Implementation of a Type and Effect System for Deadlock Avoidance in C/Pthreads

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We are going to talk about...

- Concurrency – deadlocks – deadlock freedom
- Our apprach to deadlock avoidance
- Deadlock avoidance tool
- Performance evaluation

Concurrent programming

- Computational processes executed in parallel

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Implementation

- Processes:

  independent execution units with their own state and address space

- Threads:

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Interaction/Communication

- Shared Memory:
  - common address space, needs synchronization
  - e.g. Pthreads, Java
- Message Passing:
  - cooperating processes: send, receive messages
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- Hold and wait
- No preemtion
- Circular wait

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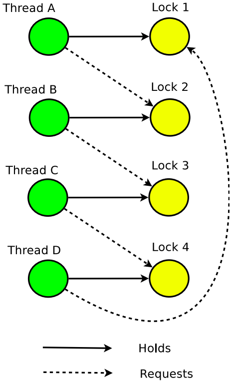

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Key idea:

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$$\underbrace{(\texttt{lock}\, x\, ;\ \ldots\ \texttt{lock}\, y\, ;\ \ldots)}_{x \leq y} \;||\; \underbrace{(\texttt{lock}\, y\, ;\ \ldots\ \texttt{lock}\, x\, ;\ \ldots)}_{y \leq x}$$

- no single global order $\Rightarrow$ reject program

Deadlock Avoidance: Boudol's Approach

Admits more programs by lifting the "ordering" restriction

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Admits more programs by lifting the “ordering” restriction

Key idea:

- statically: for each lock operation compute the “future lockset”
- dynamically: check that the “future lockset” is available before granting the lock

Future lockset: the set of locks that will be obtained before this lock is released

Boudol's Approach: Example

$$(\texttt{lock}\,x\,;\quad \ldots\ \texttt{lock}\,y\,;\ \ \ldots) \parallel (\texttt{lock}\,y\,;\quad \ldots\ \texttt{lock}\,x\,;\ \ \ldots)$$

Boudol's Approach: Example

$$(\texttt{lock}_{\{y\}}\, x\, ;\, \underbrace{\ldots\ \texttt{lock}_{\emptyset}\, y\, ;\ \ldots}_{\text{only } y \text{ is locked here}})\ \|\ (\texttt{lock}_{\{x\}}\, y\, ;\, \underbrace{\ldots\ \texttt{lock}_{\emptyset}\, x\, ;\ \ldots}_{\text{only } x \text{ is locked here}})$$

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- thread 1 tries to lock x, with future lockset $\{y\}$

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At runtime, the lock annotation is checked

- thread 1 tries to lock x, with future lockset $\{y\}$ — success!
- thread 2 tries to lock y, with future lockset $\{x\}$ — block!

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At runtime, the lock annotation is checked

- thread 1 tries to lock x, with future lockset $\{y\}$ success!
- thread 2 tries to lock y, with future lockset $\{x\}$ block!

Lock y is available, but lock x is held by thread 1

- granting y to thread 2 may lead to a deadlock !

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$$
\begin{array}{l}
\texttt{foo}\ (x,\ y,\ z)\ \{ \\
\quad \texttt{lock}_{\{y\}}\ x; \\
\quad \texttt{lock}_{\{z\}}\ y; \\
\quad \texttt{unlock}\ x; \\
\quad \texttt{lock}_{\emptyset}\ z; \\
\quad \texttt{unlock}\ z; \\
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\}
\end{array}
\qquad
\begin{array}{l}
\texttt{bar}\ (a,\ b)\ \{ \\
\quad \ldots \\
\quad \texttt{foo}\ (a,\ a,\ b) \\
\quad \ldots \\
\}
\end{array}
$$

Calling `foo` with x and y aliased.

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$\texttt{lock}_{\{a\}}\ a;$
$\texttt{lock}_{\{b\}}\ a;$
$\texttt{unlock}\ a;$
$\texttt{lock}_{\emptyset}\ b;$
$\texttt{unlock}\ b;$
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After substitution, the future locksets are wrong!

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$\texttt{lock}_{\{a\}}\ a;$ should be: $\{a, b\}$

$\texttt{lock}_{\{b\}}\ a;$ should be: $\emptyset$

$\texttt{unlock}\ a;$

$\texttt{lock}_{\emptyset}\ b;$

$\texttt{unlock}\ b;$

$\texttt{unlock}\ a$

After substitution, the future locksets are wrong!

Locking Patterns

Block Structured

```
bar (a, b) {
  lock a;
  lock b;
    ...
  unlock b;
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Stack Based Same Function

```
bar (a) {
  lock a;
  if (...) {
    lock b;
    unlock b;
    unlock a;
    return; }
   ...
  unlock a;
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```

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Stack Based Different Function

```
mylock (x) {
    lock x; }

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  mylock a;
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Unstructured Locking

```
bar (a, b) {
  lock a;
  lock b;
    ...
  unlock a;
  unlock b;
}
```

Do we really need support for unstructured locking?

Previous approaches:
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So, we gathered a codebase ($\sim$ 100 projects in C/Pthreads) and ran statistics on locking patterns.

Locking Pattern	Frequency
Block Structured	36.67%
Stack-Based (same function)	32.22%
Stack-Based (different function)	20.00%
Unstructured Locking	11.11%
Total	100.00%

Our Approach

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Novelties compared to Boudol's system:

- Support for unstructured locking
- Support for inter-procedural effects

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- track the order of `lock` and `unlock` operations
- annotate `lock` operations with a "continuation effect" (lock sequence of the code following that expression)

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\texttt{foo}\ (x,\ y,\ z)\ \{ \\
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```
foo (x, y, z) {
    lock[y+, x−, z+, z−, y−] x;
    lock[x−, z+, z−, y−] y;
    unlock x;
    lock[z−, y−] z;
    unlock z;
    unlock y
}
```

```
bar (a, b) {
    ...
    foo (a, a, b)
    ...
}
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$\texttt{lock}_{[a+,\, a-,\, b+,\, b-,\, a-]}\ a;$
$\texttt{lock}_{[a-,\, b+,\, b-,\, a-]}\ a;$
$\texttt{unlock}\ x;$
$\texttt{lock}_{[b-,\, a-]}\ b;$
$\texttt{unlock}\ b;$
$\texttt{unlock}\ a$

Future locksets are then correctly calculated
After substitution, continuation effects are still valid!

Lockset Calculation

Compute future lockset at runtime using $lock$ annotations

Input: $\underbrace{a+}_{\text{lock operation}} \quad \underbrace{a+,\ a-,\ b+,\ b-,\ a-,\ \ldots}_{\text{continuation effect}}$

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- but effects must not be intra-procedural !
- what happens if the matching unlock operation occurs after the function returns?

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$$\texttt{foo}\;(\,)\{\quad \texttt{lock}_{[y+,\,y-]}\; x;\quad \texttt{lock}_{[y-]}\; y;\quad \texttt{unlock}\; y \quad \}$$

$$\texttt{bar}\;(\,)\;\{\quad \texttt{foo}()_{[z+]};\quad \texttt{lock}_{[]}\; z \quad \}$$

$$\texttt{main}\;(\,)\;\{\quad \texttt{bar}()_{[z-,\,x-]};\quad \texttt{unlock}\; z;\; \texttt{unlock}\; x \quad \}$$

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$\qquad\qquad \texttt{lock}_{[]}\ z \quad \}$

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Stack

$z-,\quad x-$

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          lock[y-] y;
          unlock y   }

bar ( ) {  foo()[z+];
           lock[] z   }

main ( ) {  bar()[z-, x-];
            unlock z; unlock x   }
```

Stack

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Stack

$z-, \;\; x-$
$z+$

Lock/Continuation

$x+ \qquad y+, \;\; y-$

lockset = { }

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$x+$ $y+,$ $y-$

lockset = { y }

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$x+\quad y+,\ \ y-$

lockset = { $y,\ \ z$ }

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$\quad\texttt{unlock}\ y\ \ \}$

$\texttt{bar}\ (\,)\ \{\ \ \texttt{foo}()_{[z+]};$
$\quad\texttt{lock}_{[]}\ z\ \ \}$

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$\quad\texttt{unlock}\ z;\ \texttt{unlock}\ x\ \ \}$

Stack

$z-,\ \ x-$
$z+$

Lock/Continuation

$x+\quad y+,\ \ y-$

lockset = $\{\ y,\ \ z\ \}$

Inter-procedural Effects

- Function applications are also annotated with a "continuation effect"
- When a function is applied, the continuation effect is pushed on a runtime stack
- Lockset calculation may examine the stack

```
foo (){   lock[y+, y−] x;
          lock[y−] y;
          unlock y   }

bar () {   foo()[z+];
           lock[] z   }

main () {   bar()[z−, x−];
            unlock z; unlock x   }
```

Stack

$z-,\ x-$
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- Runtime lockset calculation for conditionals:

"future lockset"$((\gamma_1\ ?\ \gamma_2); \gamma) =$ "future lockset"$(\gamma_1; \gamma) \cup$ "future lockset"$(\gamma_2; \gamma)$

Loop Expressions

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$\boxed{\texttt{while}\ e\ \texttt{then}\ e_1}$

Consider:

```
lock x;
while (...) {
  lock y;
  unlock y;
  unlock x;
   ...
  lock x;
}
unlock x
```

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- Runtime lockset calculation: as in conditional expressions

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  A: Nope, it suffices that the future lockset is available momentarily before acquiring the lock.

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Target language: C/Pthreads

Analyzing C language: Not so easy . . .

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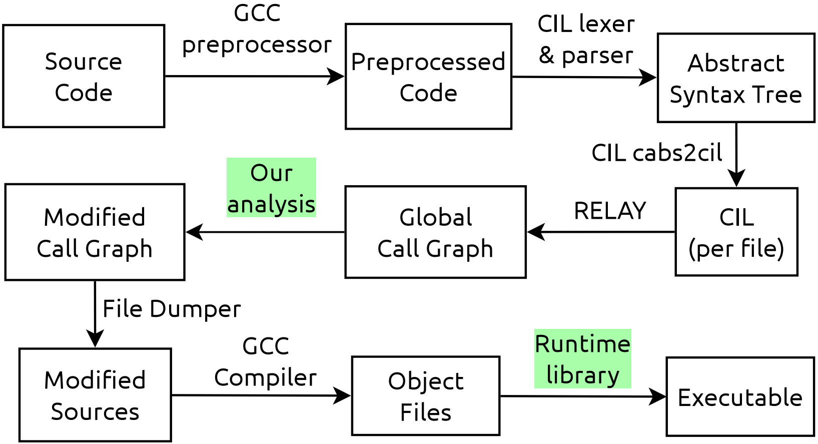
- CIL
  - Parse C, simplified intermediate language
  - Control flow graph
  - Dataflow framework
  - Function pointer analysis
- RELAY
  - Global Call Graph
  - Pointer analysis

Workflow


Source Code
GCC preprocessor
Preprocessed Code
CIL lexer & parser
Abstract Syntax Tree
CIL cabs2cil
CIL (per file)
RELAY
Global Call Graph
Our analysis
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- Symbolic Execution (module from RELAY):
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Challenge: create a linear effect from a complex CFG.

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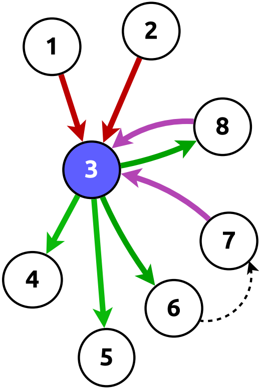

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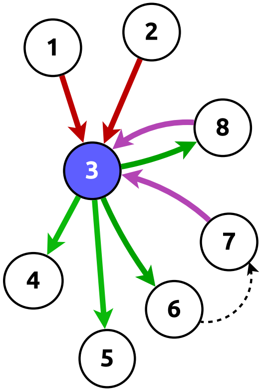

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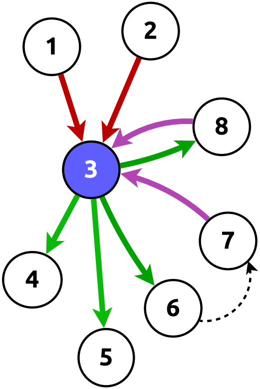

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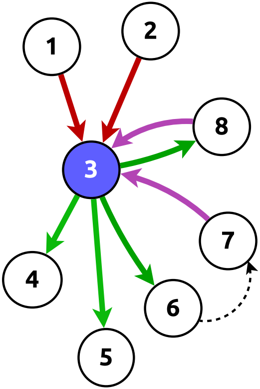

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  - Run the above alternately to a fixed point.

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Modified version

```
foo(struct bar *s, mylock_t *p)
{
  __cil_tmp5.locals = __cil_tmp4;

  __cil_tmp4[0] = (mylock *)(& s->a);
  __cil_tmp4[1] = (mylock_t *)(& s->b);
  __cil_tmp4[2] = (mylock_t *)p;
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Heap Allocation

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lock_t * foo() {
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  lock_t * a = foo(); //Loc B
  lock(a);

  lock_t * b = foo(); //Loc C
  lock(b);
}

main() {
  bar();    //Loc D

  bar();    //Loc E
}
```
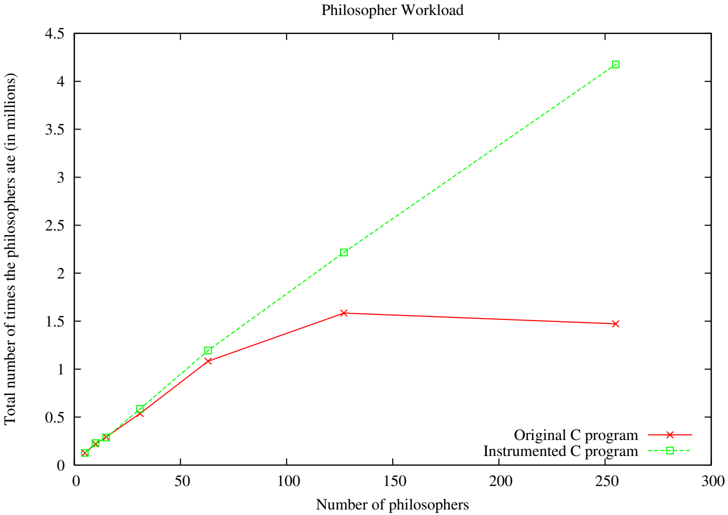
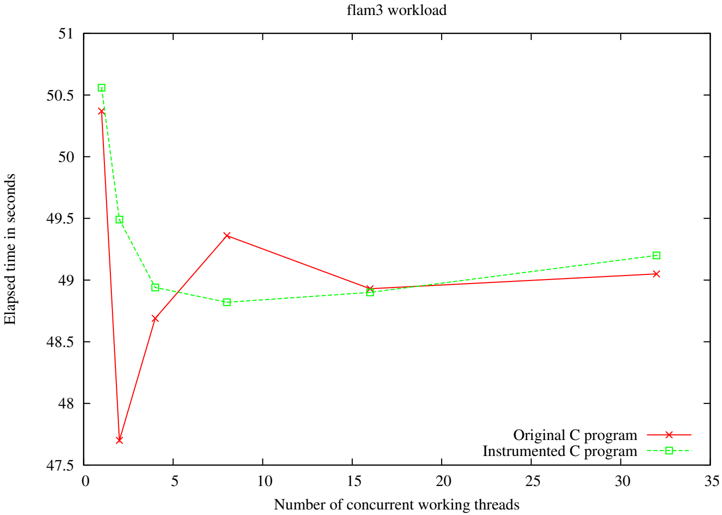

- Heap model: based on the context of allocating function
- Distinct abstract locations:
  $(Loc\ D, Loc\ B, Loc\ A)$
  $(Loc\ D, Loc\ C, Loc\ A)$
  $(Loc\ E, Loc\ B, Loc\ A)$
  $(Loc\ E, Loc\ C, Loc\ A)$
- Dynamic mapping (hashtable):
  abstract location $\leftrightarrow$
  runtime address

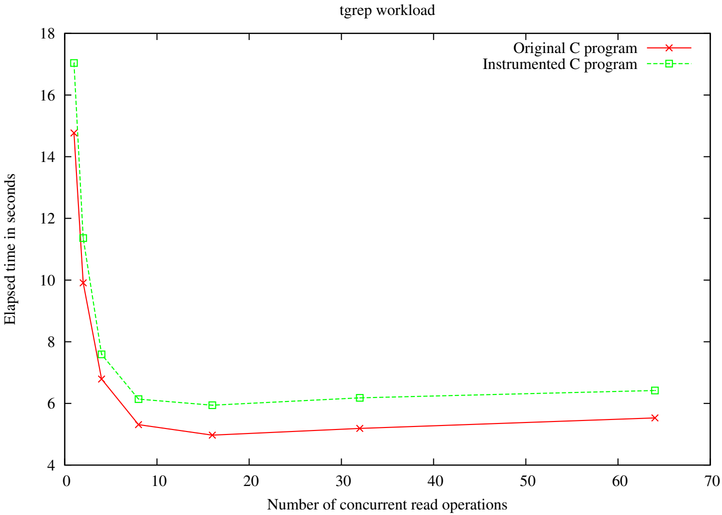
Evaluation: Dining Philosophers



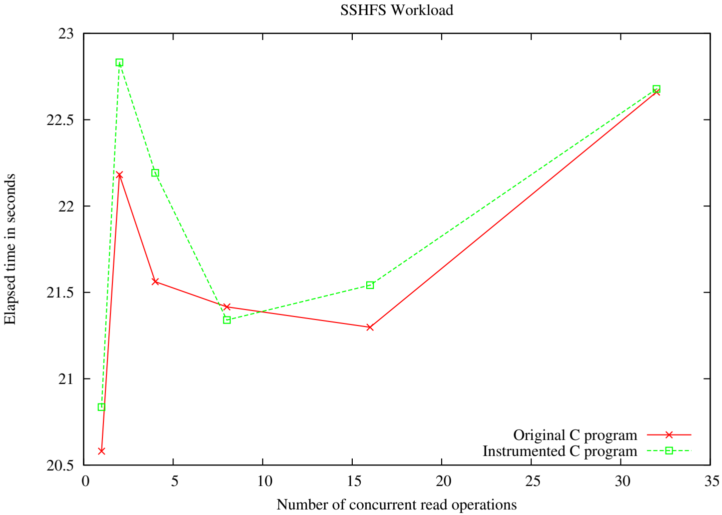
Evaluation: Cosmic Fractal Frames



Evaluation: Multi-threaded "grep"



Evaluation: File System over SSH



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- Non C code, assembly
- Pointer analysis: recursive structs, pointer arithmetic
- Heap allocation in loops, recursive functions

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- Pointer analysis: recursive structs, pointer arithmetic
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Future Work:

- Accept annotations for library code
- More precise pointer analysis, higher level of indirection
- Recursive functions (supported by type system)
- Static locksets, caching

Thank you!

Questions?