Path Projection

For User-Centered Static Analysis Tools

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Success in Static Analysis

- Coverity, Fortify, Grammatech, Klocwork, many others are selling static analysis tools
- Microsoft, Mozilla, and others are integrating static analysis into development
- Very active static analysis research community

But there's a problem...

- Research has focused on static analysis **algorithms**
- But, programmers use **tools**, not algorithms
- Static analysis tools are only useful if programmers can understand the results
- Our goal: develop ways to make static analysis tools more **user-centered**

Path Projection

- A new UI toolkit for visualizing **program paths**
  - call stacks and control-flow paths
- Paths are very common in static analysis tool output
  - Helping users understand paths will help many static analysis tools
  - We have applied Path Projection to Locksmith and BLAST
- Experimental evaluation
  - Task: triaging Locksmith error reports
  - Result: 18% improvement in completion time, similar accuracy

Case Study: Locksmith

Polyvios Pratikakis et al. (PLDI 2006)

- Static data race detector for C
  - Data race: Two or more threads access a shared variable at the same time
- Locksmith reports call stacks to possibly-racing dereferences
  - To triage, user must decide whether multiple paths are **simultaneously realizable**

Locksmith in Standard Viewer

Path Visualizer

main.c split close

```
main.c
 1  #include <unistd.h>
 2  #include <stdlib.h>
 3  #include <stdio.h>
 4  #include <string.h>
 5  #include <signal.h>
 6  #include <pthread.h>
 7
 8
 9  #include "Defs.h"
10  #include "Data.h"
11  #include "Misc.h"
12  #in
13  #i
14  #i
15  #i
16
17  ex
18
19  int main(int argc, char **argv)
20  {
21          extern char *optarg;
22          extern int optind;
23          int c; int error = 0; int ret;
24          struct hist_data h;
25          int retlog;
26
27          /* Allocate heap for download request
28           * struct request stores all the information that might be
29           * of interest
```

Standard Viewer designed to mimic typical editors/IDEs

Help

Find

Find Cancel

Path Report

Warning: Possible data race of
prev (Misc.c:<global>:15)
at:

1. <in main.c>
   main():42 -> pthread_create()
   <in Signal.c>
   signal_waiter():36
   sigalrm_handler():61
   <in Misc.c>
   updateProgressBar():193 -> dereference

   locks: -

2. <in main.c>
   main():117
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Locksmith error report with hyperlinks

Path Visualizer

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Locksmith Error Report

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Locksmith Error Report

Shared variable

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Locksmith Error Report

Shared variable

Call stacks leading to race

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Locksmith Error Report

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w/no locks held

Locksmith Error Report

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Triaging Locksmith

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Find ▶Help

Find Cancel

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Triage: are these call stacks simultaneously realizable?

Triaging Locksmith

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Find

Help

Find Cancel

Path Report

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Begin by clicking

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Path Visualizer

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42      if ((ret = pthread_create(&hthread, NULL, signal_waiter, NULL)) != 0
43              fprintf(stderr, "main: cannot create signal_waiter thread: %s, ex
44              exit(-1);
45      }
46
47      while (!error && (c = getopt(argc,argv,"p:l:n:hfv")) != -1) {
48              switch(c) {
49                      case 'p':
50                              req->port = atoi(optarg);
51                              break;
52                      case 'f':
53                              fsuggested = 1;
54                              break;
55                      case 'l':
56                              strncpy(req->lfile, optarg, MAXBUFSIZ);
57                              break;
58                      case 'n':
59                              if ((nthreads = atoi(optarg)) > MAXTHREADS) {
60                                      Log("Error: Maximum # of threads allowed is %
61                                      nthreads = 0;
62                              }
63                              break;
64                      case 'h':
65                              printf("%s\n", "EnderUNIX Aget v0.4");
66                              usage();
67                              exit(0);
68                              break;
```

Find ▶Help

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Thread creation realizable?

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58                      case 'n':
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Help

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Thread creation realizable?

main.c split close

Help

Find Cancel

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17  extern int errno;
18
19  int main(int argc, char **argv)
20  {
        extern char *optarg;
        extern int optind;
        int c; int error = 0; int ret;
        struct hist_data h;
        int retlog;

        /* Allocate heap for download request
         * struct request stores all the information that might be
         * of interest
         */
        req = (struct request *)calloc(1, sizeof(struct request));

        /* Only some signals will be emitted  */
        sigemptyset(&signal_set);
        sigaddset(&signal_set, SIGINT);
        sigaddset(&signal_set, SIGALRM);

        /* Block out all signals       */
        pthread_sigmask(1, &signal_set, NULL);

        /* Create a thread for hadling signals */
42      if ((ret = pthread_create(&hthread, NULL, signal_waiter, NULL)) != 0
43              fprintf(stderr, "main: cannot create signal_waiter thread: %s, e
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Yes, unconditionally created

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Triaging Locksmith

Keep around context

main.c split close

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47      while (!error && (c = getopt(argc,argv,"p:l:n:hfv")) != -1) {
48              switch(c) {
49
50
51
52                      case 'f':
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Easier than remembering

main.c split close

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Path Visualizer

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Find Help

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48              switch(c) {
49                      cas
50                              ;
51                              break;
52                      case 'f':
```

Call site of

Signal.c split close

```
17  extern pthread_mutex_t bwritten_mutex;
18
19  void * signal_waiter(void *arg)
20  {
21          int signal;
22
23          arg = NULL;
24
25          pthread_sigmask(2, &signal_set, NULL);
26
27          while(1) {
28
29
```

Find ▶Help

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Next call

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Signal.c split close

```
17  extern pthread_mutex_t bwritten_mutex;
18
19  void * signal_waiter(void *arg)
20  {
21          int signal;
22
23          arg = NULL;
24
```

Signal.c split close

```
54          exit(0);
55  }
56
57
58  void sigalrm_handler(void)
59  {
60          printf("Signal Alarm came\n");
61          updateProgressBar(bwritten, req->clength);
```

Skipping a few steps

Find Help

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2. <in main.c>
main():117
<in Aget.c>
resume_get():171 -> pthread_create()
<in Download.c>
http_get():121
<in Misc.c>
updateProgressBar():193 -> dereference

locks: -

Triaging Locksmith

Path Visualizer

main.c split close

```
40
41      /* Create a thread for hadling signals */
42      if ((ret = pthread_create(&hthread, NULL, signal_waiter, NULL)) != 0
43          fprintf(stderr, "main: cannot create signal_waiter thread: %s, ex
44          exit(-1);
```

Signal.c split close

```
17  extern pthread_mutex_t bwritten_mutex;
18
19  void * signal_waiter(void *arg)
20  {
21      int signal;
```

Signal.c split close

```
54      exit(0);
55  }
56
57
58  void sigalrm_handler(void)
```

Misc.c split close

```
191             putchar(' ');
192     printf("[%d%% completed]\n", ndot);
193     prev = ndot;
194 }
195
```

the dereference, finally!

Find ▶Help

Find Cancel

Path Report

Warning: Possible data race of
prev (Misc.c:<global>:15)
at:

1. <in main.c>
   main():42 -> pthread_create()
   <in Signal.c>
   signal_waiter():36
   sigalrm_handler():61
   <in Misc.c>
   updateProgressBar():193 -> dereference

   locks: -

2. <in main.c>
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   locks: -

Triaging Locksmith

Path Visualizer

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Signal.c split close

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Signal.c split close

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Misc.c split close

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193     prev = ndot;
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Help

Find

Find Cancel

Path Report

Warning: Possible data race of
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at:

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   main():42 -> pthread_create()
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   <in Misc.c>
   updateProgressBar():193 -> dereference

   locks: -

2. <in main.c>
   main():117
   <in Aget.c>
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   <in Misc.c>
   updateProgressBar():193 -> dereference

   locks: -

Triaging Locksmith

Path Visualizer

main.c split close

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Signal.c split close

```
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20  {
21      int signal;
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Signal.c split close

```
54      exit(0);
55  }
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58  void sigalrm_handler(void)
```

Misc.c split close

```
191             putchar(' ');
192     printf("[%d%% completed]\n", ndot);
193     prev = ndot;
194 }
195
```

Screen is very cluttered!

Find

Find Cancel

Help

Path Report

Warning: Possible data race of
prev (Misc.c:<global>:15)
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1. <in main.c>
main():42 -> pthread_create()
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locks: -

Triaging Locksmith

Path Visualizer

main.c split close

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Signal.c split close

```
17  extern pthread_mutex_t bwritten_mutex;
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Signal.c split close

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54      exit(0);
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```

Misc.c split close

```
191             putchar(' ');
192     printf("[%d%% completed]\n", ndot);
193     prev = ndot;
194 }
195
```

Old context is hidden!

Find ▶Help

Find Cancel

Path Report

Warning: Possible data race of
prev (Misc.c:<global>:15)
at:

1. <in main.c>
   main():42 -> pthread_create()
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   locks: -

Triaging Locksmith

Path Visualizer

main.c split close

```
40
41      /* Create a thread for hadling signals */
42      if ((ret = pthread_create(&hthread, NULL, signal_waiter, NULL)) != 0
43          fprintf(stderr, "main: cannot create signal_waiter thread: %s, e
44          exit(-1);
```

Which function is this?

Signal.c split close

```
17  extern pthread_mutex_t bwritten_mutex;
18
19  void * signal_waiter(void *arg)
20  {
21      int signal;
```

Signal.c split close

```
54      exit(0);
55  }
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57
58  void sigalrm_handler(void)
```

Old context is hidden!

Misc.c split close

```
191             putchar(' ');
192     printf("[%d%% completed]\n", ndot);
193     prev = ndot;
194 }
195
```

Where was this called?

Find ▶Help

Find Cancel

Path Report

Warning: Possible data race of
prev (Misc.c:<global>:15)
at:

1. <in main.c>
   main():42 -> pthread_create()
   <in Signal.c>
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   updateProgressBar():193 -> dereference

   locks: -

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   main():117
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   <in Download.c>
   http_get():121
   <in Misc.c>
   updateProgressBar():193 -> dereference

   locks: -

A Thousand Cuts

A Thousand Cuts

- Read error report
- Click hyperlink 1
- Read code
- Scroll up
- Scroll down
- Split window
- Focus
- Back to error report
- Click hyperlink 2
- Read code
- Scroll down
- Split window
- Focus
- Back to error report
- Click hyperlink 3
- Read code
- Scroll down
- Split window
- Focus
- Back to error report
- Collapse splits
- (resize window, move window...)

- Many little distractions from actual task
- Seemingly straightforward task becomes complex!

Path Projection

- Designed for tracing paths

main.c - main()

```
19  int main(int argc, char **argv)
20  {
42      if ((ret = pthread_create(&hthread, NULL, signal_wait
```

main.c - signal_waiter()

```
19  void * signal_waiter(void *arg)
20  {
27      while(1) {
33          if (signal == SIGINT) {
35          } else if (signal == SIGALRM) {
36              sigalrm_handler();
```

Signal.c - sigalrm_handler()

```
58  void sigalrm_handler(void)
59  {
61      updateProgressBar(bwritten, req->clength);
```

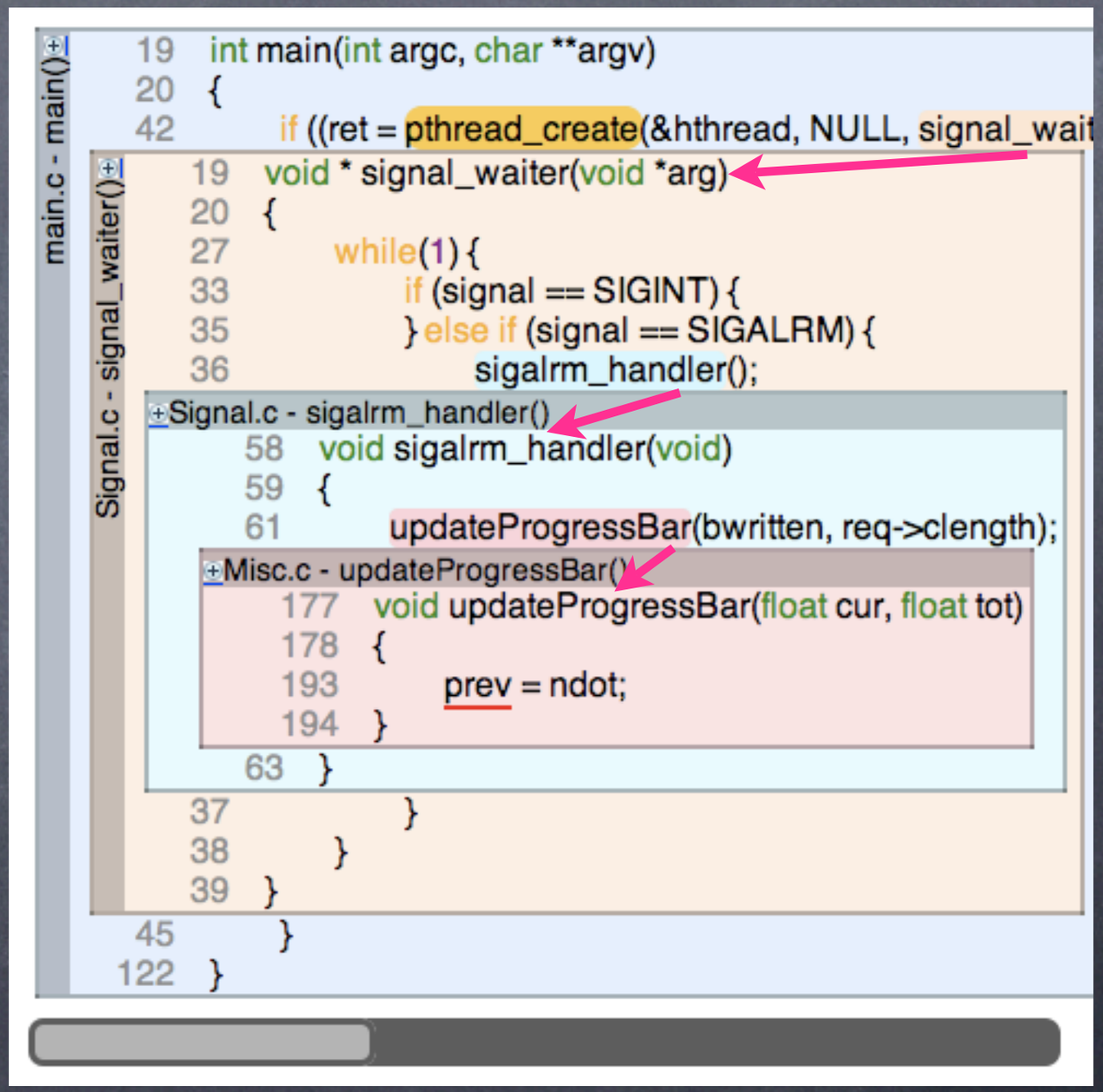
Misc.c - updateProgressBar()

```
177 void updateProgressBar(float cur, float tot)
178 {
193     prev = ndot;
194 }
```

```
63  }
37          }
38      }
39  }
45      }
122 }
```

Path Projection

- Designed for tracing paths
- Function call inlining:
  - Inline function directly below call site

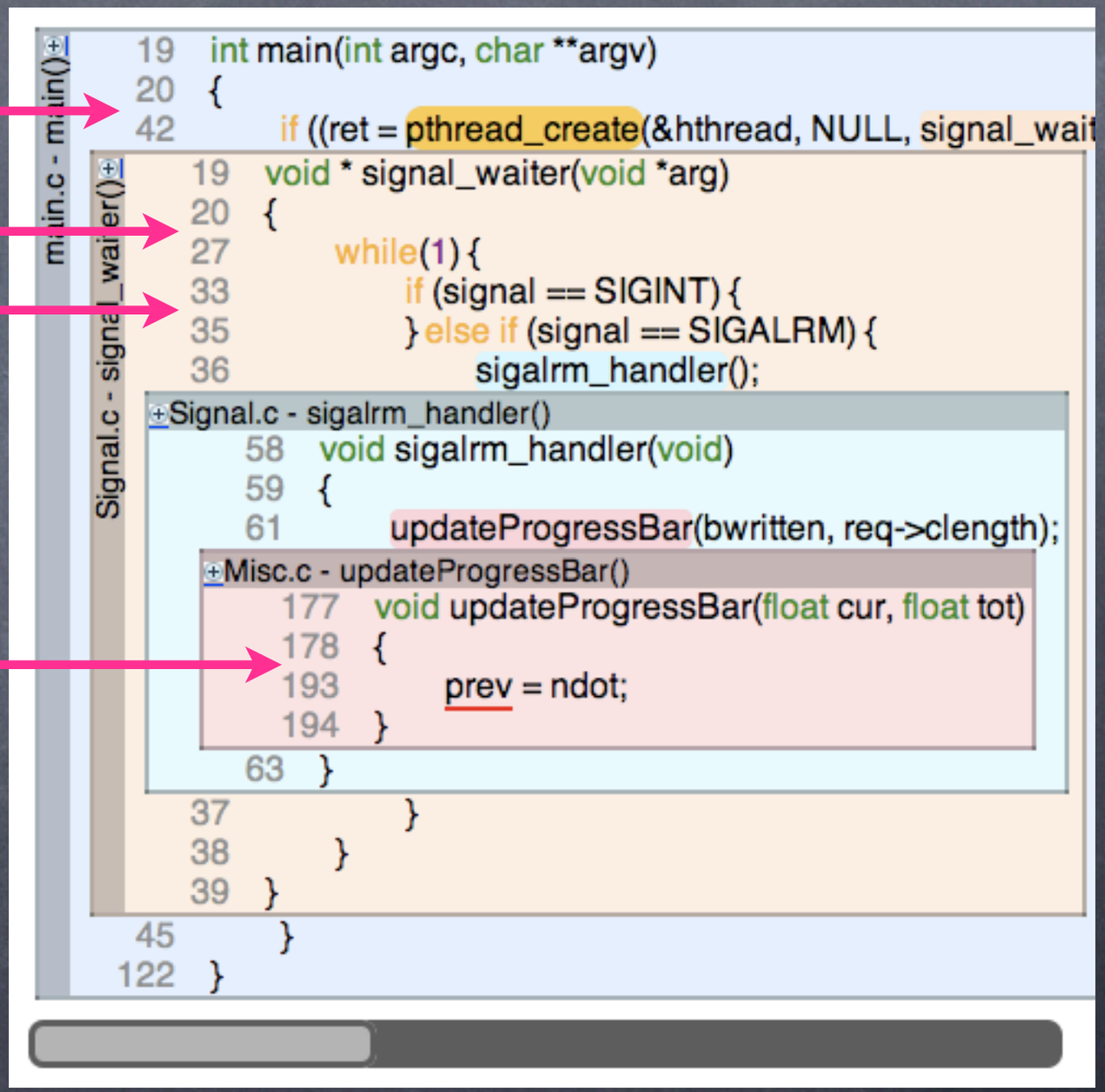


Path Projection

- Designed for tracing paths
- Function call inlining:

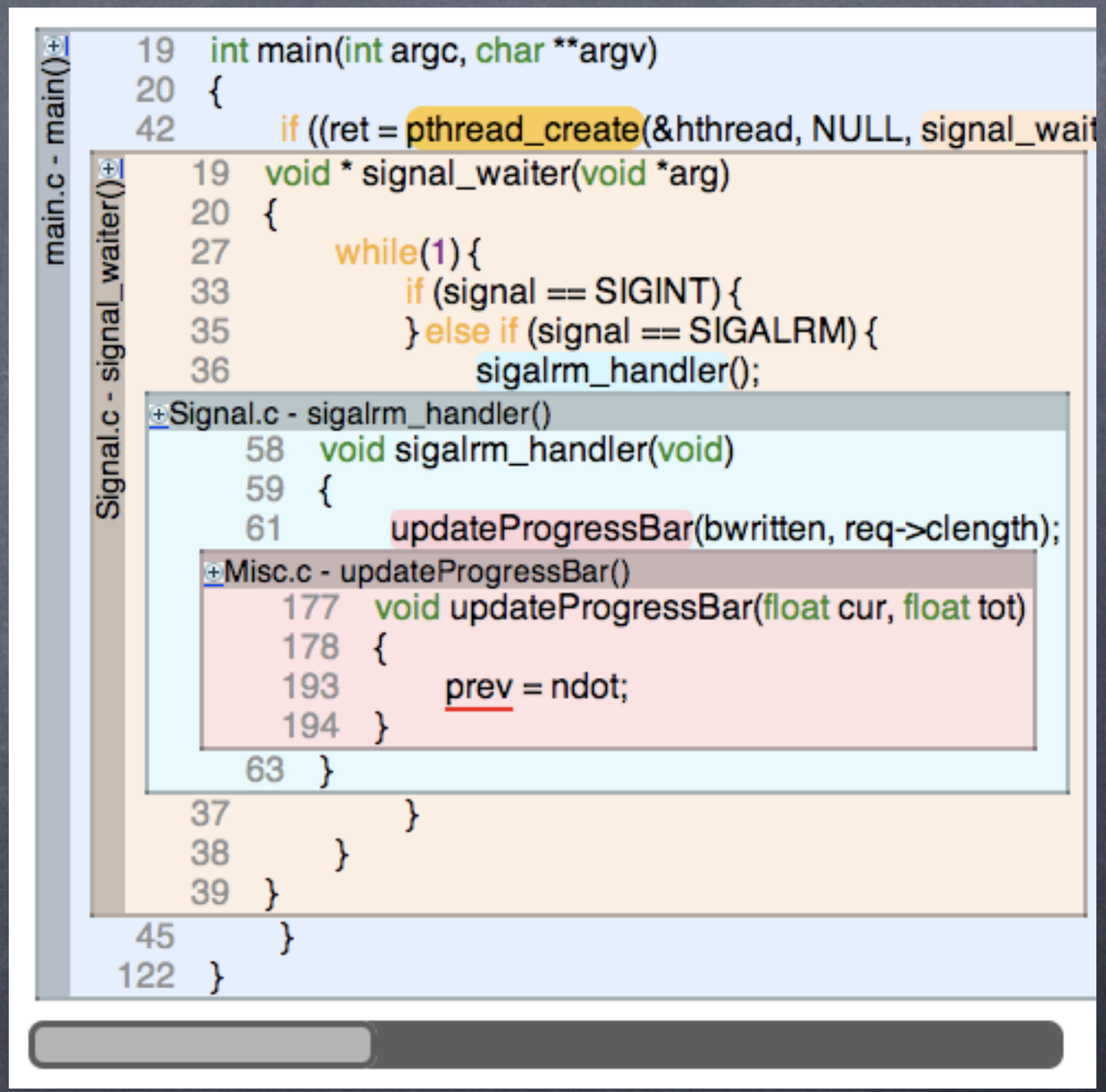
  Inline function directly below call site
- Path-derived code folding:

  Show only implicated lines and lexical control-blocks



Path Projection

- Designed for tracing paths
- Function call inlining:
  - Inline function directly below call site
- Path-derived code folding:
  - Show only implicated lines and lexical control-blocks
- Show as much code as possible on one screen



main.c - main()

```
19  int main(int argc, char **argv)
20  {
42      if ((ret = pthread_create(&hthread, NULL, signal_wait
```

Signal.c - signal_waiter()

```
19  void * signal_waiter(void *arg)
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27      while(1) {
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36              sigalrm_handler();
```

Signal.c - sigalrm_handler()

```
58  void sigalrm_handler(void)
59  {
61      updateProgressBar(bwritten, req->clength);
```

Misc.c - updateProgressBar()

```
177 void updateProgressBar(float cur, float tot)
178 {
193     prev = ndot;
194 }
```

```
63  }
37          }
38      }
39  }
45      }
122 }
```

Path Projection

Path Visualizer

Path 1 of 2

main.c - main()

```
19  int main(int argc, char **argv)
20  {
42      if ((ret = pthread_create(&hthread, NULL, signal_wait
```

Signal.c - signal_waiter()

```
19  void * signal_waiter(void *arg)
20  {
27      while(1) {
33          if (signal == SIGINT) {
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36              sigalrm_handler();
```

Signal.c - sigalrm_handler()

```
58  void sigalrm_handler(void)
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61      updateProgressBar(bwritten, req->clength);
```

Misc.c - updateProgressBar()

```
177 void updateProgressBar(float cur, float tot)
178 {
193     prev = ndot;
194 }
```

```
63  }
37          }
38      }
39  }
45      }
122 }
```

main.c - main()

```
19  i
20  {
42
45
116
117
```

Aget.c - resume_get()

```
133
134
166
171
```

Download.c - http_get()

```
172
174
175
177
```

Show paths side by side

Help

Multi-query

Find

- "pthread_create"
- "pthread_join"
- "pthread_mutex_lock"
- "pthread_mutex_unlock"

Path Report

Warning: Possible data race of
prev (Misc.c:<global>:15)
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1. <in main.c>
   main():42 -> pthread_create()
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   locks: -

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Path Projection

Path Visualizer

Path 2 of 2

```
main.c - main()
 19  int main(int argc, char **argv)
 20  {
 42      if ((ret = pthread_create(&hthread, NULL, signal_wait
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116      if ((retlog = read_log(&h)) != -1)
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Aget.c - resume_get()
133  void resume_get(struct hist_data *h)
134  {
166      for (i = 0; i < nthreads; i++) {
171          pthread_create(&(wthread[i].tid), NULL, http_

Download.c - http_get()
 37  void * http_get(void *arg) {
106      pthread_mutex_lock(&bwritten_mutex);
108      pthread_mutex_unlock(&bwritten_mutex);
110      while (td->offset < foffset) {
118          pthread_mutex_lock(&bwritten_mutex);
120          pthread_mutex_unlock(&bwritten_mutex)
121          updateProgressBar(bwritten, td->clength)

Misc.c - updateProgressBar()
177  void updateProgressBar(float cur, float tot)
178  {
193      prev = ndot;
194  }
122      }
124      if (td->offset == td->foffset) {
125          pthread_mutex_lock(&http_get_ok_mutex
127          pthread_mutex_unlock(&http_get_ok_mu
128      }
135  }
```

Show paths side by side

Help

Multi-query

Find

- ✘ "pthread_create"
- ✘ "pthread_join"
- ✘ "pthread_mutex_lock"
- ✘ "pthread_mutex_unlock"

Path Report

Warning: Possible data race of
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Path Projection

Path Visualizer

Path 2 of 2

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125          pthread_mutex_lock(&http_get_ok_mutex
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128      }
135  }
172      }
174      for (i = 0; i < nthreads; i++)
175          pthread_join(wthread[i].tid, NULL);
177      if (http_get_ok == nthreads)
```

Multiple searches (despite folds)

Help

Multi-query

Find

- ✘ "pthread_create"
- ✘ "pthread_join"
- ✘ "pthread_mutex_lock"
- ✘ "pthread_mutex_unlock"

main():42 -> pthread_create()
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Path Projection

Path Visualizer

Path 2 of 2

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main.c - main()
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177  void updateProgressBar(float cur, float tot)
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174      for (i = 0; i < nthreads; i++)
175          pthread_join(wthread[i].tid, NULL);
177      if (http_get_ok == nthreads)
```

Multi-query

Help

Find

- "pthread_create"
- "pthread_join"
- "pthread_mutex_lock"
- "pthread_mutex_unlock"

Multiple searches (despite folds)

main():42 -> pthread_create()
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<in Misc.c>
updateProgressBar():193 -> dereference

locks: -

Path Projection

Continuing example...

Path

-query

Help

Find

- "pthread_create"
- "pthread_join"
- "pthread_mutex_lock"
- "pthread_mutex_unlock"

Path Report

Warning: Possible data race of
prev (Misc.c:<global>:15)
at:

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   <in Signal.c>
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   locks: -

main.c - main()

```
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117         resume_get(&h);
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Aget.c - resume_get()

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133 void resume_get(struct hist_data *h)
134 {
166     for (i = 0; i < nthreads; i++) {
171         pthread_create(&(wthread[i].tid), NULL, http_
```

Download.c - http_get()

```
37  void * http_get(void *arg) {
106     pthread_mutex_lock(&bwritten_mutex);
108     pthread_mutex_unlock(&bwritten_mutex);
110     while (td->offset < foffset) {
118         pthread_mutex_lock(&bwritten_mutex);
120         pthread_mutex_unlock(&bwritten_mutex)
121         updateProgressBar(bwritten, td->clength)
```

Misc.c - updateProgressBar()

```
177 void updateProgressBar(float cur, float tot)
178 {
193     prev = ndot;
194 }
```

```
122     }
124     if (td->offset == td->foffset) {
125         pthread_mutex_lock(&http_get_ok_mutex
127         pthread_mutex_unlock(&http_get_ok_mu
128     }
135 }
172 }
174 for (i = 0; i < nthreads; i++)
175     pthread_join(wthread[i].tid, NULL);
177 if (http_get_ok == nthreads)
```

Path Projection

from 1st call stack

Path Visualizer

Path 2 of 2

```
19  int main(int argc, char **argv)
20  {
42      if ((ret = pthread_create(&hthread, NULL, signal_wait
45      }
116     if ((retlog = read_log(&h)) != -1)
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127         pthread_mutex_unlock(&http_get_ok_mu
128     }
135 }
172 }
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175     pthread_join(wthread[i].tid, NULL);
177 if (http_get_ok == nthreads)
```

Multi-query

Help

Find

- "pthread_create"
- "pthread_join"
- "pthread_mutex_lock"
- "pthread_mutex_unlock"

Path Report

Warning: Possible data race of
prev (Misc.c:<global>:15)
at:

1. <in main.c>
   main():42 -> pthread_create()
   <in Signal.c>
   signal_waiter():36
   sigalrm_handler():61
   <in Misc.c>
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   locks: -

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   main():117
   <in Aget.c>
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   <in Download.c>
   http_get():121
   <in Misc.c>
   updateProgressBar():193 -> dereference

   locks: -

Path Projection

Path Visualizer

Path 2 of 2

from 2nd call stack

```
main.c - main()
 19  int main(int argc, char **argv)
 20  {
 42      if ((ret = pthread_create(&hthread, NULL, signal_wait
 45      }
116      if ((retlog = read_log(&h)) != -1)
117          resume_get(&h);

133  void resume_get(struct hist_data *h)
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166      for (i = 0; i < nthreads; i++) {
171          pthread_create(&(wthread[i].tid), NULL, http_

Aget.c - http_get()
 37  void * http_get(void *arg) {
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118          pthread_mutex_lock(&bwritten_mutex);
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Download.c - updateProgressBar()
177  void updateProgressBar(float cur, float tot)
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193      prev = ndot;
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122      }
124      if (td->offset == td->foffset) {
125          pthread_mutex_lock(&http_get_ok_mutex
127          pthread_mutex_unlock(&http_get_ok_mu
128      }
135  }
172  }
174  for (i = 0; i < nthreads; i++)
175      pthread_join(wthread[i].tid, NULL);
```

Multi-query

Help

Find

- ✘ "pthread_create"
- ✘ "pthread_join"
- ✘ "pthread_mutex_lock"
- ✘ "pthread_mutex_unlock"

Path Report

Warning: Possible data race of
prev (Misc.c:<global>:15)
at:

1. <in main.c>
   main():42 -> pthread_create()
   <in Signal.c>
   signal_waiter():36
   sigalrm_handler():61
   <in Misc.c>
   updateProgressBar():193 -> dereference

   locks: -

2. <in main.c>
   main():117
   <in Aget.c>
   resume_get():171 -> pthread_create()
   <in Download.c>
   http_get():121
   <in Misc.c>
   updateProgressBar():193 -> dereference

   locks: -

Path Projection

Path Visualizer

Path 2 of 2

from 2nd call stack

dereference

```
main.c - main()
 19  int main(int argc, char **argv)
 20  {
 42      if ((ret = pthread_create(&hthread, NULL, signal_wait
 45      }
116      if ((retlog = read_log(&h)) != -1)
117          resume_get(&h);

133  void resume_get(struct hist_data *h)
134  {
166      for (i = 0; i < nthreads; i++) {
171          pthread_create(&(wthread[i].tid), NULL, http_

Aget.c - http_get()
 37  void * http_get(void *arg) {
106      pthread_mutex_lock(&bwritten_mutex);
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110      while (td->offset < foffset) {
118          pthread_mutex_lock(&bwritten_mutex);
120          pthread_mutex_unlock(&bwritten_mutex)
121          updateProgressBar(bwritten, td->clength)

Download.c - Misc.c - updateProgressBar()
177  void updateProgressBar(float cur, float tot)
178  {
194      prev = ndot;
194  }
122      }
124      if (td->offset == td->foffset) {
125          pthread_mutex_lock(&http_get_ok_mutex
127          pthread_mutex_unlock(&http_get_ok_mu
128      }
135  }
172  }
174  for (i = 0; i < nthreads; i++)
175      pthread_join(wthread[i].tid, NULL);
177  if (http_get_ok == nthreads)
```

Multi-query

Help

Find

- ✘ "pthread_create"
- ✘ "pthread_join"
- ✘ "pthread_mutex_lock"
- ✘ "pthread_mutex_unlock"

Path Report

Warning: Possible data race of
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Path Projection

Path Visualizer

Path 2 of 2

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Misc.c - updateProgressBar()
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178  {
193      prev = ndot;
194  }

122      }
124      if (td->offset == td->foffset) {
125          pthread_mutex_lock(&http_get_ok_mutex
127          pthread_mutex_unlock(&http_get_ok_mu
128      }
135  }
172  }
174  for (i = 0; i < nthreads; i++)
175      pthread_join(wthread[i].tid, NULL);
177  if (http_get_ok == nthreads)
```

condition for thread creation

in loop

condition for dereference

Multi-query

Help

Find

✘ "pthread_mutex_unlock"

Path Report

Warning: Possible data race of
prev (Misc.c:<global>:15)
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1. <in main.c>
   main():42 -> pthread_create()
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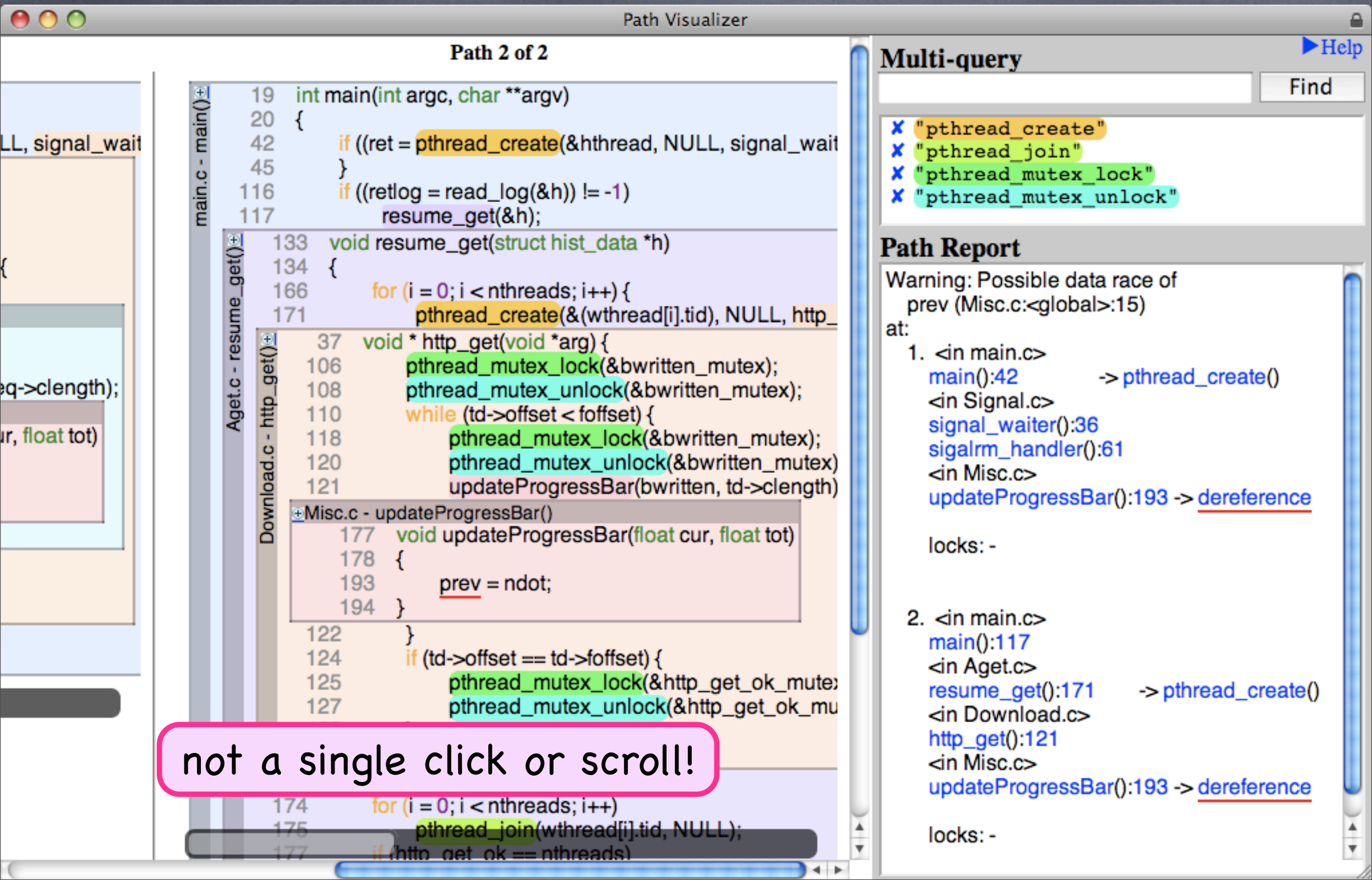
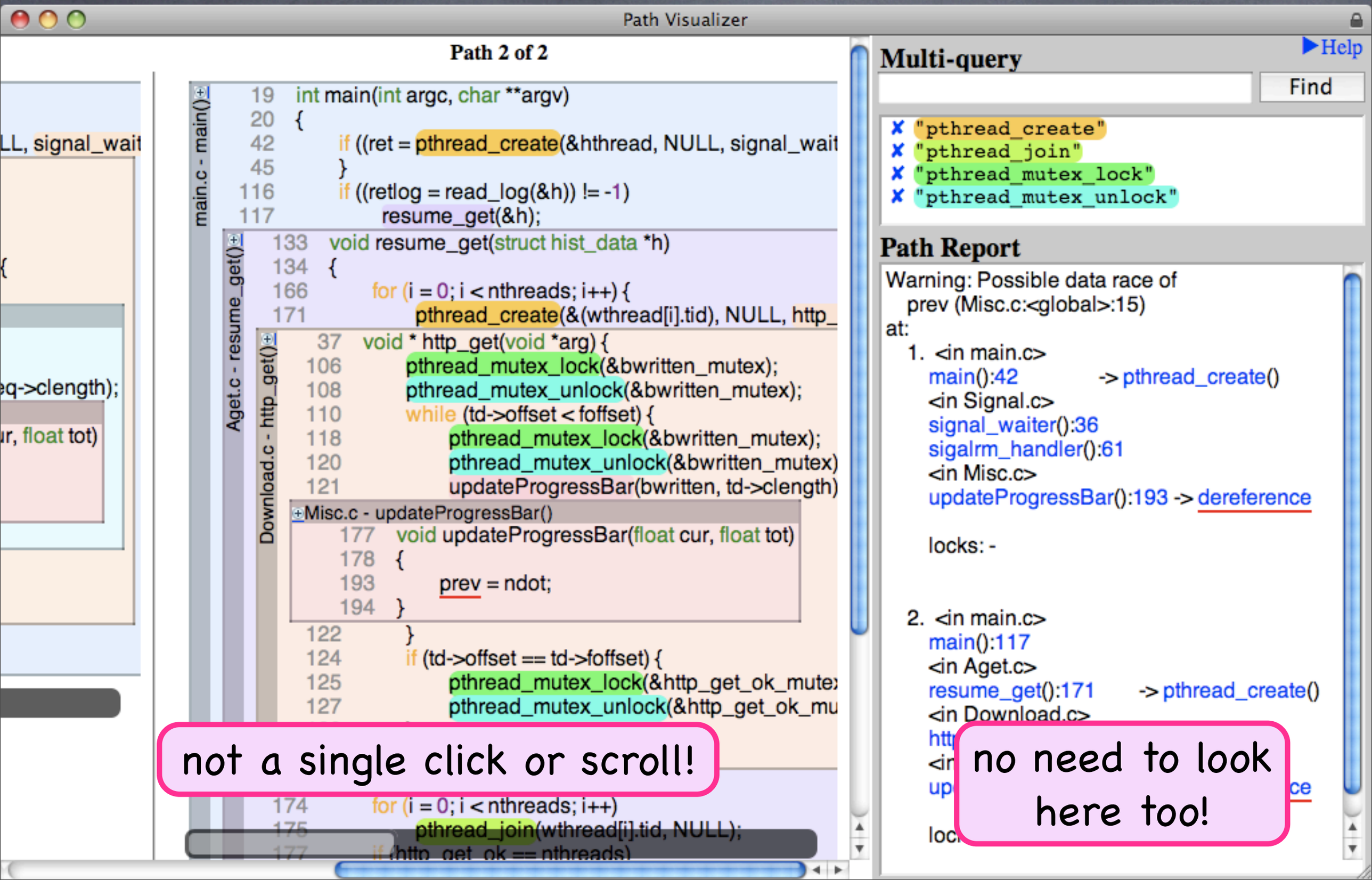
   locks: -

Path Projection



Path Projection



Path Projection

What's foffset?

Path 2

```
main.c - main()
 19  int main(int argc, char **argv)
 20  {
 42      if ((ret = pthread_create(&hthread, NULL, signal_wait
 45      }
116      if ((retlog = read_log(&h)) != -1)
117          resume_get(&h);

Aget.c - resume_get()
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166      for (i = 0; i < nthreads; i++) {
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Download.c - http_get()
 37  void * http_get(void *arg) {
106      pthread_mutex_lock(&bwritten_mutex);
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110      while (td->offset < foffset) {
118          pthread_mutex_lock(&bwritten_mutex);
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177  void updateProgressBar(float cur, float tot)
178  {
193      prev = ndot;
194  }

122      }
124      if (td->offset == td->foffset) {
125          pthread_mutex_lock(&http_get_ok_mutex
127          pthread_mutex_unlock(&http_get_ok_mu
128      }
135  }
172  }
174  for (i = 0; i < nthreads; i++)
175      pthread_join(wthread[i].tid, NULL);
177  if (http_get_ok == nthreads)
```

Help

Multi-query

Find

- "pthread_create"
- "pthread_join"
- "pthread_mutex_lock"
- "pthread_mutex_unlock"

Path Report

Warning: Possible data race of
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   main():42 -> pthread_create()
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Path Projection

Path Visualizer

Path 2 of 2

main.c - main()

```
 19  int main(int argc, char **argv)
 20  {
 42      if ((ret = pthread_create(&hthread, NULL, signal_wait
 45      }
116      if ((retlog = read_log(&h)) != -1)
117          resume_get(&h);
```

Aget.c - resume_get()

```
133  void resume_get(struct hist_data *h)
134  {
166      for (i = 0; i < nthreads; i++) {
171          pthread_create(&(wthread[i].tid), NULL, http_
```

Download.c - http_get()

```
 37  void * http_get(void *arg) {
 42      long foffset;
 54      foffset = td->foffset;
 99      if ((dr - i ) > foffset)
100          dw = pwrite(td->fd, s, (foffset - i), td->soffse
101      else
102          dw = pwrite(td->fd, s, (dr - i), td->soffset);
106      pthread_mutex_lock(&bwritten_mutex);
108      pthread_mutex_unlock(&bwritten_mutex);
110      while (td->offset < foffset) {
113          if ((td->offset + dr) > foffset)
114              dw = pwrite(td->fd, rbuf, foffset - td->c
115          else
116              dw = pwrite(td->fd, rbuf, dr, td->offset)
118          pthread_mutex_lock(&bwritten_mutex);
120          pthread_mutex_unlock(&bwritten_mutex)
121          updateProgressBar(bwritten, td->clength)
```

Misc.c - updateProgressBar()

```
177  void updateProgressBar(float cur, float tot)
178  {
193      prev = ndot;
194  }
```

Help

Multi-query

foffset — Find

- "pthread_create"
- "pthread_join"
- "pthread_mutex_lock"
- "pthread_mutex_unlock"
- "foffset"

Path Report

Warning: Possible data race of
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Path Projection

What's in read_log?

main.c - main()

```
 19  int main(int argc, char **argv)
 20  {
 42      if ((ret = pthread_create(&hthread, NULL, signal_wait
 45      }
116      if ((retlog = read_log(&h)) != -1)
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```

main.c - resume_get()

```
133  void resume_get(struct hist_data *h)
134  {
166      for (i = 0; i < nthreads; i++) {
171          pthread_create(&(wthread[i].tid), NULL, http_
```

Aget.c - resum

Download.c - http_get()

```
 37  void * http_get(void *arg) {
 42      long foffset;
 54      foffset = td->foffset;
 99      if ((dr - i ) > foffset)
100          dw = pwrite(td->fd, s, (foffset - i), td->soffse
101      else
102          dw = pwrite(td->fd, s, (dr - i), td->soffset);
106      pthread_mutex_lock(&bwritten_mutex);
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110      while (td->offset < foffset) {
113          if ((td->offset + dr) > foffset)
114              dw = pwrite(td->fd, rbuf, foffset - td->c
115          else
116              dw = pwrite(td->fd, rbuf, dr, td->offset)
118          pthread_mutex_lock(&bwritten_mutex);
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121          updateProgressBar(bwritten, td->clength)
```

Misc.c - updateProgressBar()

```
177  void updateProgressBar(float cur, float tot)
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193      prev = ndot;
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```

Multi-query

Help

foffset | Find

- "pthread_create"
- "pthread_join"
- "pthread_mutex_lock"
- "pthread_mutex_unlock"
- "foffset"

Path Report

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Path Projection

Path Visualizer

Path 2 of 2

```
main.c - main()
 19  int main(int argc, char **argv)
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 42      if ((ret = pthread_create(&hthread, NULL, signal_wait
 45      }
116      if ((retlog = read_log(&h)) != -1)
```

Resume.c - read_log()

```
 52  int read_log(struct hist_data *h)
 53  {
 90  }
```

```
117          resume_get(&h)
```

```
Aget.c - resume_get()
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120          pthread_mutex_unlock(&bwritten_mutex)
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```

Misc.c - updateProgressBar()

Reveal definition (initially folded)

▶Help

Multi-query

foffset | Find

- ✘ "pthread_create"
- ✘ "pthread_join"
- ✘ "pthread_mutex_lock"
- ✘ "pthread_mutex_unlock"
- ✘ "foffset"

Path Report

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Pilot User Study

- We discovered that static analysis is...

Rocket Science

- In our pilot studies, non-expert users had great trouble triaging Locksmith error reports:
  - ad hoc, inconsistent procedure
  - neglected some causes of false positives
  - sidetracked by non-causes of false positives
- Even with extensive tutorials!

Rocket Science 101

- Our solution: **triaging checklist**

- Checklists are **tool-/error-specific**
  - Different tools have different imprecision & error reports

- Anecdotally, **41%** faster at triaging using checklist

Locksmith Triaging Checklist

- To triage Locksmith:

  check if any pair of paths are simultaneously realizable

  different cases: threads in loop, parent-child, child-child

- For example:

  Source of imprecision: Locksmith is path-insensitive

  Possible false positive: child-child threads may be mutually exclusive

For threads leading to dereferences in Paths 1 and 2:

Are they parent-child (or child-parent), or child-child?

○ Parent-child / ◉ Child-child

Child-child threads.	Y	N
Are the children mutually exclusive (i.e., **only one** can be spawned by their common parent/ancestor)?	○	○
If no, there is likely a race. Are there reasons to show otherwise?	????	
Explain: ????		

Locksmith Triaging Checklist

- To triage Locksmith:

  check if any pair of paths are simultaneously realizable

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Explain: ????		

User Study

- Which is better: Standard Viewer (SV) or Path Projection (PP)?
  - Quantitatively: completion time
  - Qualitatively: user ratings
- Data race triaging task using Locksmith

User Study Issues

- Large variance between participants
  - Participants have different skill level
  - Are differences due to participant or UI?
- Within-subjects: each participant use both interfaces
  - Compare UI results for each participant

User Study Issues

- Order and carryover effect
  - Participants get better over time (learning)
  - Participants biased by initial UI or problem
- Counter-balance: divide participants into two groups
  - SV-PP: Standard Viewer, then Path Projection
  - PP-SV: Path Projection, then Standard Viewer

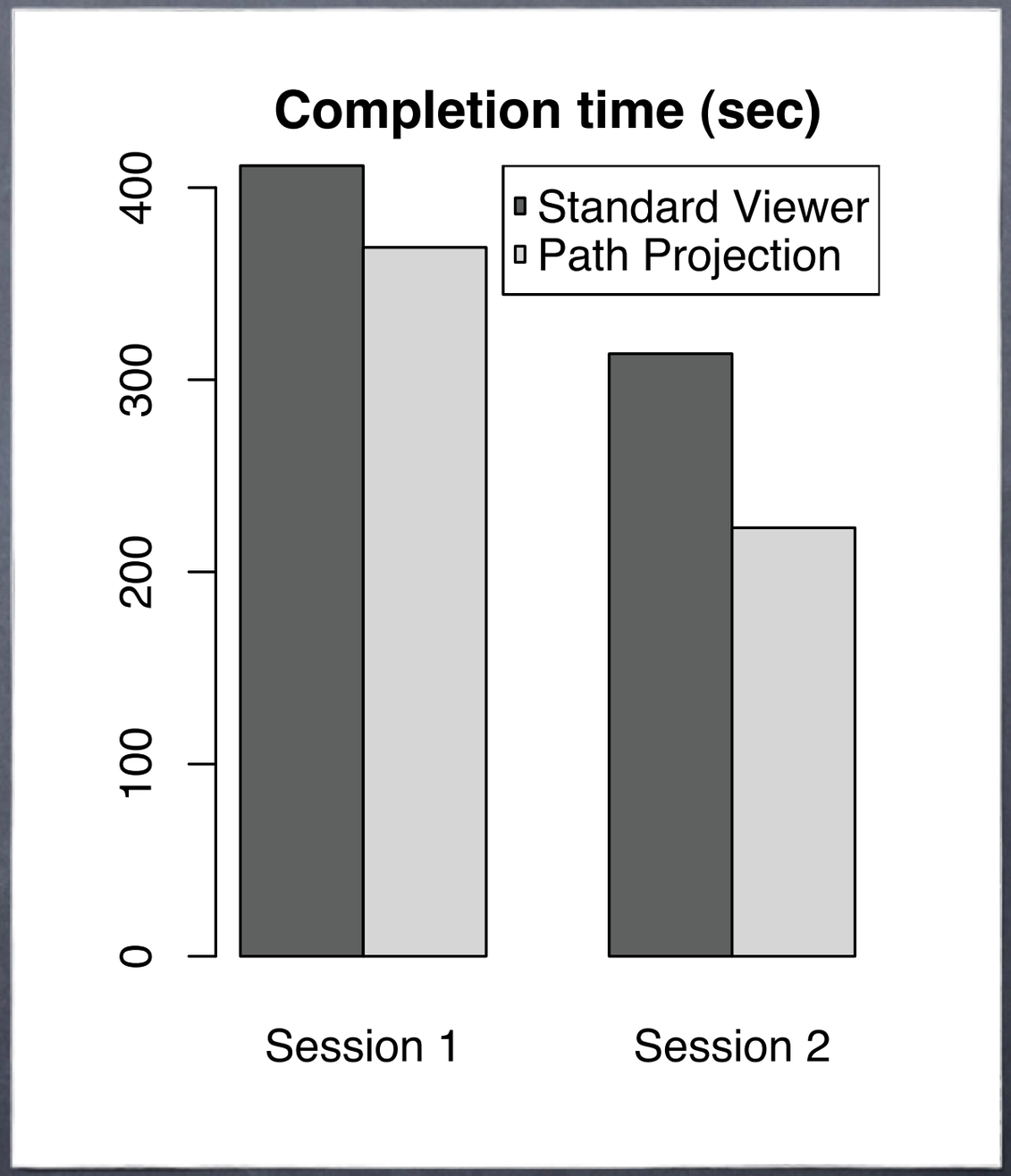
User Study: Locksmith Task

- 6 trials from Locksmith corpus (unfamiliar to users)
- One warning per trial
  - no need to manage warnings
- Only verify that paths are simultaneously realizable
  - No aliasing/imprecise lock state (future work)

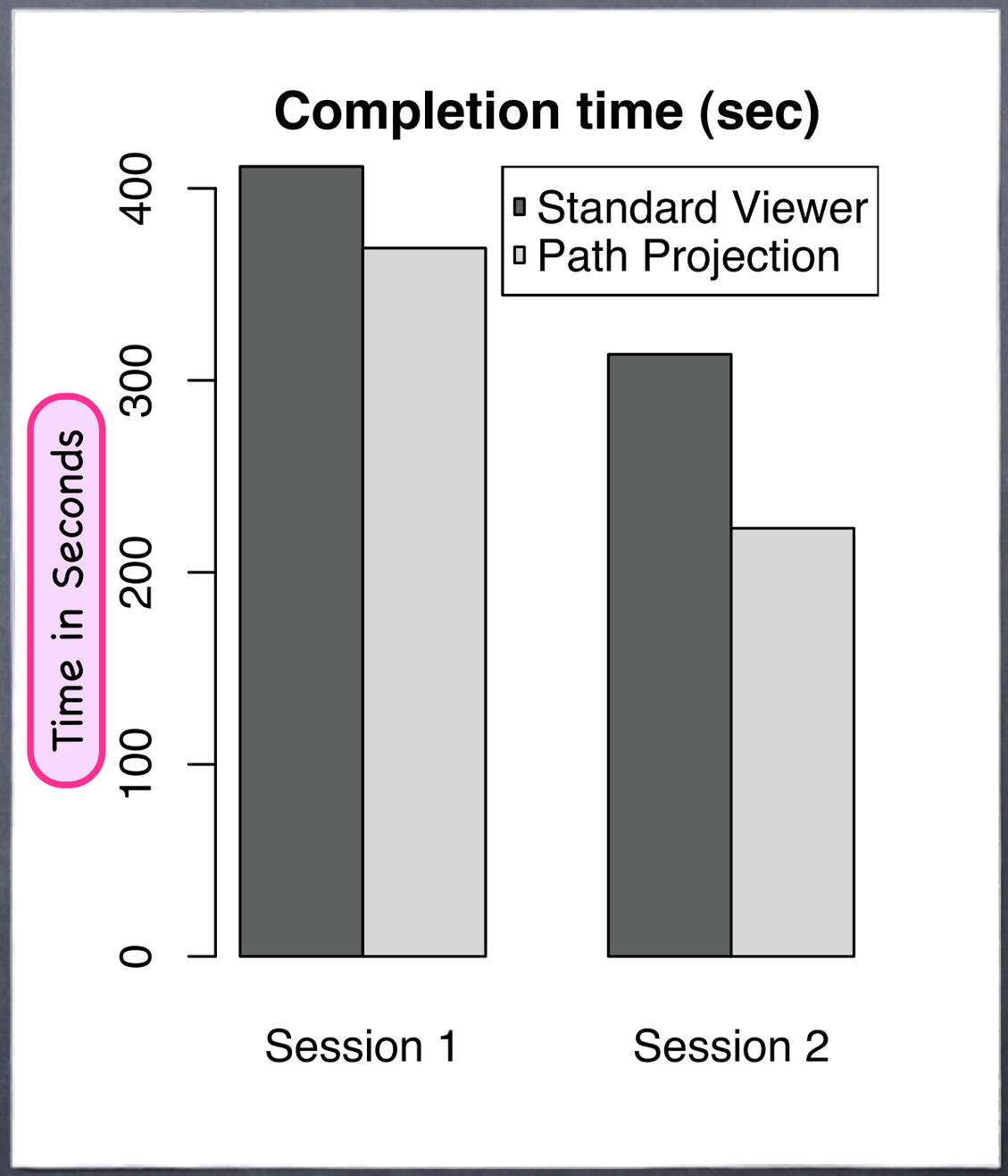
User Study: Misc.

- 8 student participants
  - 3 undergraduates, 5 graduates
  - Prior experience in C, multithreading (not necessarily C)
  - Self-rated 3-4 (1: no experience to 5: very experienced)
  - 2 had experience in Locksmith and Eraser

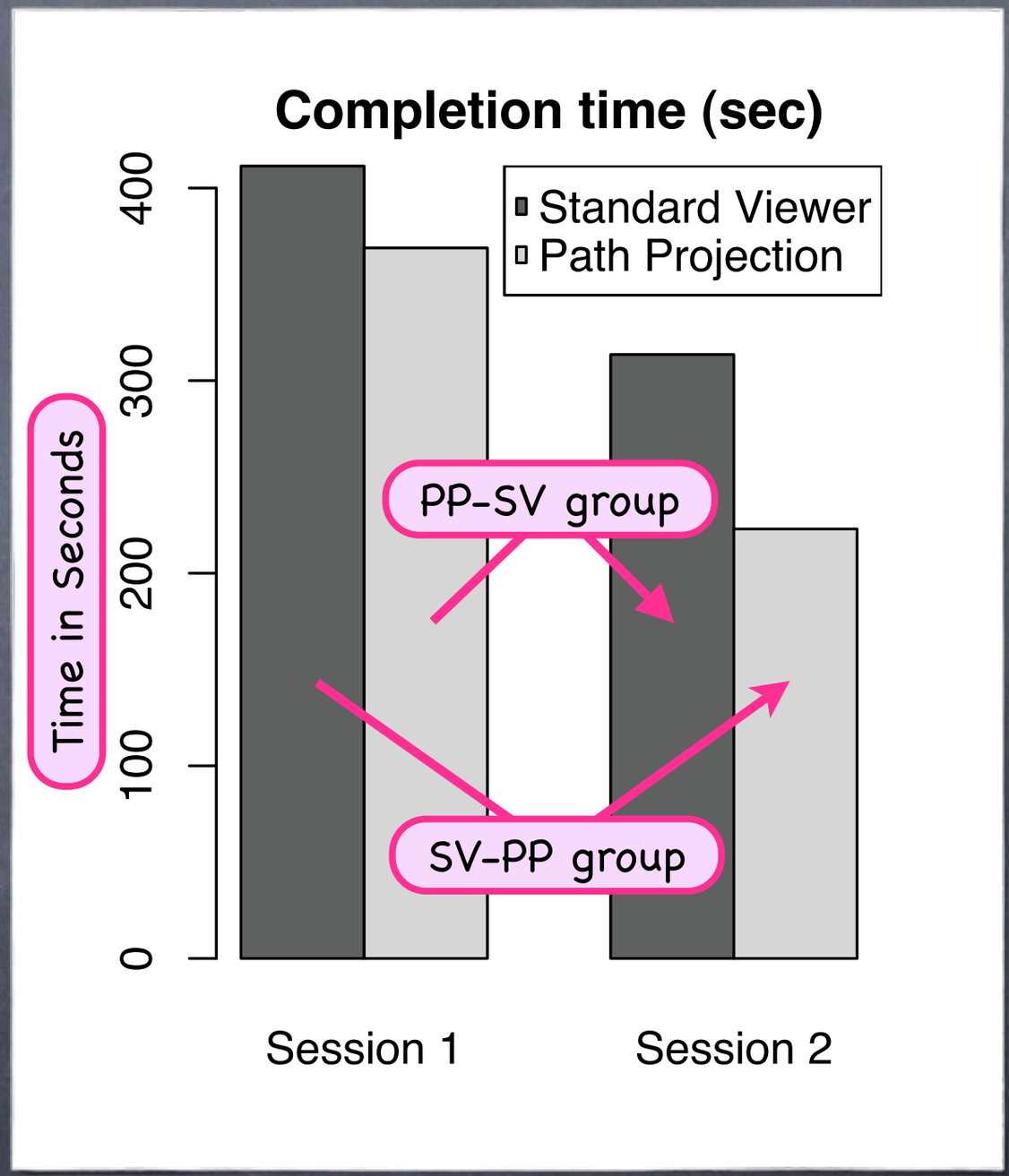
Quantitative (Chart guide)



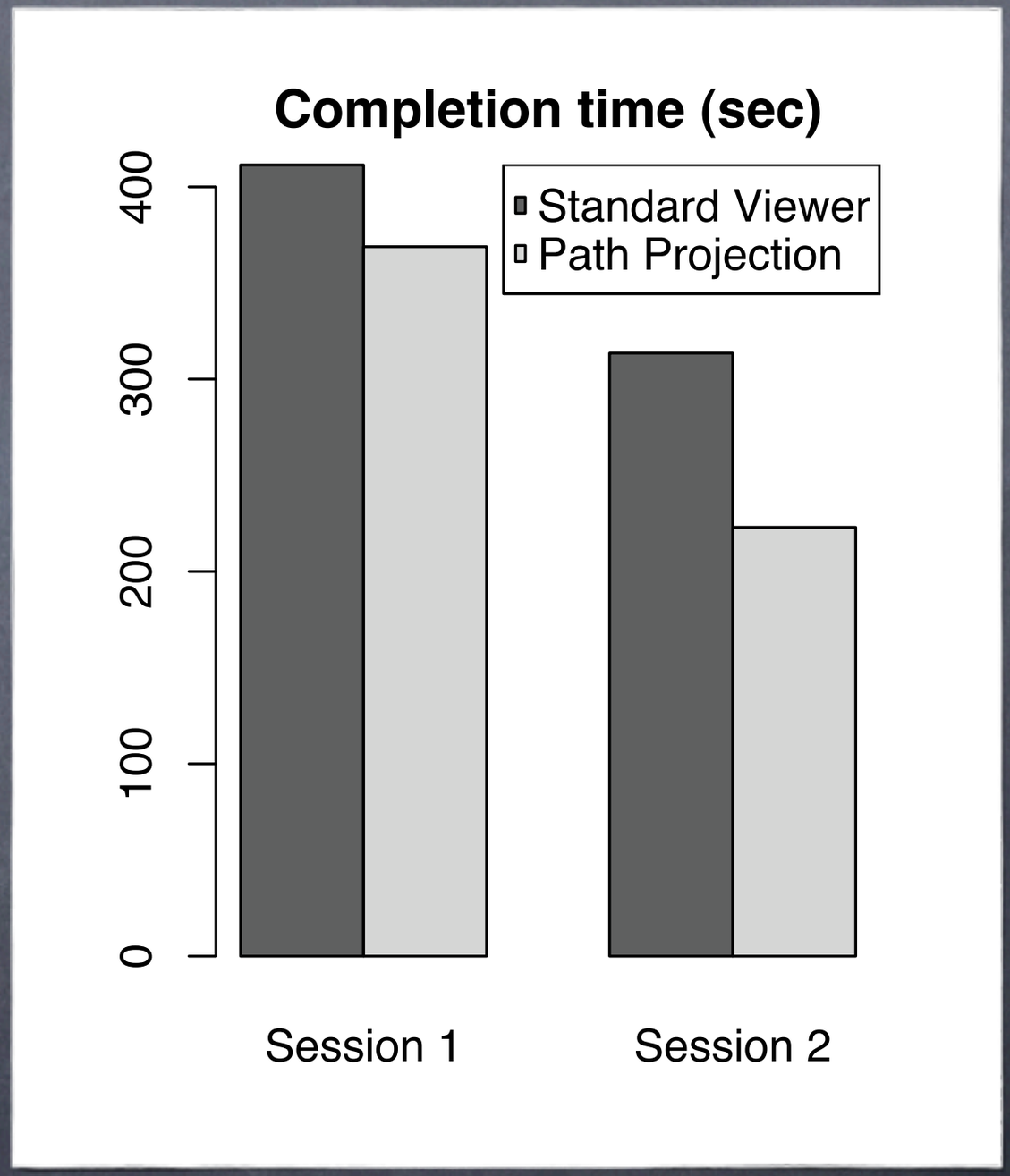
Quantitative (Chart guide)



Quantitative (Chart guide)



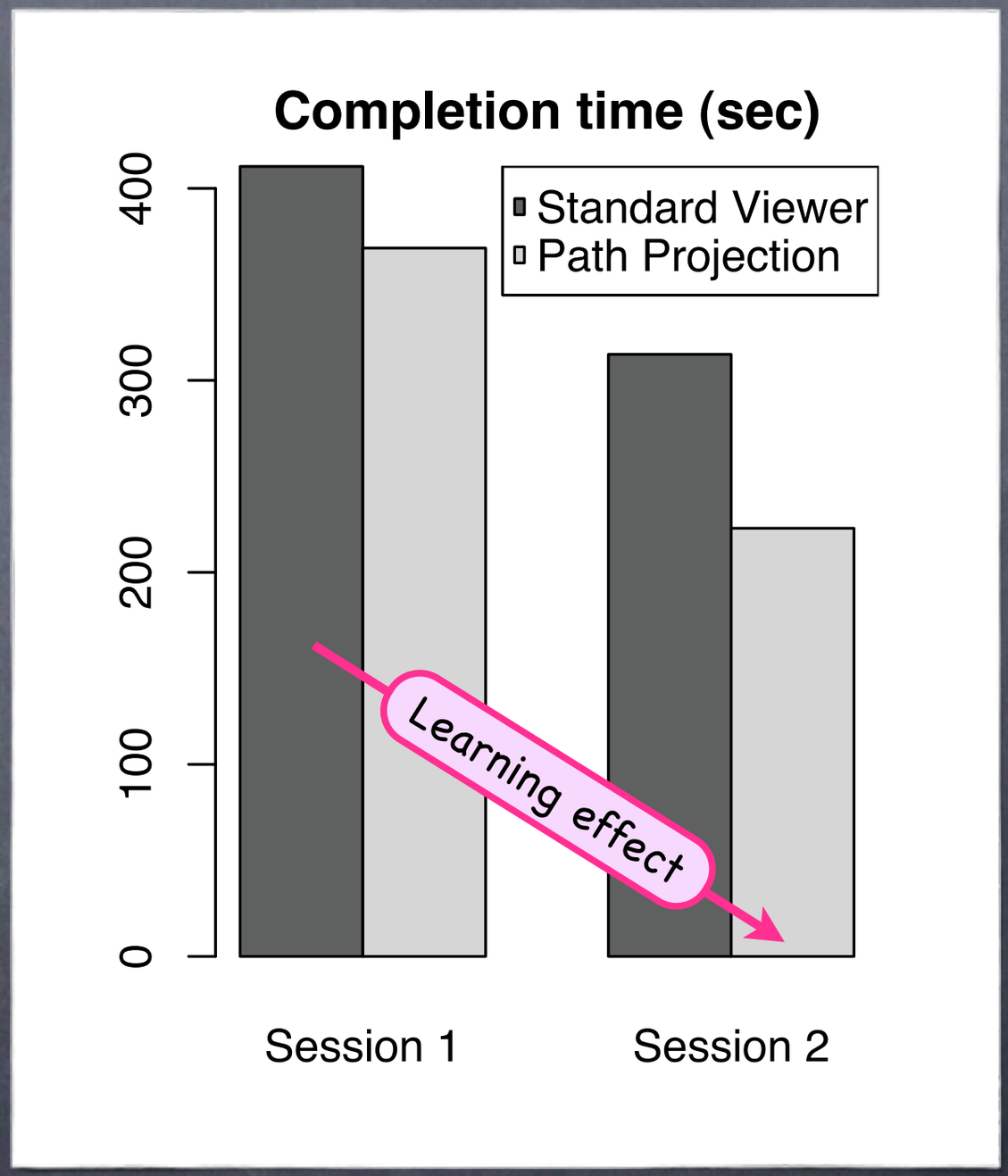
Faster Completion Time



Faster Completion Time

- Learning effect

  all improved in Session 2*



*statistically significant ($p<0.05$)

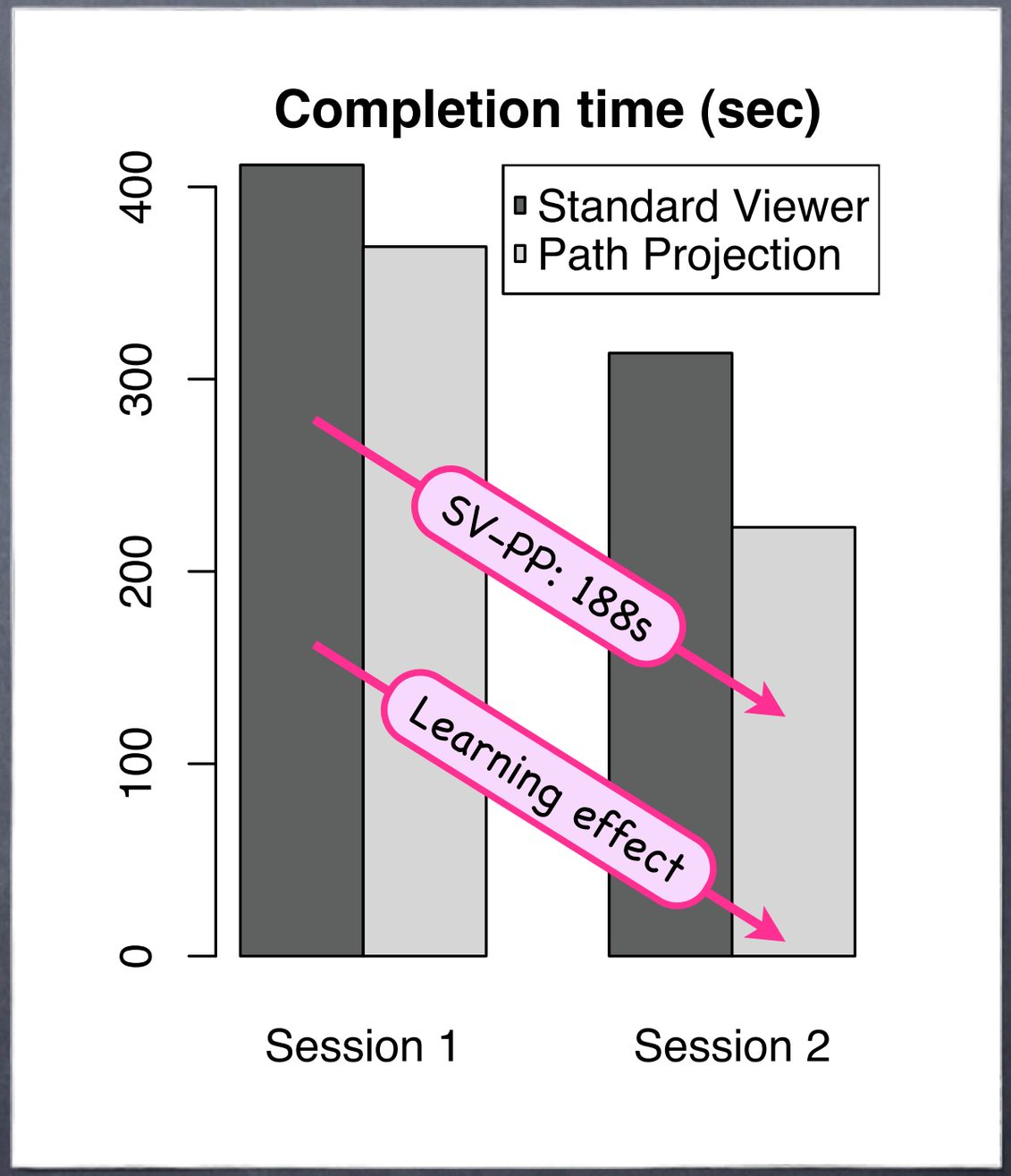
Faster Completion Time

- Learning effect

  all improved in Session 2*

- SV-PP improved by 188s*

  (effect size d=1.276)



*statistically significant ($p<0.05$)

Faster Completion Time

- Learning effect

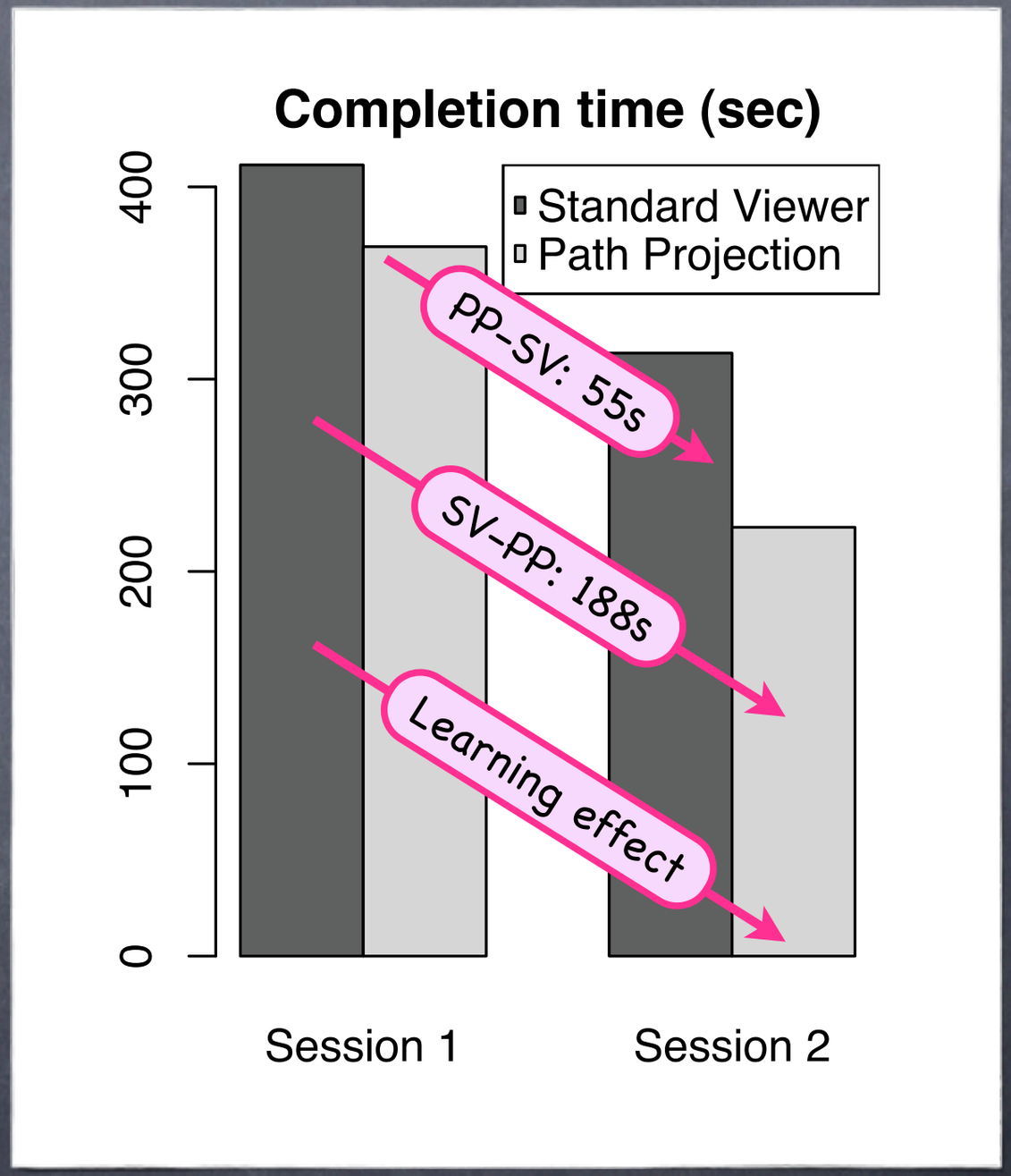
  all improved in Session 2*

- SV-PP improved by 188s*

  (effect size d=1.276)

- PP-SV improved by 55s*

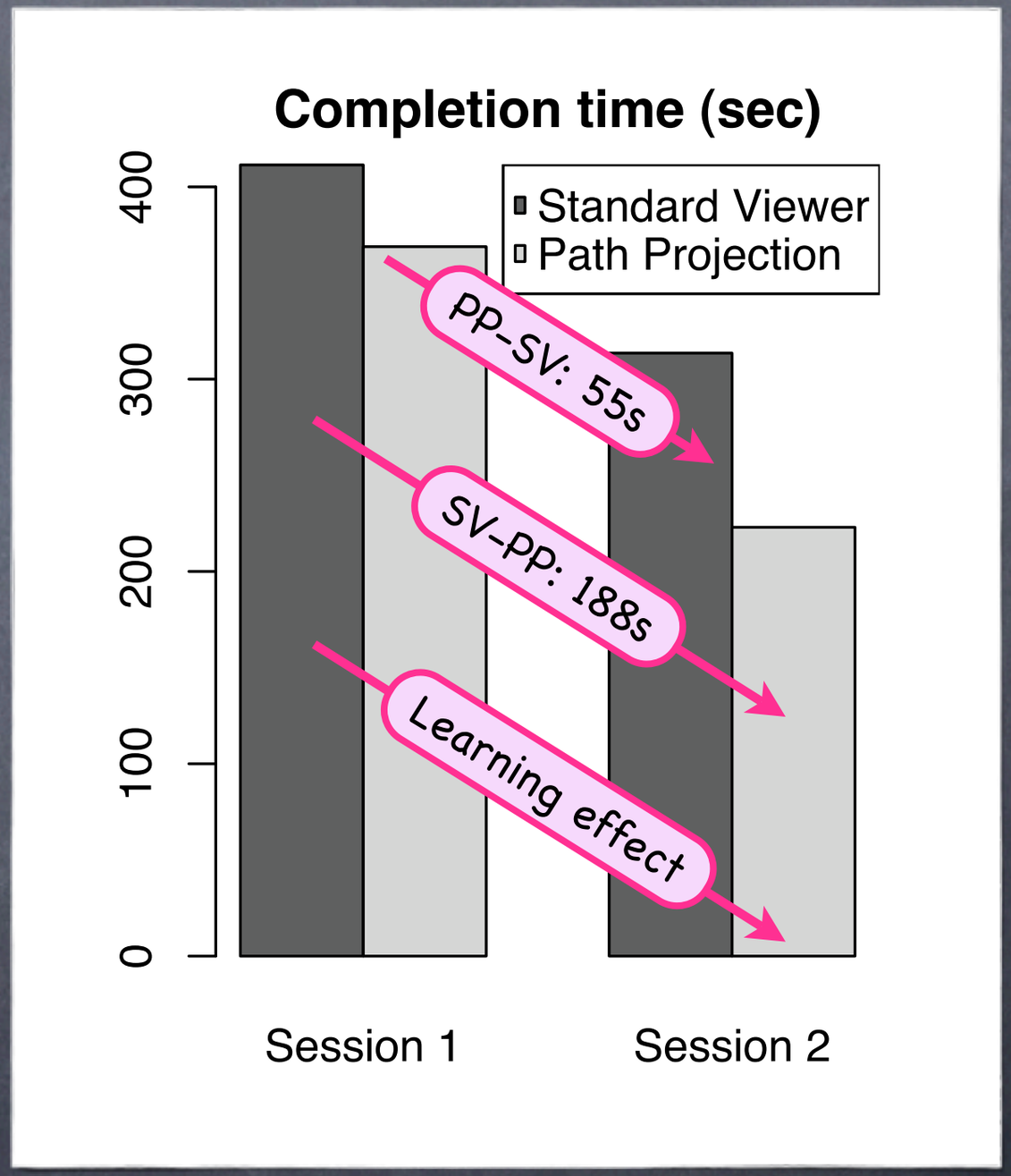
  (effect size d=0.375)



*statistically significant ($p<0.05$)

Faster Completion Time

- Learning effect
  - all improved in Session 2*
- SV-PP improved by 188s*
  - (effect size d=1.276)
- PP-SV improved by 55s*
  - (effect size d=0.375)
- Similar # mistakes
  - 10 in PP (10.9%), 9 in SV (9.8%)
- **18%** faster on average

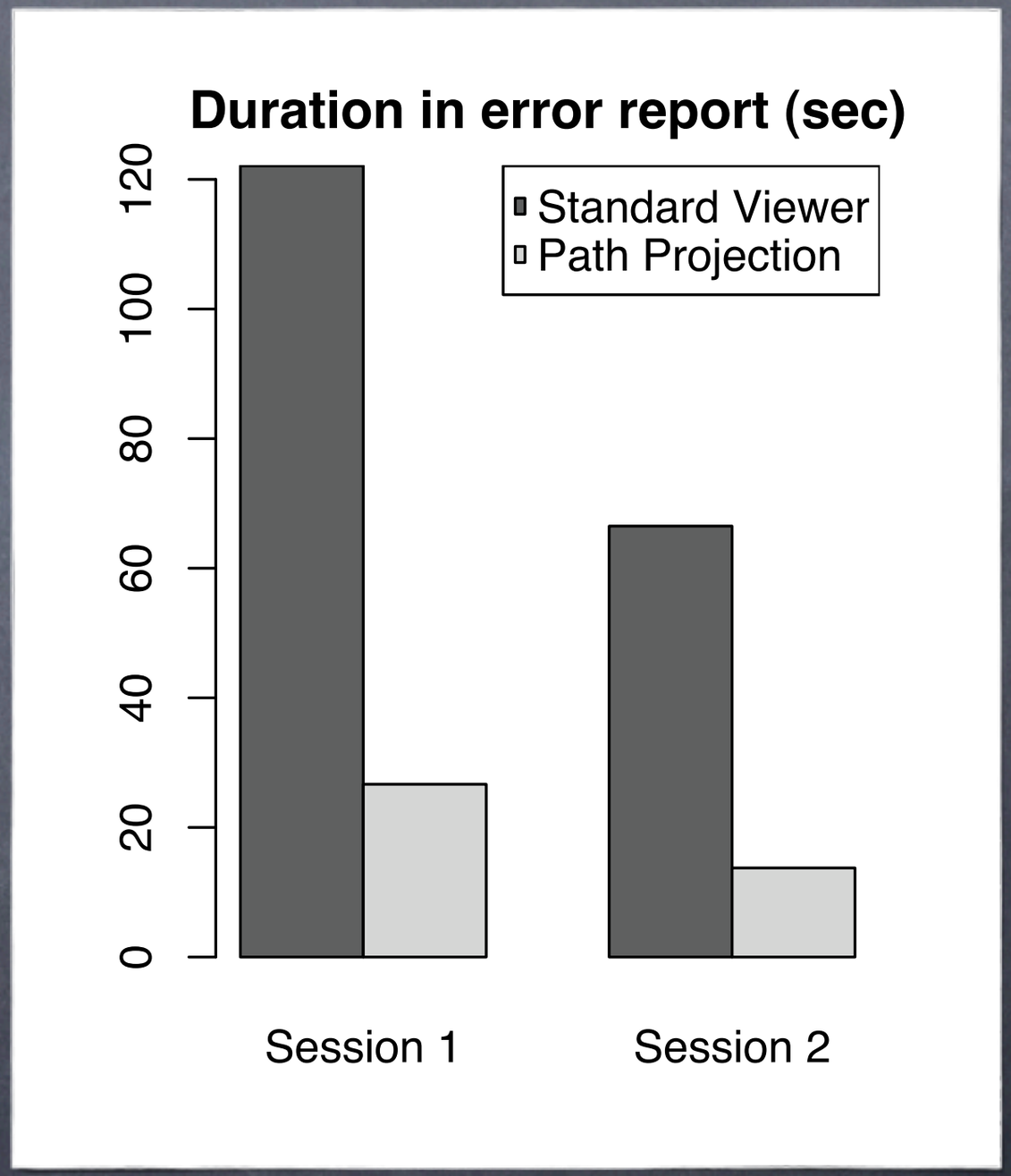


*statistically significant ($p<0.05$)

Less Use of Error Report

- Duration where pointer is over error report

  (e.g., using hyperlinks)



Less Use of Error Report

- Duration where pointer is over error report

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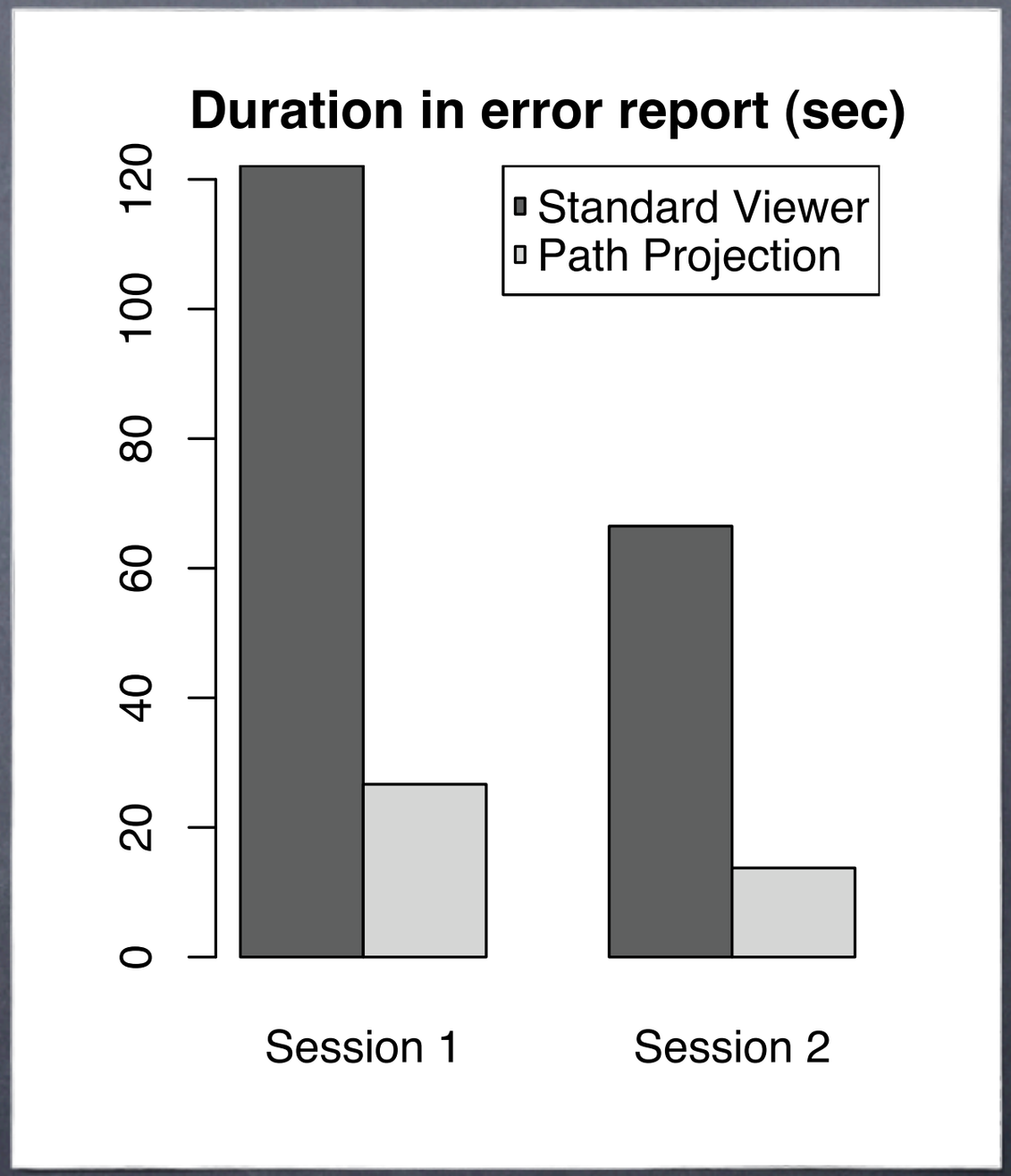
- On average, only 20s with PP vs. 94s with SV*



*statistically significant ($p<0.05$)

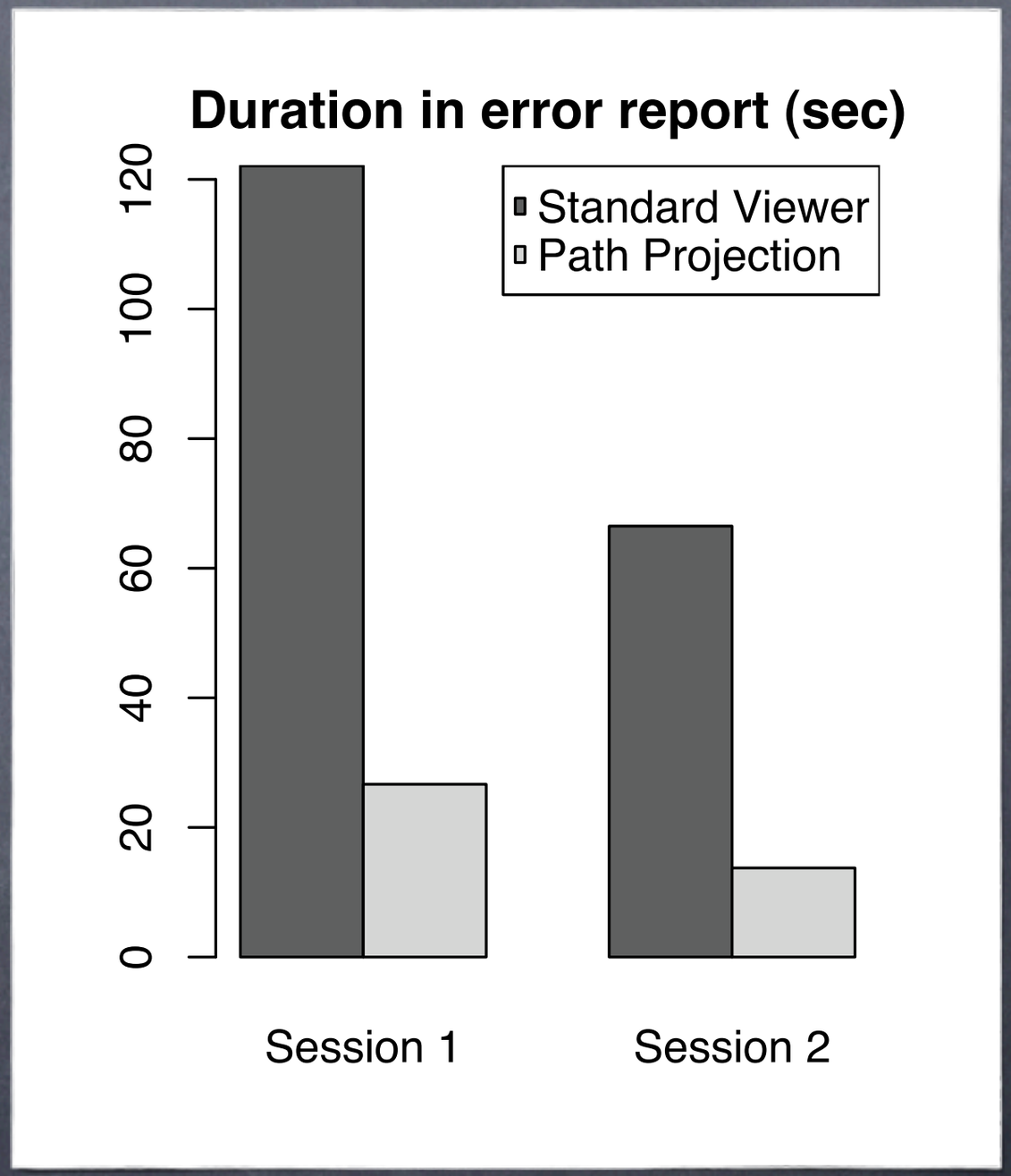
Less Use of Error Report

- Duration where pointer is over error report

  (e.g., using hyperlinks)

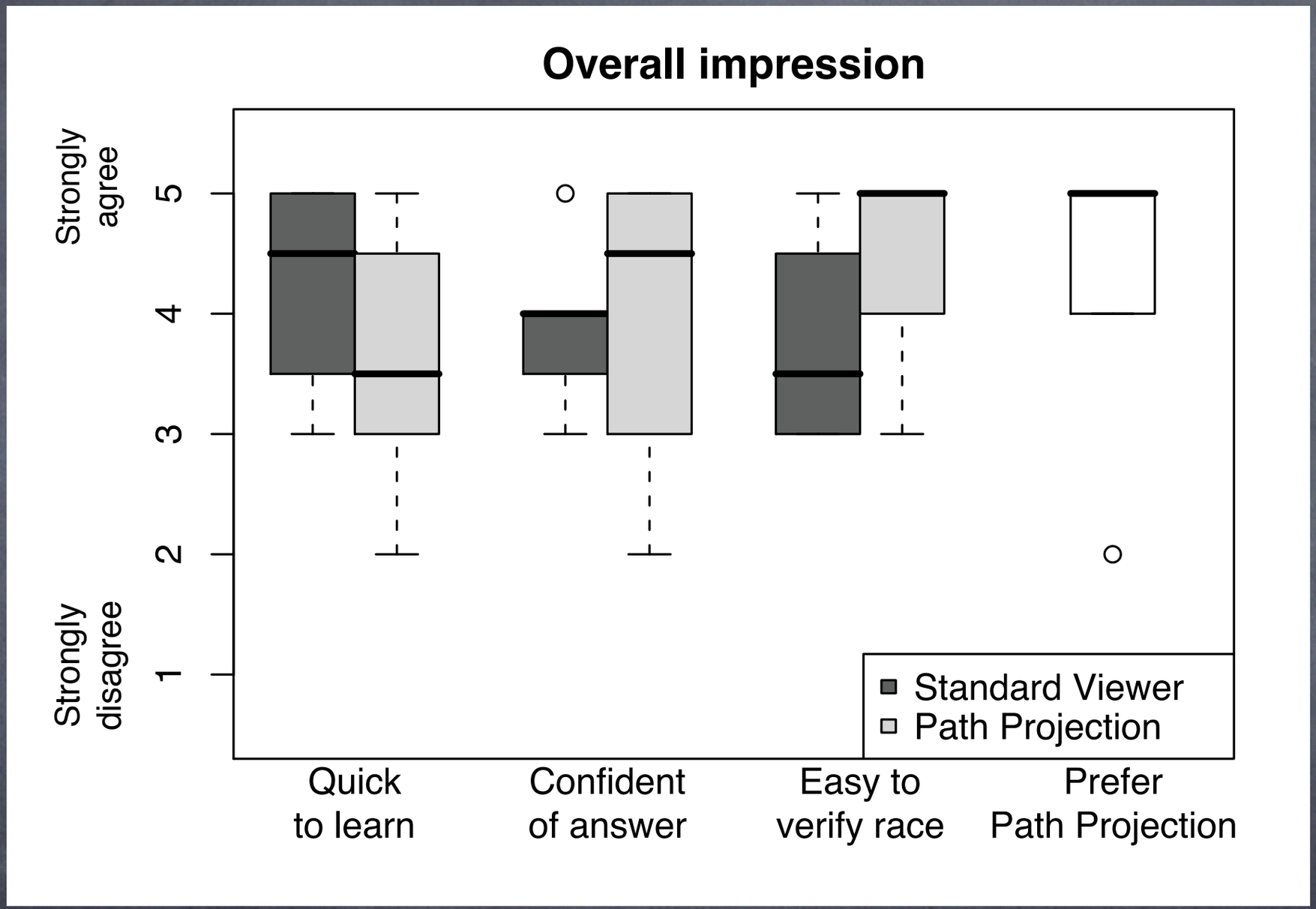
- On average, only 20s with PP vs. 94s with SV*

- "Necessary for [SV], but just a convenience in [PP]."



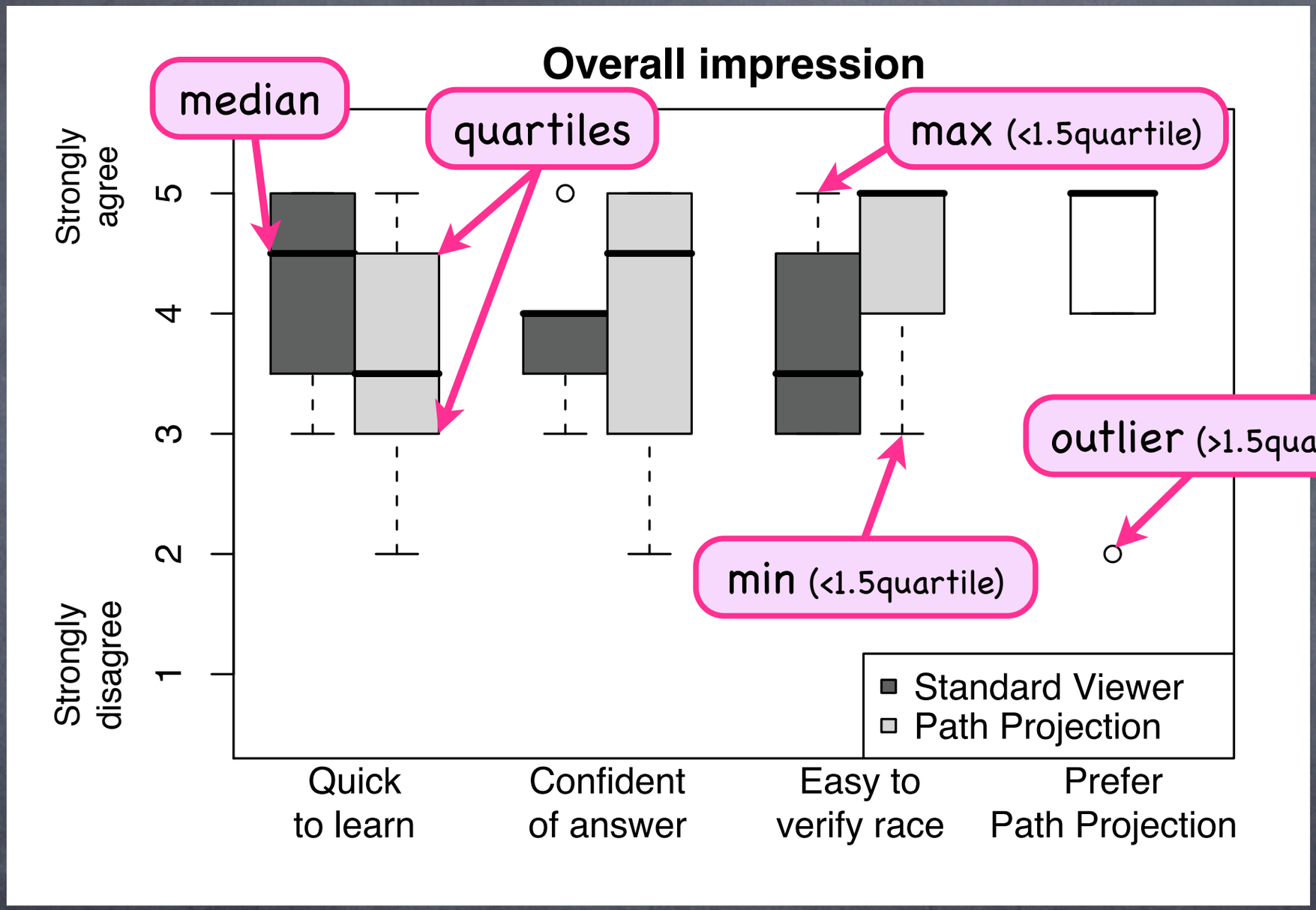
*statistically significant ($p<0.05$)

Qualitative (Boxplot Guide)



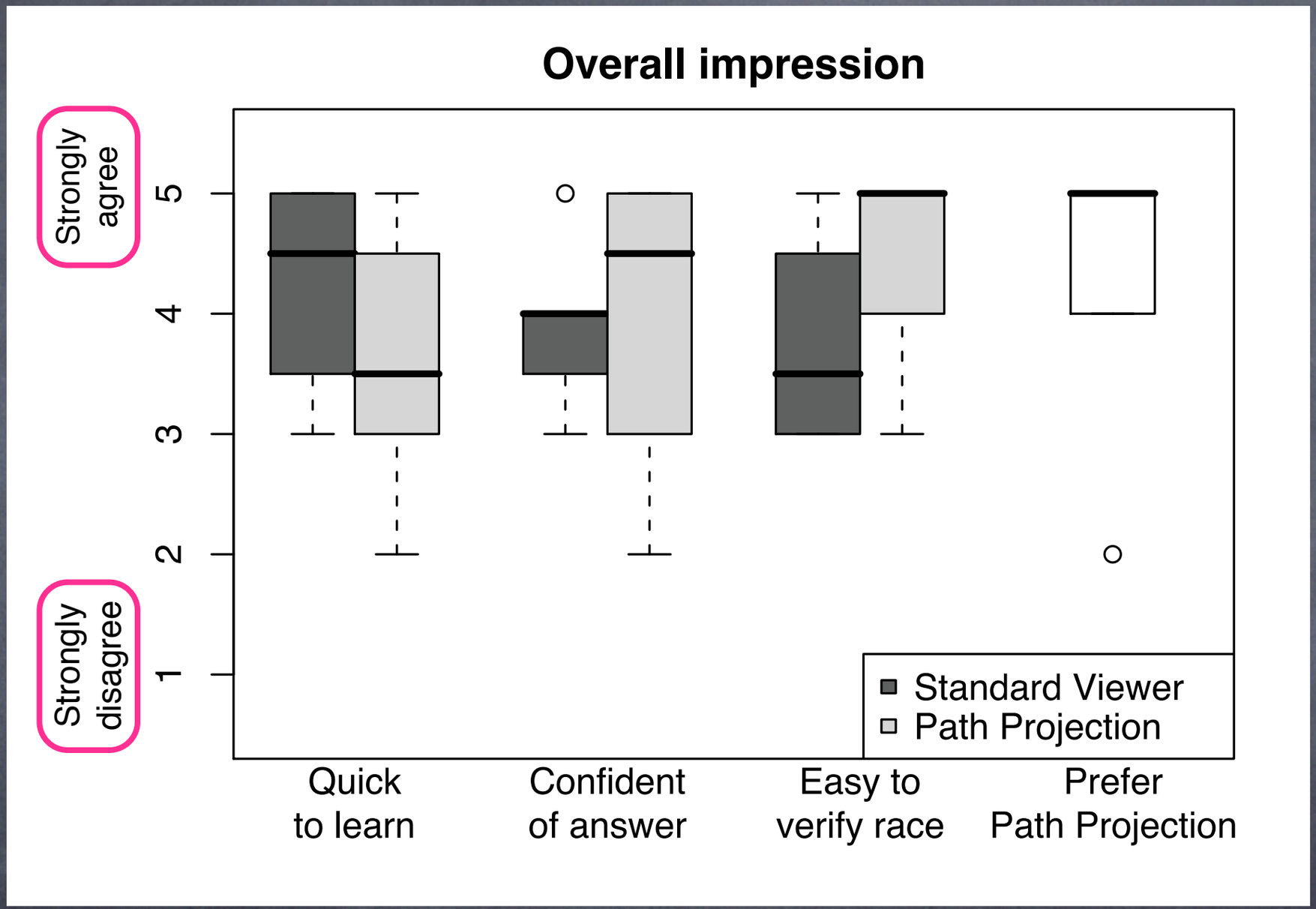
- We asked participants to rate on 1-5 scale

Qualitative (Boxplot Guide)

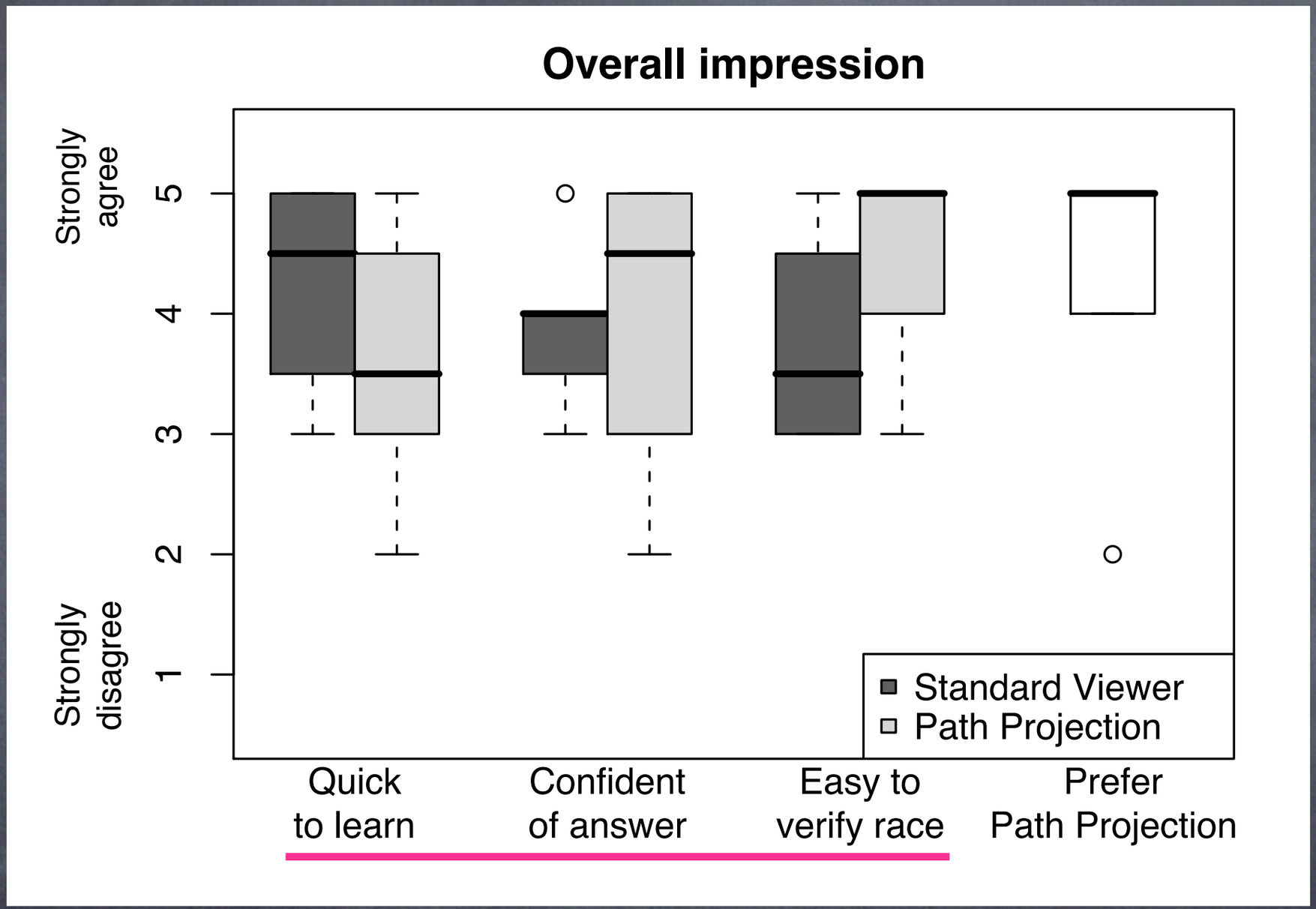


- We asked participants to rate on 1-5 scale
- Results summarized in boxplots

Prefer Path Projection

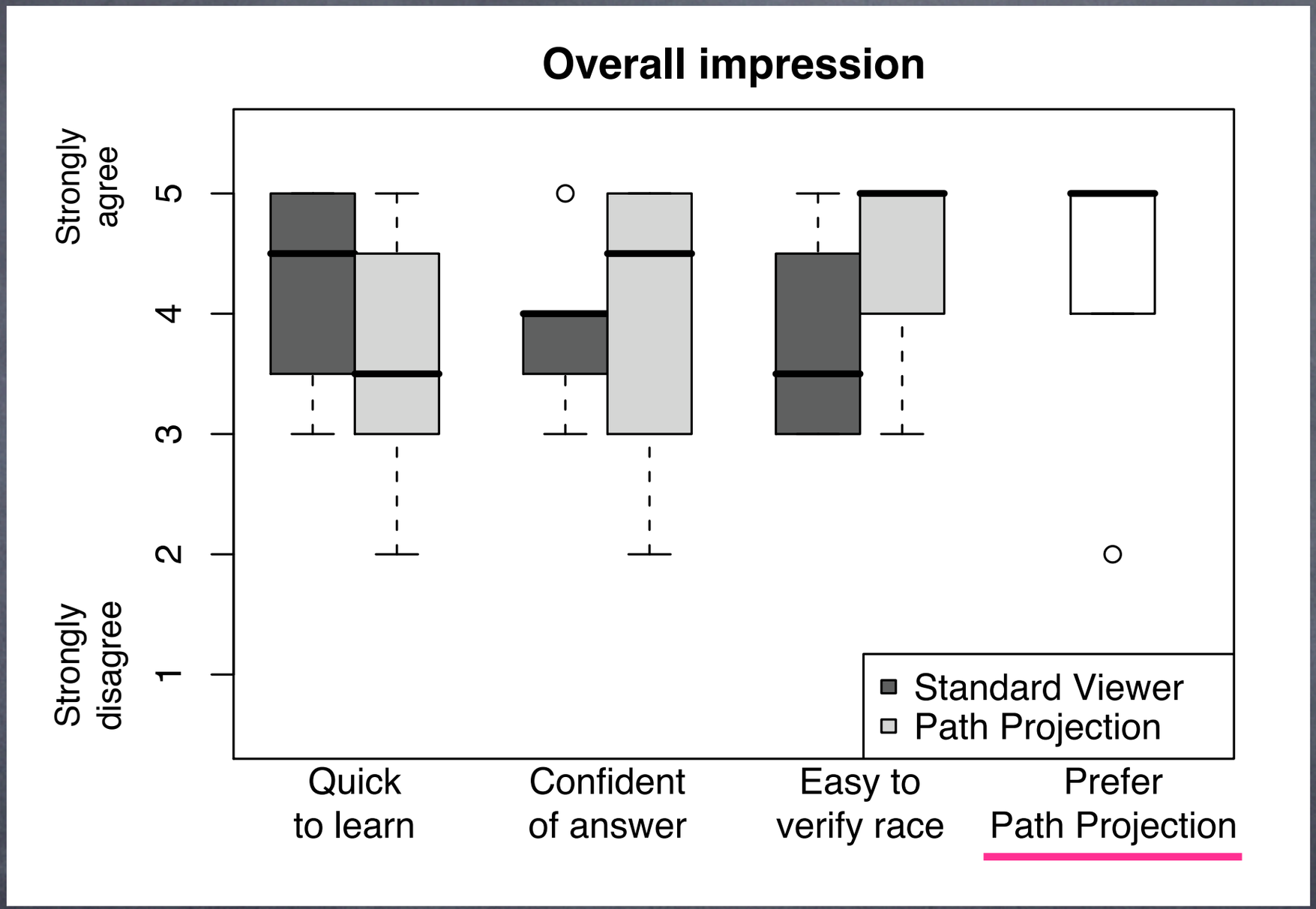


Prefer Path Projection



- Quick/confident/easy: not statistically significant

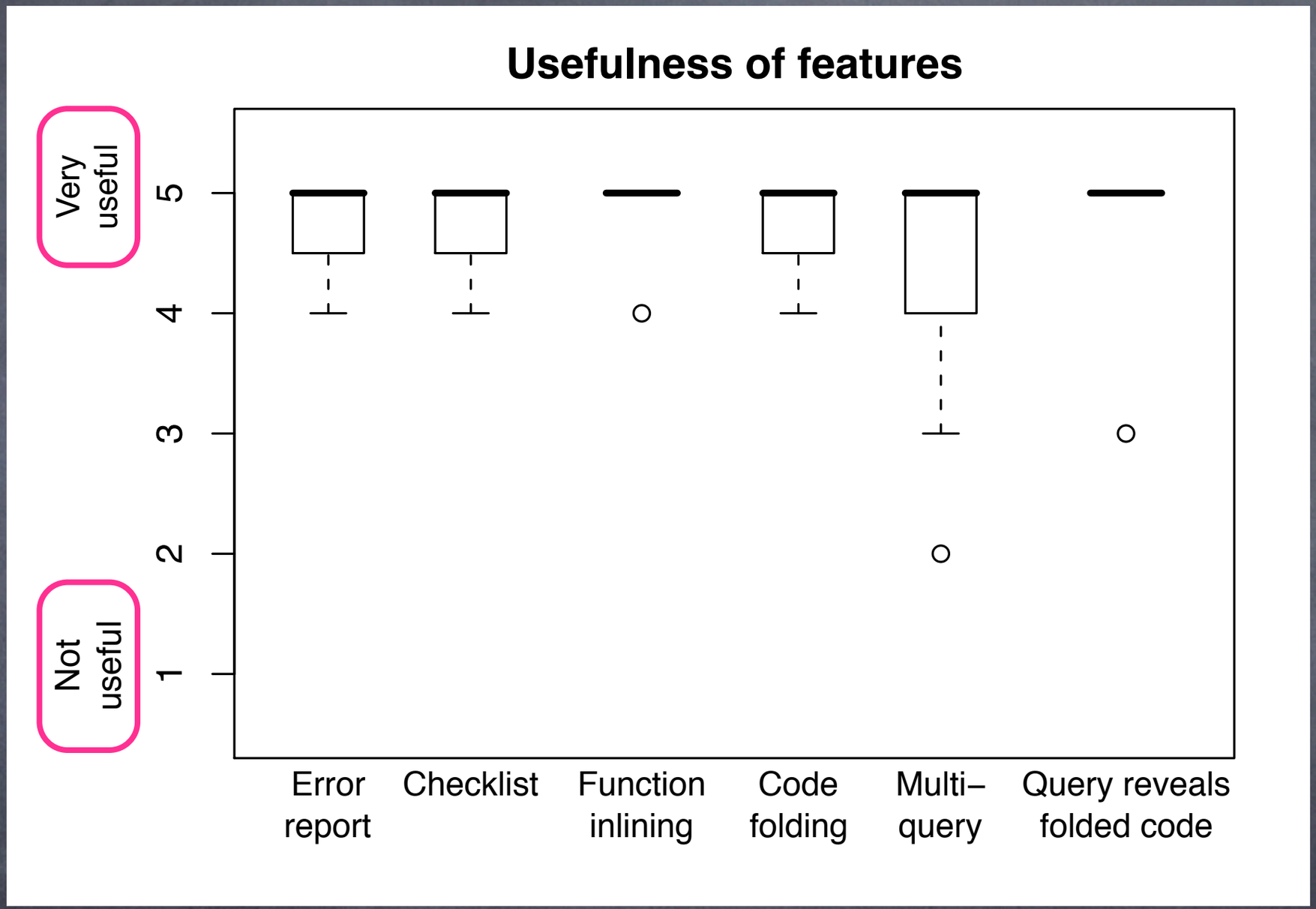
Prefer Path Projection



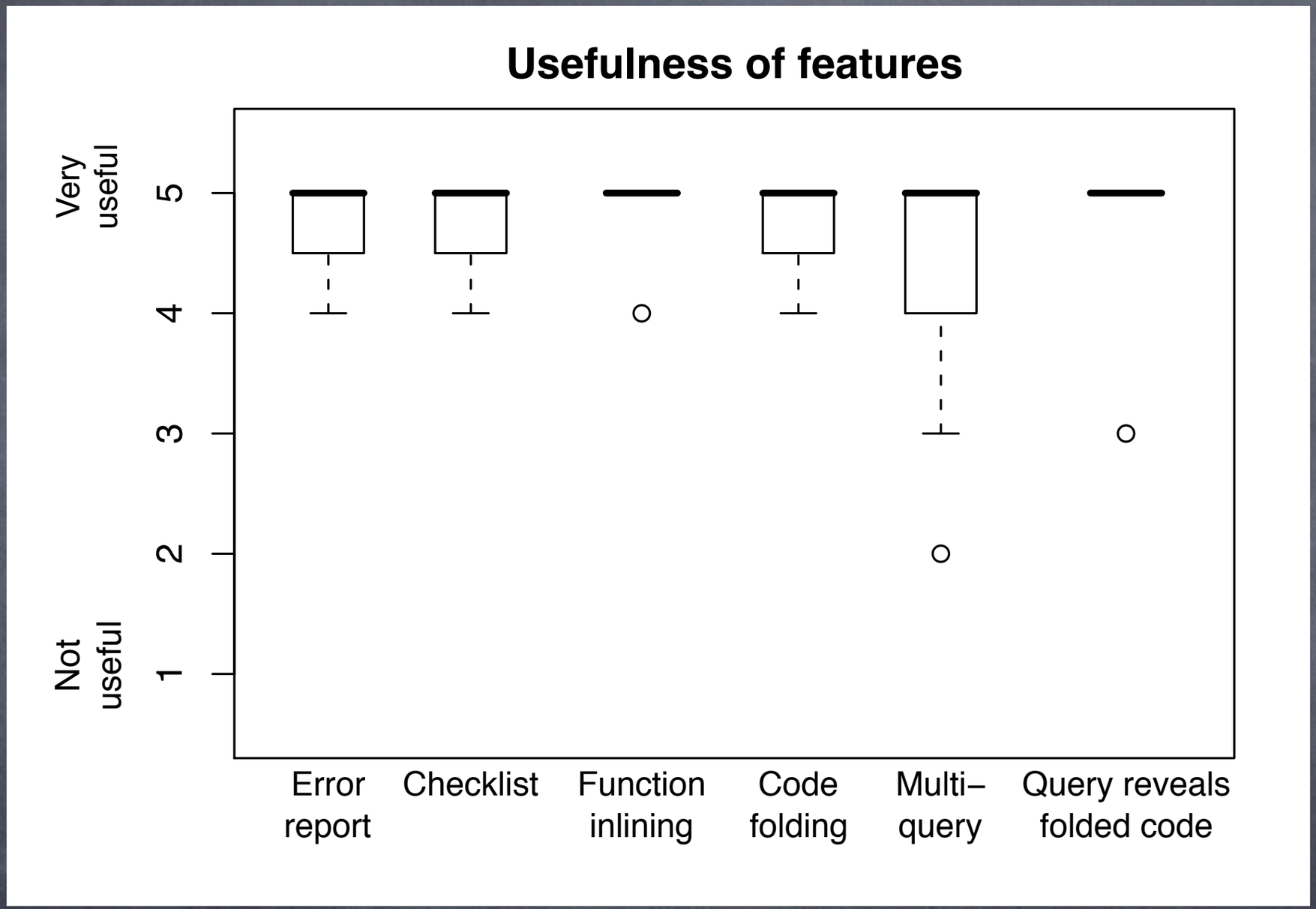
- Quick/confident/easy: not statistically significant
- Preference: all but one preferred PP to SV*

*statistically significant ($p<0.05$)

Path Projection Features



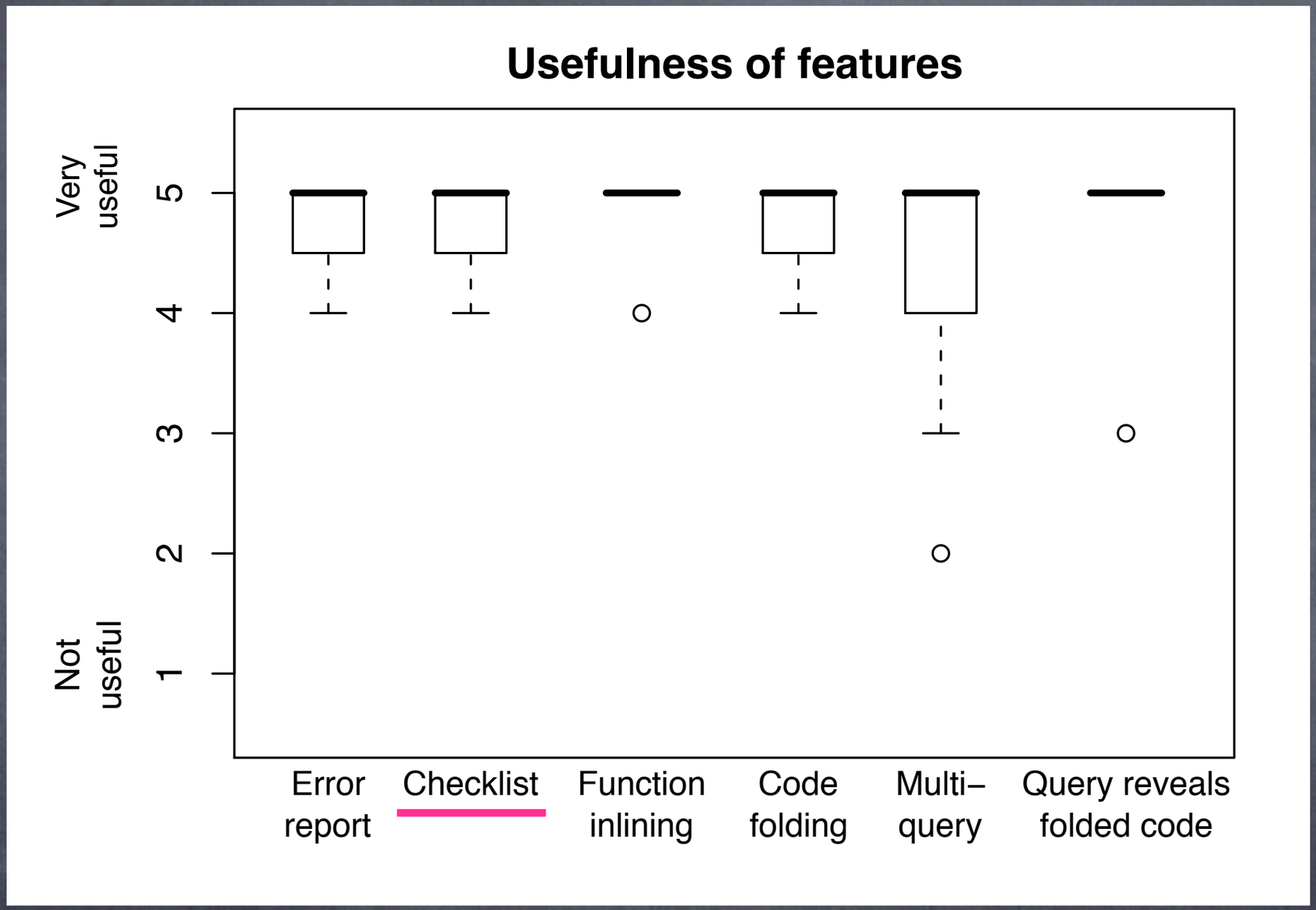
Path Projection Features



- Generally favorable towards PP features*

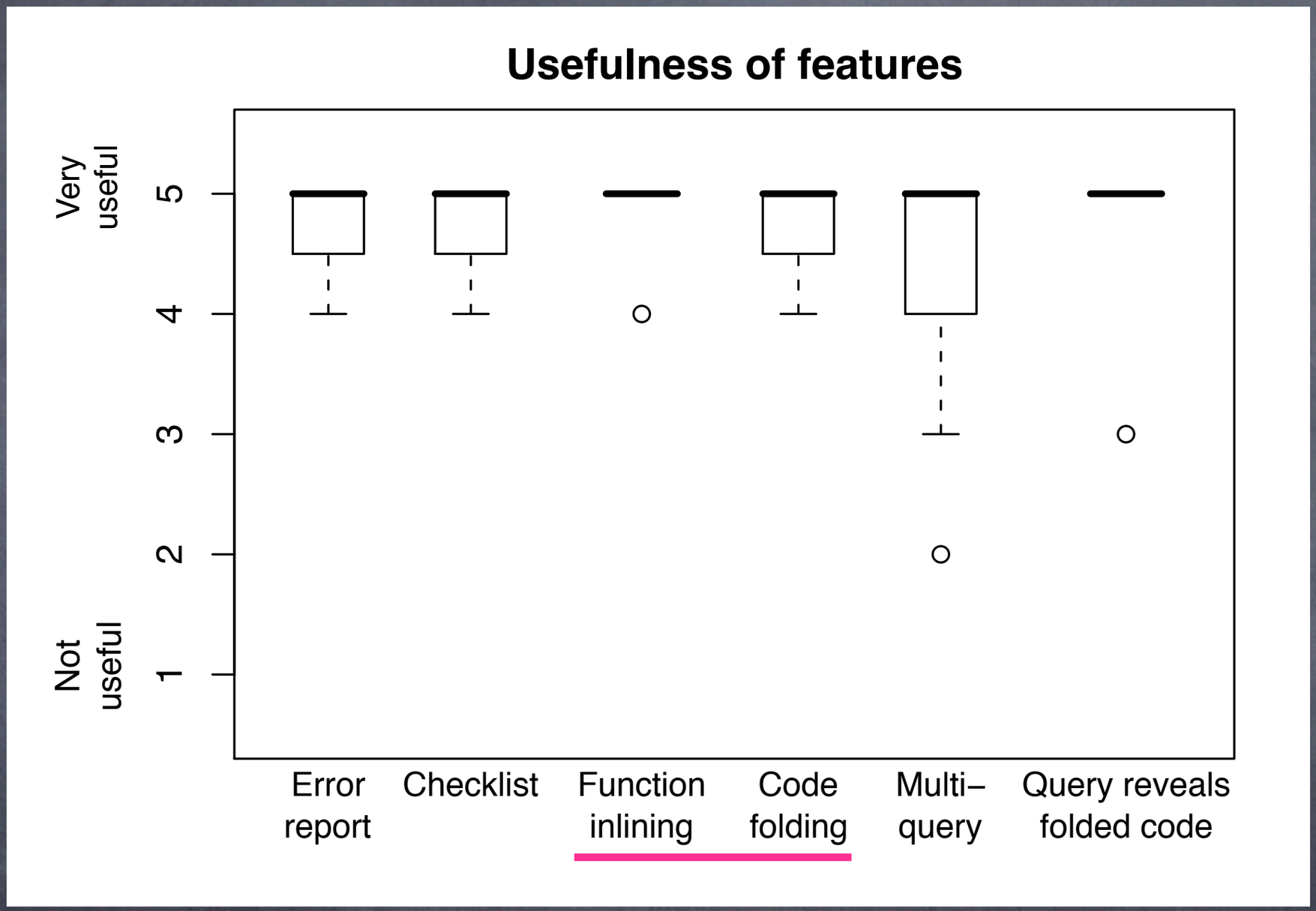
*statistically significant ($p<0.05$)

Path Projection Features



- Checklist: "saved me from having to memorize rules"

Path Projection Features



- Checklist: "saved me from having to memorize rules"
- Surprisingly, favored function inlining/code folding

  code folding was "the best feature" or "my favorite feature"

Threats To Validity

- Experimental design limitations
  - small number of users and trials
  - not static analysis experts, unfamiliar programs
  - statistically significant despite limitations
- Standard Viewer not "real" editor
  - deliberate choice to avoid bias from prior experience
- The checklist might bias users
  - checklist designed for Locksmith, not SV or PP
  - both interfaces use the same checklist

Conclusion

- Path Projection: a new UI toolkit for visualizing program paths
- Can be used with any static analysis tools
  - Takes an XML path report as input
- Our study showed that it improves completion time (18%) with similar accuracy and users liked it
- Try it at: http://www.cs.umd.edu/projects/PL/PP/