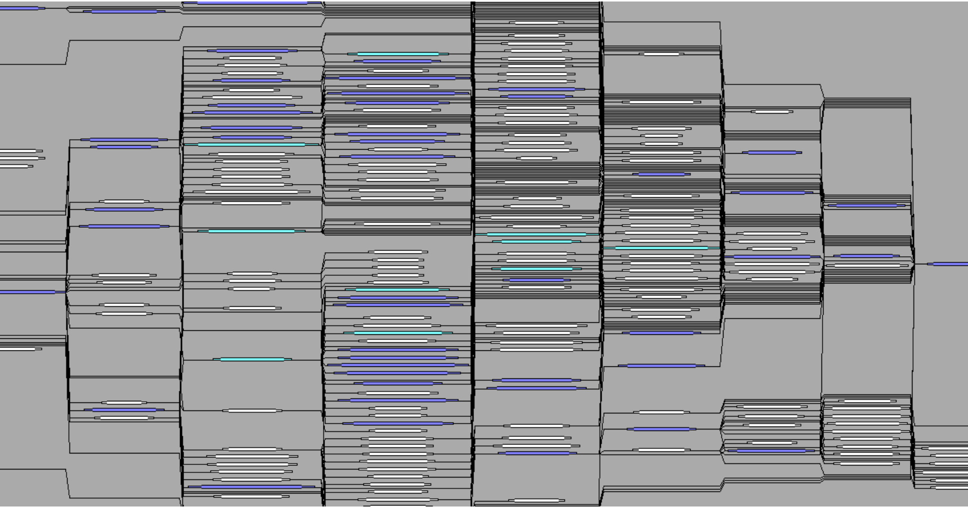
Analysis time normalized with respect to Open64's compile times (-O2)

Heap objects reduced by QUDA over FULCRA



Number of heap objects reduced by QUDA over FULCRA in percentage terms

Heap distribution with full heap cloning (175.vpr)



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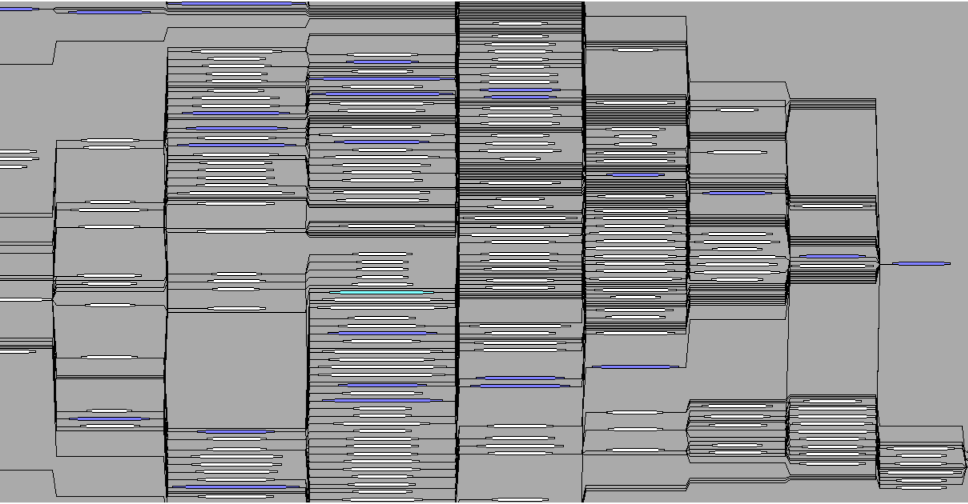
PLC, UNSW

Heap distribution with QUDA (175.vpr)



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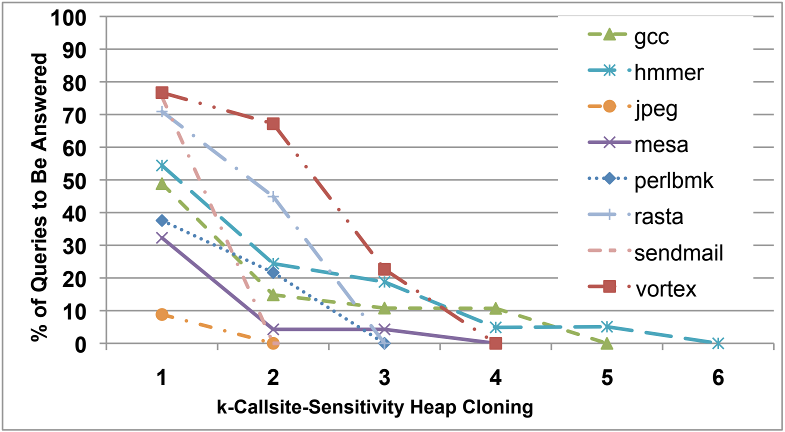
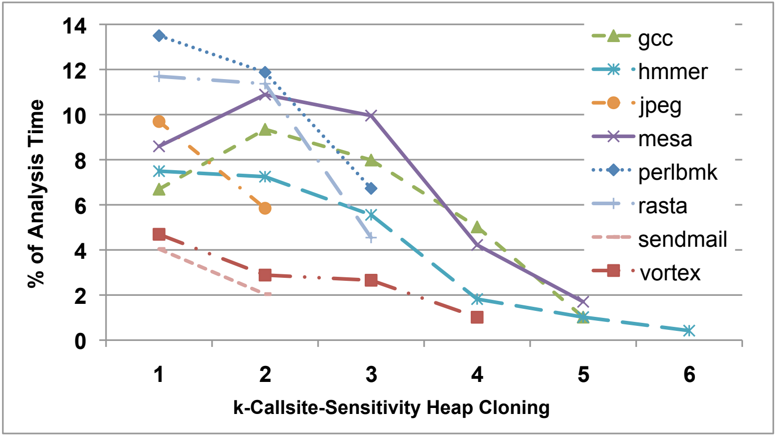
Alias queries to be answered at each iteration



Analysis time per iteration over the total



Conclusion

Novel heap cloning approach: same precision as full heap cloning but significantly more scalable

- Heap-aware analysis
- Query-directed
- Adaptive

Challenges and opportunities:

- Iterative compilation (prioritising queries in hot functions)
- Bug detection (scaling precise pointer analysis)