Accelerating Dynamic Data Race Detection Using Static Thread Interference Analysis

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Outline

- Motivation
- Analysis phases
- Evalution

Dynamic Data Race Detector: ThreadSanitizer

ThreadSanitizer (TSan) finds data races in multithreaded programs by inserting instrumentations at compile-time to perform runtime checks for all memory accesses.

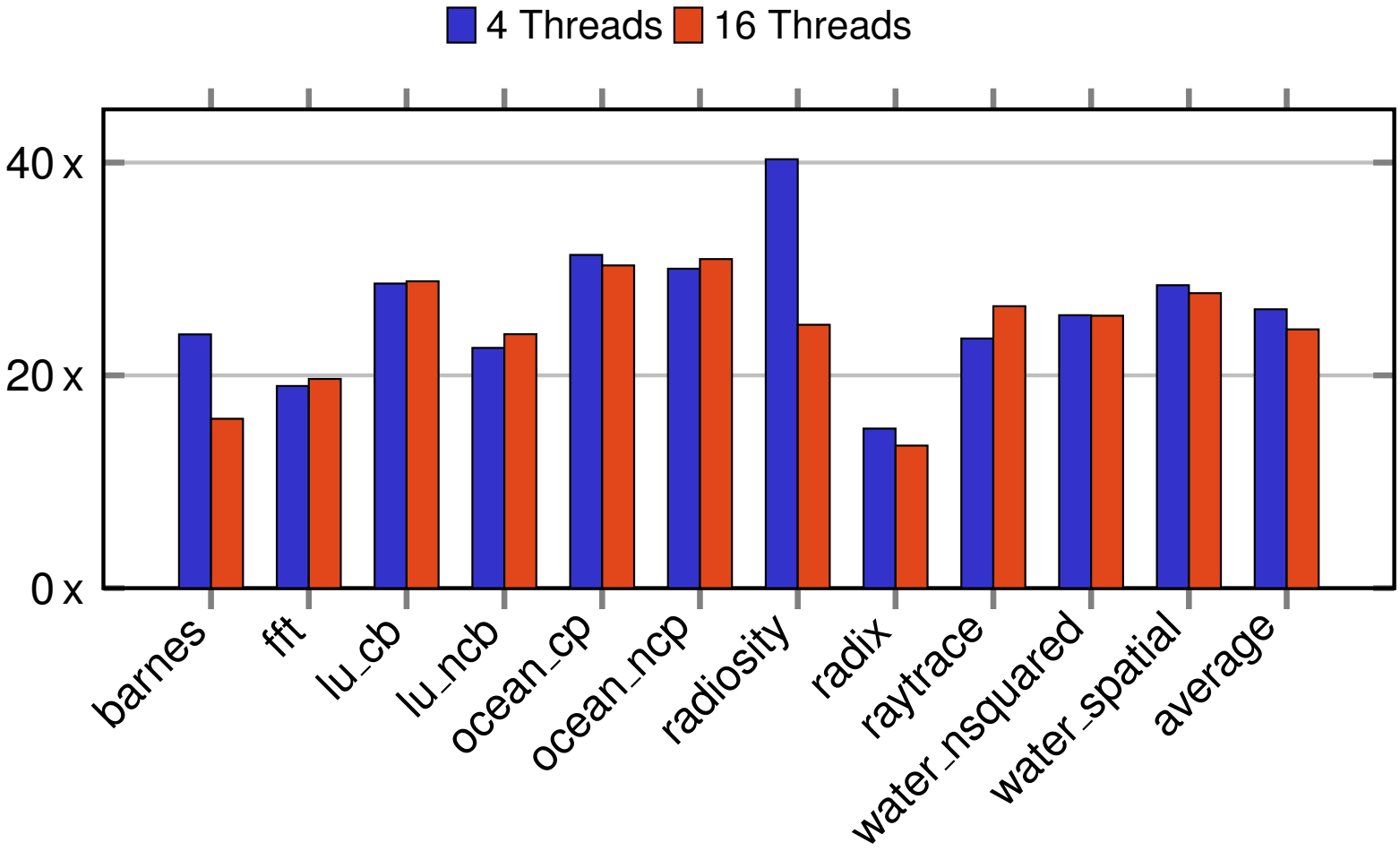
```
void foo(int *p) {
  *p = 42;
}
```

Orignial C code

```
void foo(int *p) {
  __tsan_func_entry(__builtin_return_address(0));
  __tsan_write4(p);
  *p = 42;
  __tsan_func_exit();
}
```

Code after instrumentation

TSan performance slowdown over native code for SPLASH2 benchmarks (under compiler option -O0)



Machine: Ubuntu Linux 3.11.0-15-generic Intel Xeon Quad Core HT, 3.7GHZ, 64GB

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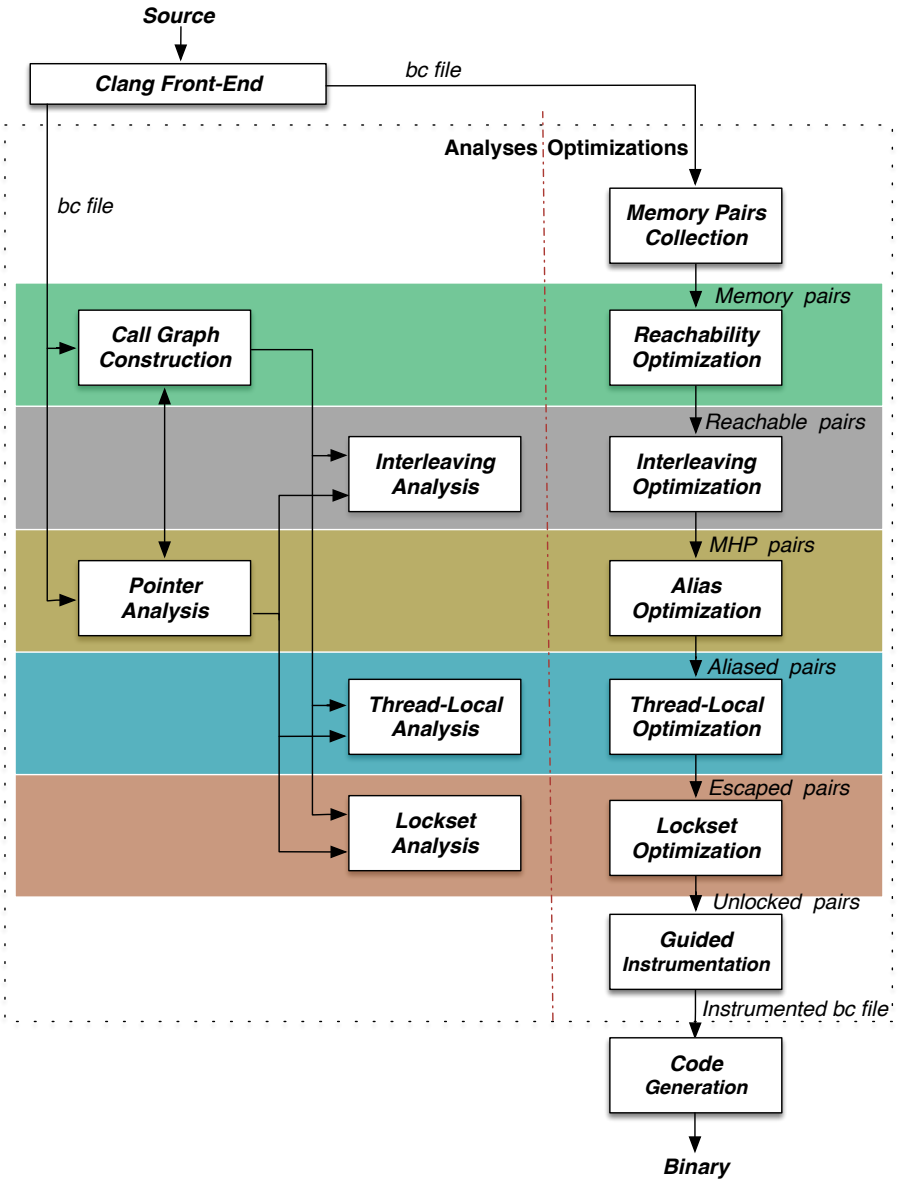
Framework



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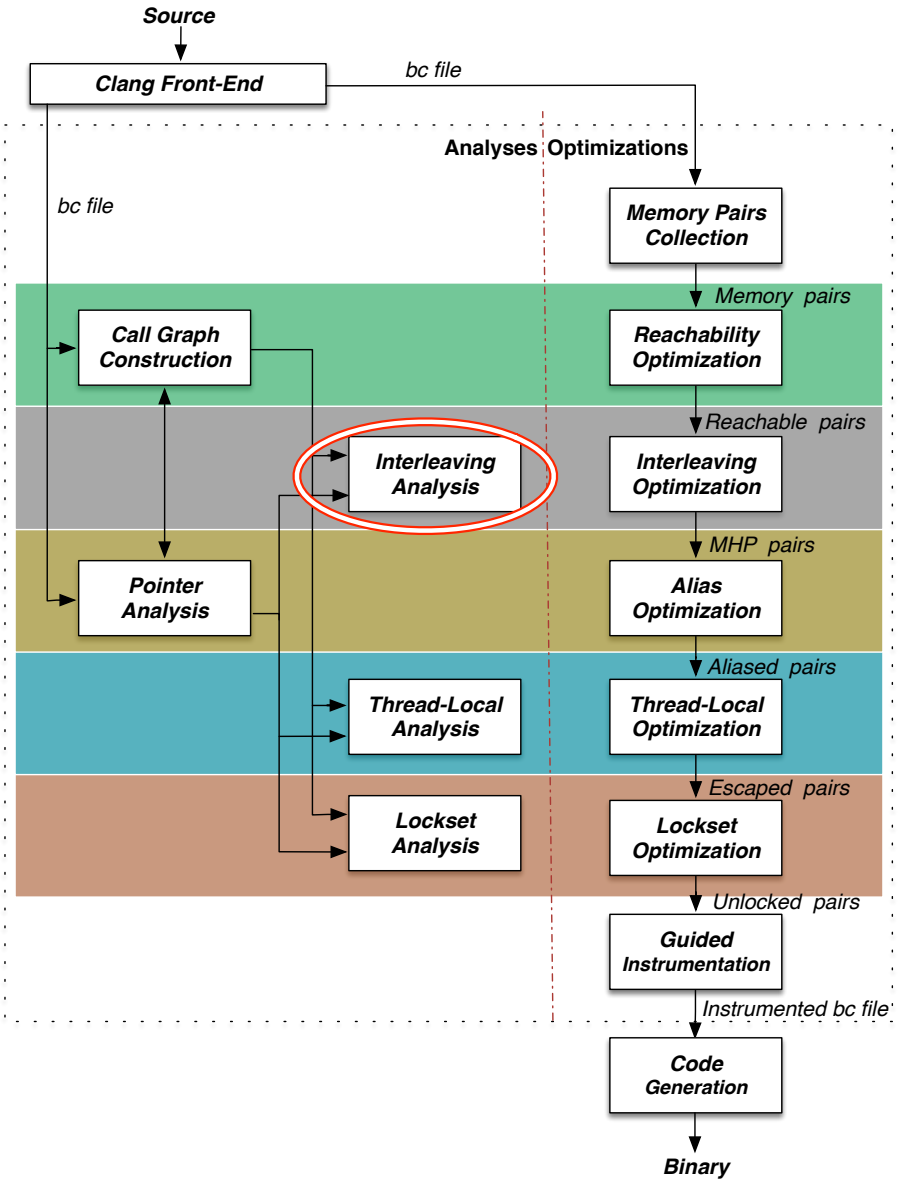

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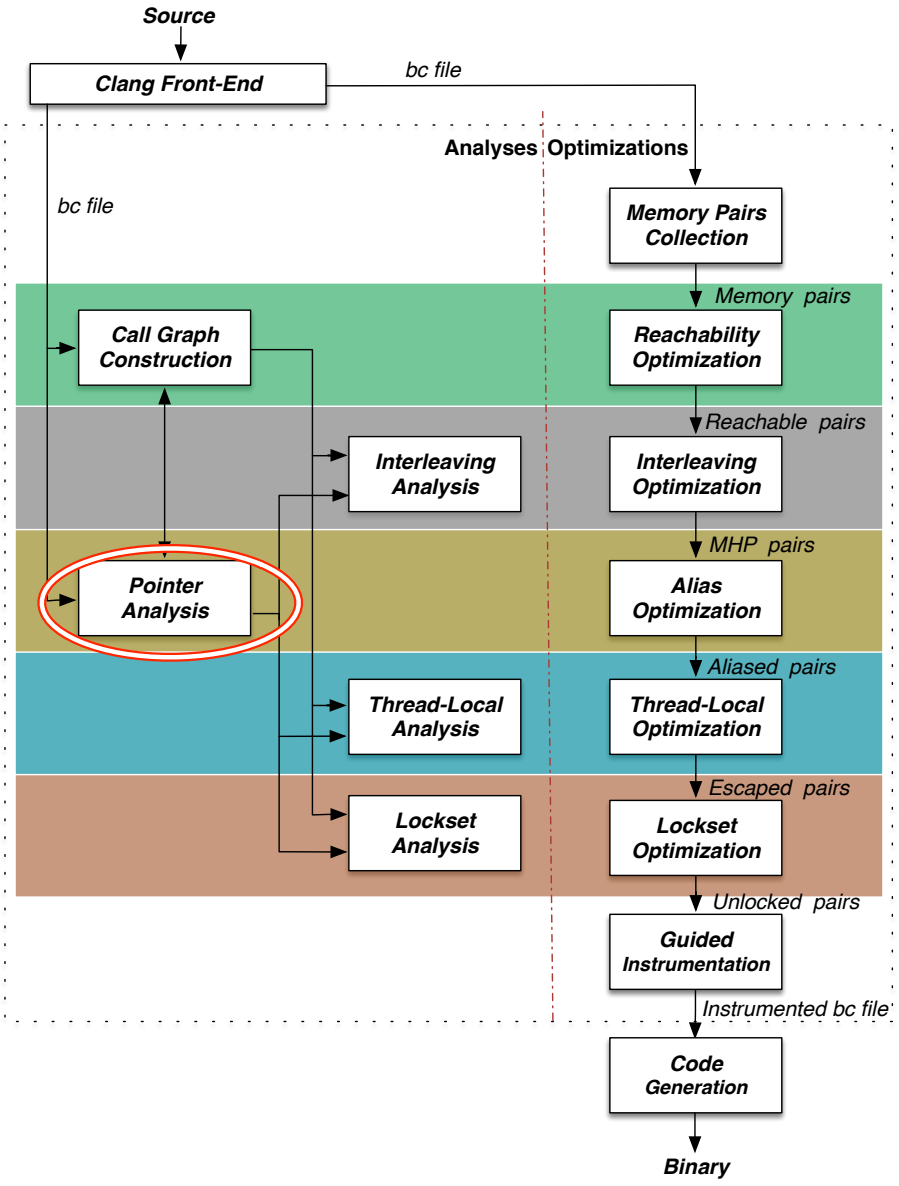

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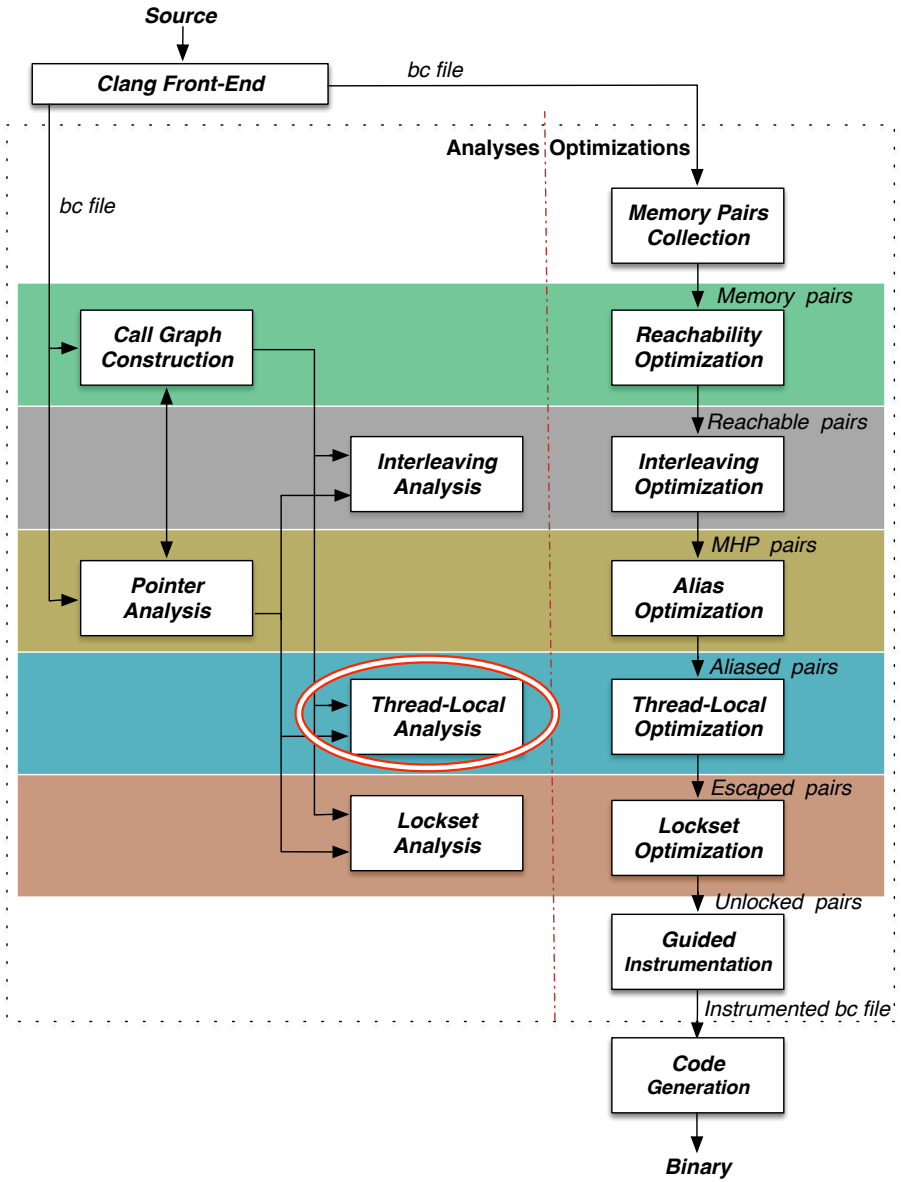

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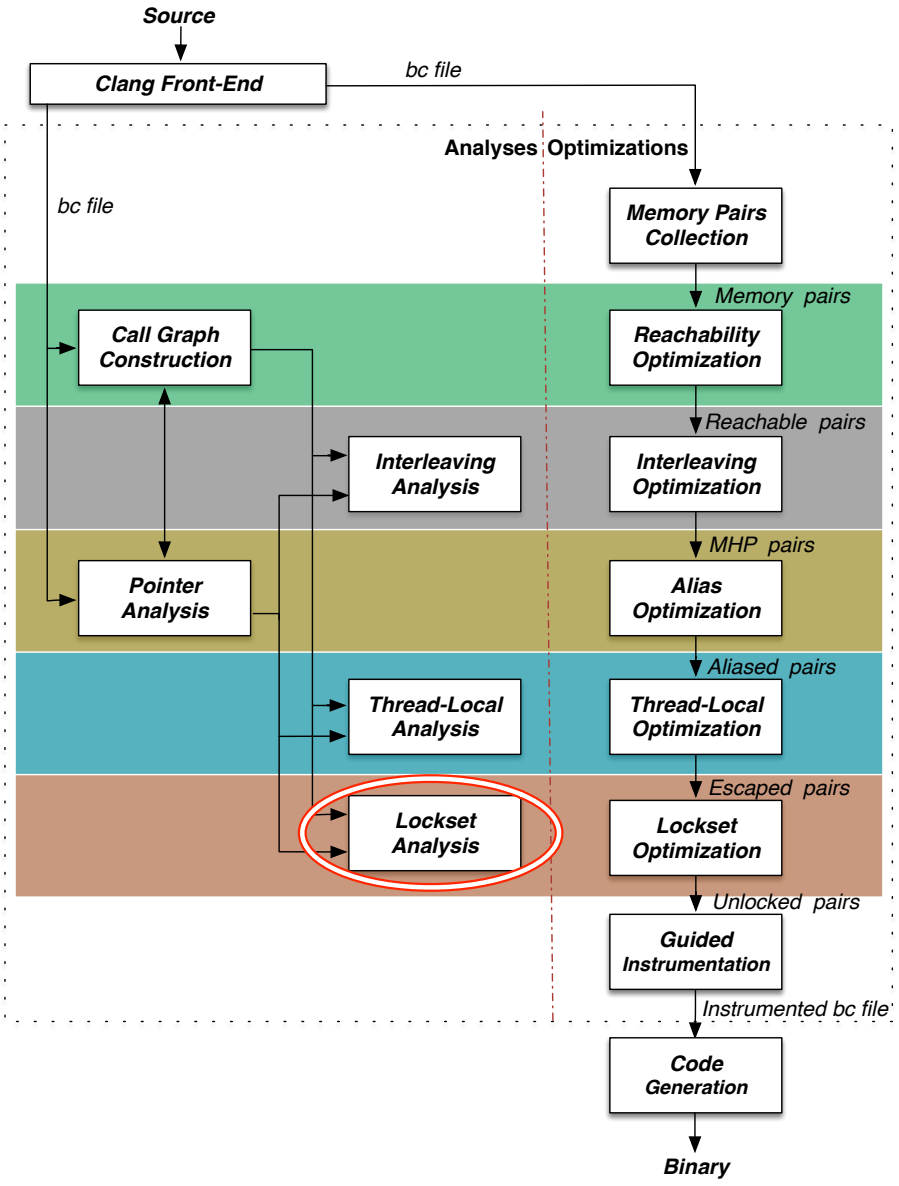
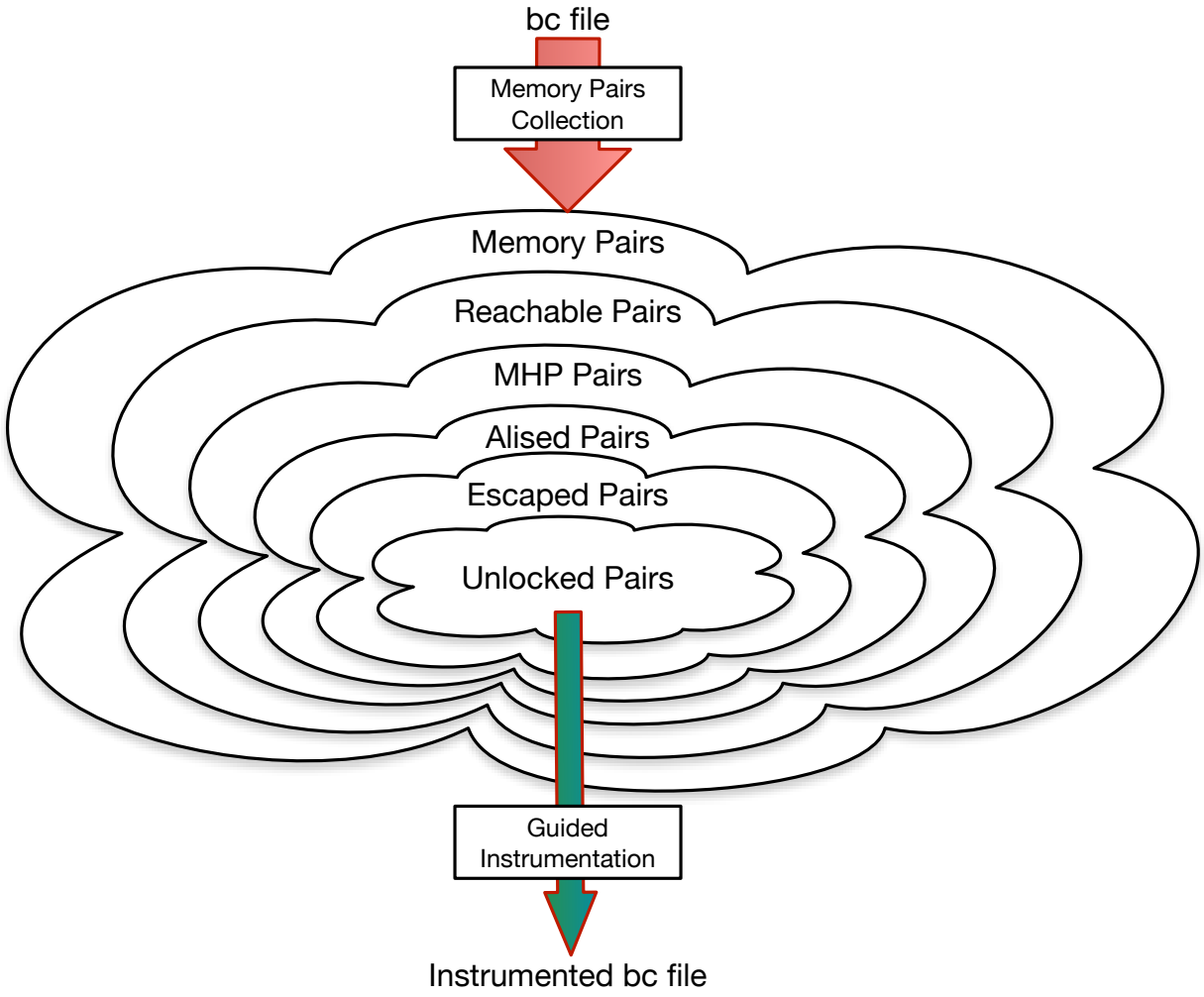


Refining Pairs

Only statements in the paris that are not filtered are instrumented for runtime check.



Context-Sensitive Abstract Threads

An abstract thread *t* refers to a call of pthread_create() at a context-sensitive fork site during the analysis.

```
void main(){          void foo(){

cs1: foo();           cs3: fork(t1, bar);
cs2: foo();               }

}
```

t1 *refers to fork site under context [1,3]*

t1' *refers to fork site under context [2,3]*

t1 and t1' are context-sensitive threads

Context-Sensitive Abstract Threads

An abstract thread *t* refers to a call of pthread_create() at a context-sensitive fork site during the analysis.

```
void main(){

cs1: foo();
cs2: foo();

}
```

```
void foo(){

cs3: fork(t1, bar);
   }
```

```
void main(){

   for(i=0;i<10;i++){
      fork(t[i], foo)
   }

}
```

t1 *refers to fork site under context [1,3]*

t1' *refers to fork site under context [2,3]*

t1 and t1' are context-sensitive threads

t is multi-forked thread

A thread *t* always refers to a context-sensitive fork site, i.e., a unique runtime thread unless $t \in \mathcal{M}$ is *multi-forked*, in which case, t may represent more than one runtime thread.

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Context-sensitive Thread Interleaving Analysis

$(t_1, c_1, s_1) \parallel (t_2, c_2, s_2)$ holds if:

$$\begin{cases} t_2 \in \mathcal{I}(t_1, c_1, s_1) \wedge t_1 \in \mathcal{I}(t_2, c_2, s_2) & \text{if } t_1 \neq t_2 \\ t_1 \in \mathcal{M} & \text{otherwise} \end{cases}$$

where $\mathcal{I}(t, c, s)$: denotes a set of interleaved threads may run in parallel with s in thread t under calling context c,
$\mathcal{M}$ is the set of multi-forked threads.

Interleaving Analysis

Computing $\mathcal{I}(t, c, s)$ is formalized as a forward data-flow problem $(V, \sqcap, F)$.

- V: the set of all thread interleaving facts.
- $\sqcap$: meet operator ($\cup$).
- F: $V \to V$ transfer functions associated with each node in an ICFG.

Interleaving Analysis Rule

$$\texttt{[I-DESCENDANT]}\quad \frac{t \xrightarrow{(c,fk_i)} t' \quad (t,c,fk_i) \rightarrow (t,c,\ell) \quad (c',\ell') = \mathit{Entry}(\mathcal{S}_{t'})}{\{t'\} \subseteq \mathcal{I}(t,c,\ell) \quad \{t\} \subseteq \mathcal{I}(t',c',\ell')}$$

$$\texttt{[I-SIBLING]}\quad \frac{t \bowtie t' \quad (c,\ell) = \mathit{Entry}(\mathcal{S}_t) \quad (c',\ell') = \mathit{Entry}(\mathcal{S}_{t'}) \quad t \not\succ t' \wedge t' \not\succ t}{\{t\} \subseteq \mathcal{I}(t',c',\ell') \quad \{t'\} \subseteq \mathcal{I}(t,c,\ell)}$$

$$\texttt{[I-JOIN]}\quad \frac{t \xleftarrow{(c,jn_i)} t'}{\mathcal{I}(t,c,jn_i) = \mathcal{I}(t,c,jn_i) \backslash \{t'\}}$$

$$\texttt{[I-CALL]}\quad \frac{(t,c,\ell) \xrightarrow{call_i} (t,c',\ell') \quad c' = c.\mathit{push}(i)}{\mathcal{I}(t,c,\ell) \subseteq \mathcal{I}(t,c',\ell')}$$

$$\texttt{[I-INTRA]}\quad \frac{(t,c,\ell) \rightarrow (t,c,\ell')}{\mathcal{I}(t,c,\ell) \subseteq \mathcal{I}(t,c,\ell')}$$

$$\texttt{[I-RET]}\quad \frac{(t,c,\ell) \xrightarrow{ret_i} (t,c',\ell') \quad i = c.\mathit{peek}() \quad c' = c.\mathit{pop}()}{\mathcal{I}(t,c,\ell) \subseteq \mathcal{I}(t,c',\ell')}$$

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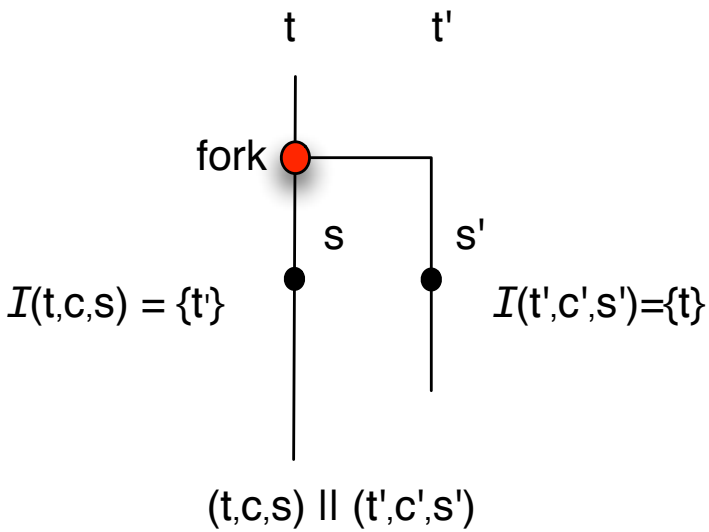

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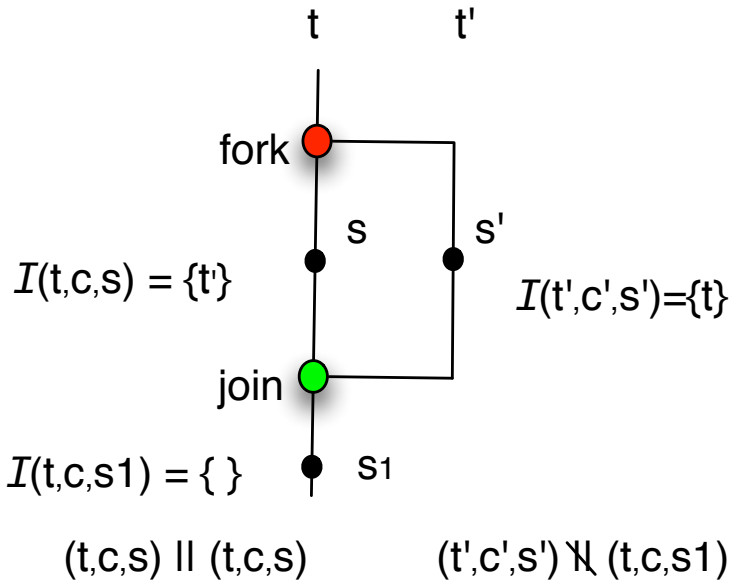

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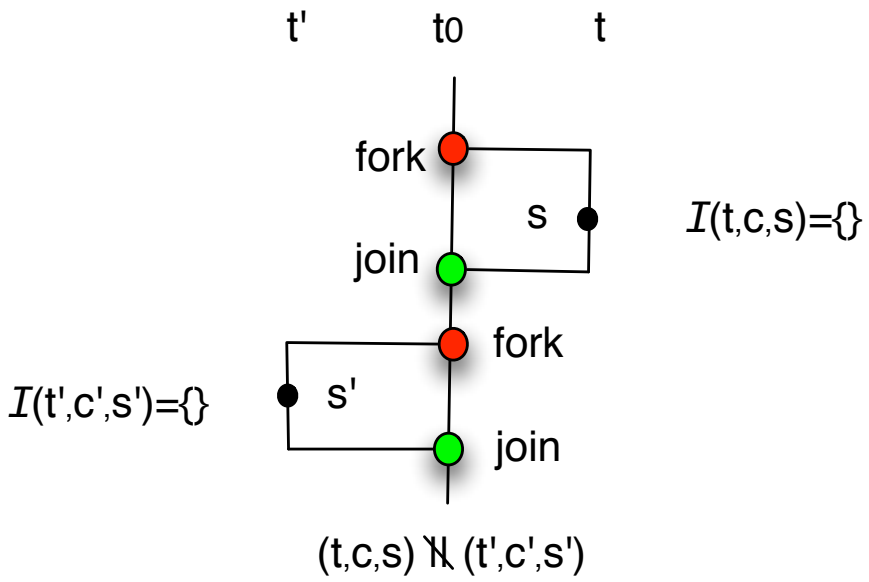

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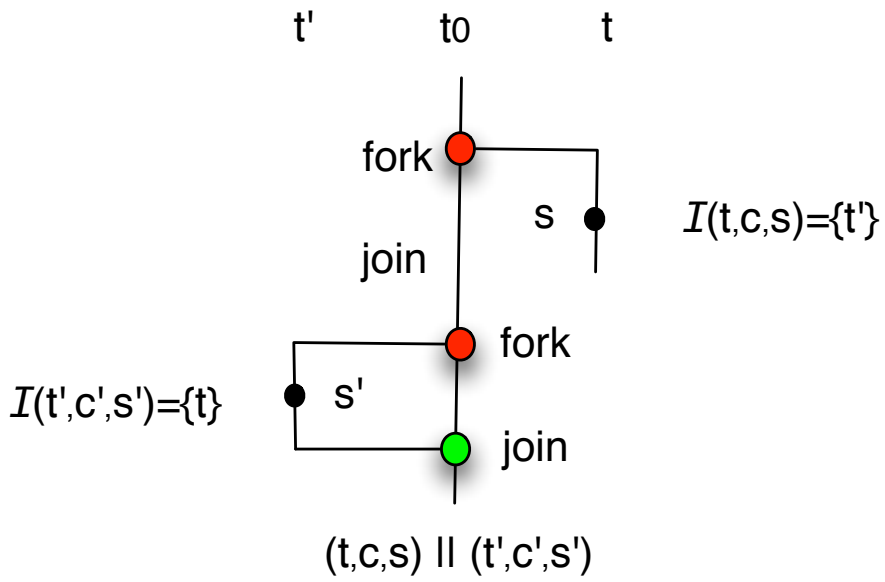

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Alias Analysis

Obtain aliasing pairs by refining MHP store-load and store-store pairs $[(t, c, s), (t', c', s')]$, where $Alias(*p, *q)$ is the set of objects pointed to by both p and q.

$$\frac{s : *p = \_ \qquad s' : \_ = *q \ \text{ or } \ *q = \_ \qquad (t, c, s) \parallel (t', c', s') \qquad o \in Alias(*p, *q)}{s \overset{o}{\hookrightarrow} s'}$$

```
   int x,y;
   int *p,*q,*r;
   p=&x;
   q=&x;
   r=&y;

   void main(){
    fork(t, foo);
s1:  *p=...;
s2:  *r=...;

   }

   void foo(){
s3: ...=*q;
   }
```

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Thread-Local Analysis

An object is not *thread-local*, i.e. *escaping*, if it escapes via

- arguments at a forksite
- global pointers

```
    void main(){
      int x,y;
      fork(t,foo,&x);
s1:   x=...;
      join(t);
s3:   y=...;
    }

    void foo(int* p){
s2:   ...=*p;
    }
```

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Lockset Analysis

Statements from different lock-unlock spans, are interference-free if these spans are protected by a common lock.
Our framework does this by performing a flow- and context-sensitive analysis for lock/unlock operations

```
    int x;
    mutex m;
    void main(){
      fork(t,foo);
s1:   x=...;
      lock(m);
s3:   x=...;
      unlock(m);
      join(t);
    }

    void foo(){
      lock(m);
s2:   ...=x;
      unlock(m);
    }
```

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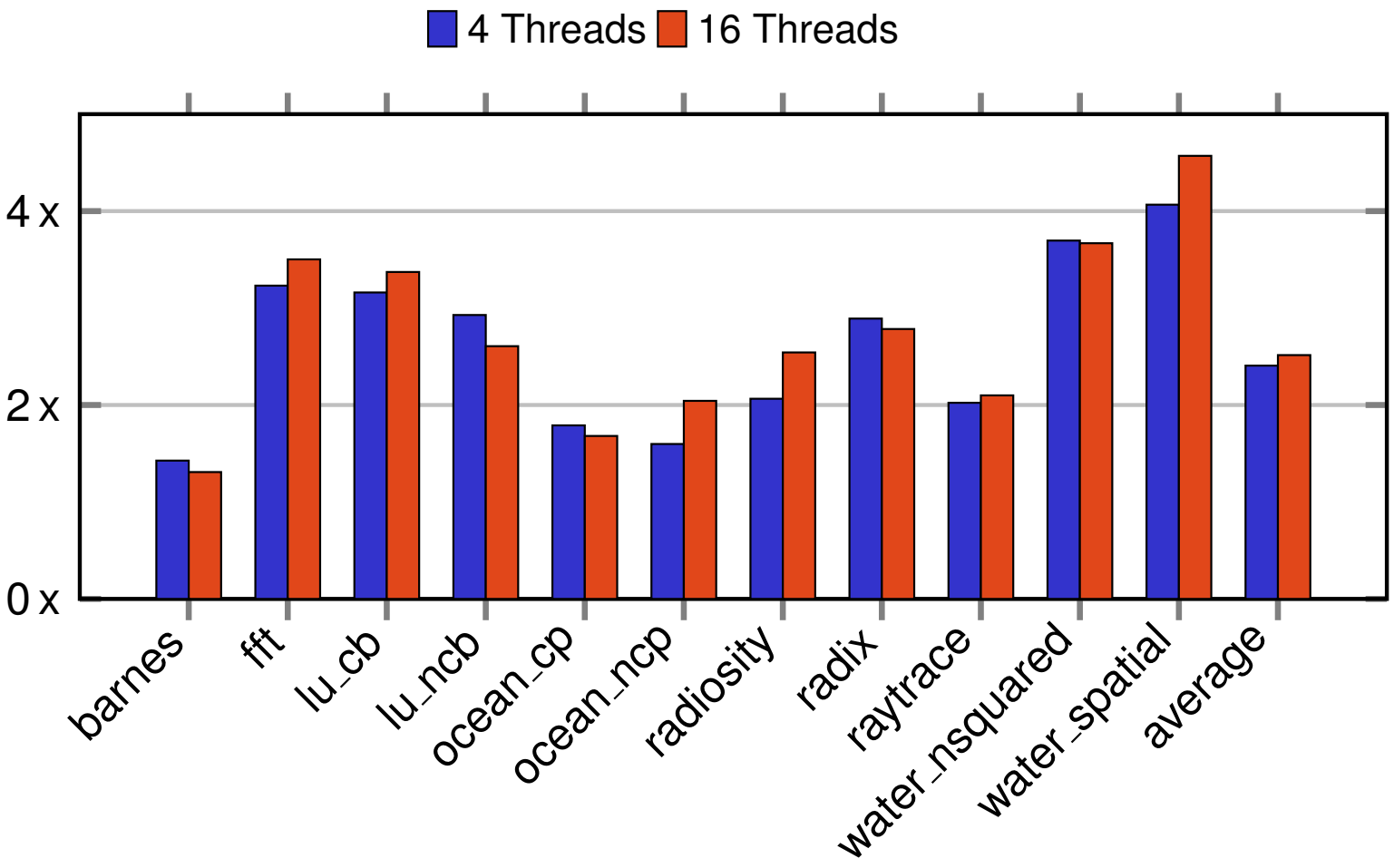
Evaluation

- Implementation:
  - On top of our previous open-source tool SVF (http://unsw-corg.github.io/SVF/)
  - Based on our previous papers CGO ’16 and ICPP ’15
- Benchmarks:
  - 11 SPLASH2 Pthread benchmarks
- Machine setup:
  - Ubuntu Linux 3.11.0-15-generic Intel Xeon Quad Core HT, 3.7GHZ, 64GB

Instrumentation Statistics (under Option -O0)

	Pthread API				TSan		Our Approach	
	Fork	Join	Lock	Unlock	Read	Write	Read	Write
barnes	1	1	12	12	2188	1222	982	601
fft	1	1	8	8	1048	387	576	261
lu_cb	1	1	6	6	1097	408	396	199
lu_ncb	1	1	6	6	840	303	392	182
ocean_cp	1	1	24	24	9531	2301	5722	1809
ocean_ncp	1	1	23	23	5465	1381	2909	1103
radiosity	3	3	38	50	5250	1917	3006	1500
radix	1	1	13	13	777	354	329	208
raytrace	1	1	13	16	6049	2368	2865	1057
water_nsquared	1	1	18	18	2188	703	1313	510
water_spatial	1	1	19	19	2437	833	1168	440

Speedups over Original TSan (under Option -O0)



Thanks!

Q & A