# Static Versioning of Global State for Race Condition Detection

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# Outline

# Example: Real-World Data Race

```
int control()
{
  ...
  if (sensor_valid &&
      sensor >= min_threshold &&
      sensor <= max_threshold)
  {
    control_car(sensor);
    ...
  }
}
```

# Example: Real-World Data Race

```
int sensor;

int control()
{
  ...
  if (sensor_valid &&
      sensor >= min_threshold &&
      sensor <= max_threshold)
  {
    control_car(sensor);
    ...
  }
}
```

```
interrupt void isr()
{
  ...
  sensor_valid =
    read_port(0x23, &sensor);
}
```

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int sensor;

int control()
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interrupt void isr()
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# Example: Real-World Data Race

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int sensor;

int control()
{
  ...
  if (sensor_valid &&
     sensor >= min_threshold &&
     sensor <= max_threshold)
  {
    control_car(sensor);
    ...
  }
}
```

consistent
data?

```
interrupt void isr()
{
  ...
  sensor_valid =
    read_port(0x23, &sensor);
}
```

# Data Races

## Definition (Data Race)

A data race occurs if two threads access a common storage location without ordering constraints, and one of the accesses modifies the storage contents.

Presence of data race means:

- possibly missing explicit synchronization
- for non-atomic accesses, possibility of illegal bit-patterns

Absence of data race means:

- some serialization of accesses exists
- no illegal bit-patterns are created

# Race detection

- data races can indicate programming errors
- confidence in absence of races through static analysis
- many analysis algorithms exist for data race detection
- some data races can be tolerated if the shared variable is accessed atomically
- however, some critical race conditions are not data races
- this work aims at detection of all potentially harmful race conditions

# Example: Static State Versioning

```
int f()
{
  lock(&m);
  int l1 = sens_1;
  int l2 = sens_2;
  unlock(&m);
  ...
  int l3 = sens_3;
  ...
  if (l1 < l2) ...;
  ...
  if (l2 < l3) ...;
}
```

- Shared Variables: `sens_1`, `sens_2`, `sens_3`

# Example: Static State Versioning

```
int f()
{
  lock(&m);
  int l1 = sens_1;
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  if (l1 < l2) ...;
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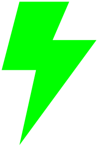
```



Data Race!
Problem?

- Shared Variables: `sens_1`, `sens_2`, `sens_3`
- Data Race because of read of `sens_3`
- no synchronization necessary if **`int`**s read atomically, Data Race uninteresting

# Example: Static State Versioning

```
int f()
{
  lock(&m);              version 1
  int l1 = sens_1;
  int l2 = sens_2;
  unlock(&m);
  ...
  int l3 = sens_3;       version 2
  ...
  if (l1 < l2) ...;
  ...
  if (l2 < l3) ...;
}
```

- Shared Variables: `sens_1`, `sens_2`, `sens_3`
- Data Race because of read of `sens_3`
- no synchronization necessary if **`int`**s read atomically, Data Race uninteresting
- Versioning of reads

# Example: Static State Versioning

```
int f()
{
  lock(&m);            version 1
  int l1 = sens_1;
  int l2 = sens_2;
  unlock(&m);
  ...
  int l3 = sens_3;     version 2
  ...
  if (l1 < l2) ...;
  ...
  if (l2 < l3) ...;
}
```

consistent?

- Shared Variables: `sens_1`, `sens_2`, `sens_3`
- Data Race because of read of `sens_3`
- no synchronization necessary if **`ints`** read atomically, Data Race uninteresting
- Versioning of reads
- Use of different versions indicates programming error

# Violation of Atomicity: uninteresting warnings

**Example (Conflict accesses on `g` in `thread2` and `thread3`, but inconsistent expression only in `thread3`)**

```
int g;

void *thread1(void *p)
{   while (1) g = read_sensor_value();   }

void *thread2(void *p)
{   while (1) act_1(5 * g + 17);   }

void *thread3(void *p)
{   while (1) act_2(g * g);   }
```

# Violation of Atomicity: nonatomic expressions

**Example (Free of data races, but the `mutex_lock`-calls around `g1+g2` have no effect)**

```
void *t1(void *p)         void *t2(void *p)
{ mutex_lock(&m);         { mutex_lock(&n);
  g1 = ...;                 g2 = ...;
  mutex_unlock(&m);         mutex_unlock(&n);
}                         }

int main()
{  create(t1); create(t2);
   mutex_lock(&m); mutex_lock(&n);
   res = g1 + g2;
   mutex_unlock(&n); mutex_unlock(&m);
}
```

# Stale Updates

## Example (Nonatomic increments)

```
pthread_mutex_lock(&m);
int local = global;
pthread_mutex_unlock(&m);

local += 17;

pthread_mutex_lock(&m);
global = local;
pthread_mutex_unlock(&m);
```

The LHS's version (`global` directly before the assignment) differs from the RHS's version (`local`).

# State Versioning Algorithm

1. translate source code into intermediate representation, use only atomic read and write operations
2. represent interfering data flow explicitly by insertion of $\psi$-nodes for
   - conflict reads
   - uses of shared variables in protected regions
3. assign versions to reads in every function independent of calling context, in bottom-up traversal of the call graph
4. adjust versions depending on context in top-down traversal of the call graph
5. produce warning list for potentially inconsistent expressions

# Lockset analysis

- determine the set of all possible (mutex-) locks: $L_{\text{full}}$
- associate each site $s$ in the program with the set of mutex-locks $l_{\text{act}}(s) \subseteq L_{\text{full}}$ that are active
  - use monotonic analysis framework over $(2^{L_{\text{full}}}, \subseteq)$
  - initial value $\varnothing$ at function entry, $L_{\text{full}}$ for all other basic blocks
  - at confluence points use intersection as meet operator
  - distinguish different caller locksets at call sites

# Interference flow for conflict reads

- determine shared objects
- use locksets to determine conflict reads
- place $\psi$-node in front of every conflict read

## Example (Insertion of $\psi$-nodes for conflict reads)

$$
\begin{array}{lcl}
\texttt{s = 0;} & & s_{m1} = 0; \\
 & \Rightarrow & s_{m2} = \psi(s_{m1}, \boxed{s_{t1}}, \ldots, \boxed{s_{tn}}); \\
 & & s_{m3} = \psi(s_{m1}, \boxed{s_{t1}}, \ldots, \boxed{s_{tn}}); \\
\texttt{s = s + s;} & & s_{m4} = s_{m2} + s_{m3};
\end{array}
$$

So far ...

- Synchronization is ignored

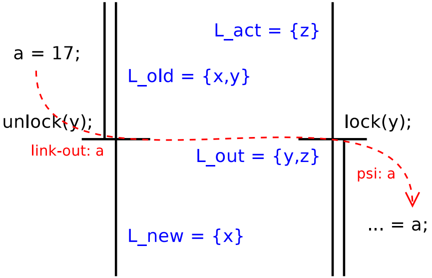
# Interference flow for protected regions

- identify protected regions
- regions protected by a common lock are mutually exclusive
- data flow can only occur from end to beginning of mutually exclusive regions

$\Rightarrow$ Add Link-out and $\psi$ nodes

- interference flow for multiple objects is stored into a single $\psi$-node

$$
\begin{aligned}
A = \{(l_{\text{old}}, l_{\text{new}}) \in 2^{L_{\text{full}}} \times 2^{L_{\text{full}}} :\ & l_{\text{old}} \cap \mathrm{L}_{\text{out}}(bb) \neq \varnothing \\
\wedge \quad & l_{\text{new}} \cap \mathrm{L}_{\text{out}}(bb) = \varnothing \\
\wedge \quad & l_{\text{old}} \cap \mathrm{L}_{\text{act}}(bb) = \varnothing \\
\wedge \quad & l_{\text{new}} \cap \mathrm{L}_{\text{act}}(bb) = \varnothing \}
\end{aligned}
$$



# State Version Analysis

- every execution of a $\psi$-node represents a unique observation of global state
- a unique version is assigned to every observation
- versions are propagated along the data flow paths
- every expression is assigned a version based on the versions that flow into the expression
- if values of more than one version flow into an expression, it is considered potentially inconsistent

# Bottom-up Pass

- state space: set of mappings **Var** $\rightarrow \{\perp, \top, \psi_1, \ldots, \psi_n\}$
- optimistic assumption: caller does not propagate versions into callee function
- analyze functions separately in reverse topological order
- multiple iterations for loops and recursion until fixed point is reached
- transfer function propagates versions across copy-statements
- if a node $a = \psi_i$ is encountered, all variables of version $i$ are set to $\perp$ and $a$'s version is set to $i$
- at call sites, use result of callee's analysis, treat every version $j$ of the callee like an encounter of a node $\psi_j$

# Top-down Pass

- use the active state at a call site to propagate versions into the callee function
- propagate versions along the def-use data flow links inside the callee to update versions
- contexts at different call sites can be distinguished or can be joined before the propagation

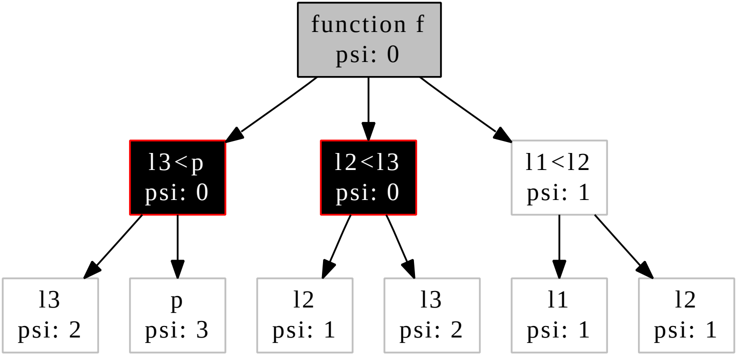
| | l1 | l2 | l3 | p | xpr |
|---|---|---|---|---|---|
| `void f(int p)` | $\top$ | $\top$ | $\top$ | $\top$ | |
| `{` | | | | | |
| `lock(&m);` | | | | | |
| `sens_1,2 =` $\psi_1$`(sens_1,2,...);` | | | | | |
| `int l1 = sens_1;` | 1 | $\top$ | $\top$ | $\top$ | |
| `int l2 = sens_2;` | 1 | 1 | $\top$ | $\top$ | |
| `unlock(&m);` | | | | | |
| `...` | | | | | |
| `sens_3 =` $\psi_2$`(sens_3,...);` | | | | | |
| `int l3 = sens_3;` | 1 | 1 | 2 | $\top$ | |
| `if (l1 < l2) ...;` | 1 | 1 | 2 | $\top$ | |
| `if (l2 < l3) ...;` | 1 | 1 | 2 | $\top$ | |
| `if (l3 < p) ...;` | 1 | 1 | 2 | $\top$ | |
| `}` | | | | | |

| | `l1` | `l2` | `l3` | `p` | xpr |
|---|---|---|---|---|---|
| **`void`** `f(`**`int`** `p)` | $\top$ | $\top$ | $\top$ | $\top$ | |
| `{` | | | | | |
| `lock(&m);` | | | | | |
| `sens_1,2 =` $\psi_1$`(sens_1,2,...);` | | | | | |
| **`int`** `l1 = sens_1;` | 1 | $\top$ | $\top$ | $\top$ | |
| **`int`** `l2 = sens_2;` | 1 | 1 | $\top$ | $\top$ | |
| `unlock(&m);` | | | | | |
| `...` | | | | | |
| `sens_3 =` $\psi_2$`(sens_3,...);` | | | | | |
| **`int`** `l3 = sens_3;` | 1 | 1 | 2 | $\top$ | |
| **`if`** `(l1 < l2) ...;` | 1 | 1 | 2 | $\top$ | 1 |
| **`if`** `(l2 < l3) ...;` | 1 | 1 | 2 | $\top$ | $\perp$ |
| **`if`** `(l3 < p) ...;` | 1 | 1 | 2 | $\top$ | 2 |
| `}` | | | | | |

| f($\psi_3$(...)); | l1 | l2 | l3 | p | xpr |
|---|---|---|---|---|---|
| **void** f(**int** p) | $\top$ | $\top$ | $\top$ | 3 | |
| { | | | | | |
| lock(&m); | | | | | |
| sens_1,2 = $\psi_1$(sens_1,2,...); | | | | | |
| **int** l1 = sens_1; | 1 | $\top$ | $\top$ | $\top$ | |
| **int** l2 = sens_2; | 1 | 1 | $\top$ | $\top$ | |
| unlock(&m); | | | | | |
| ... | | | | | |
| sens_3 = $\psi_2$(sens_3,...); | | | | | |
| **int** l3 = sens_3; | 1 | 1 | 2 | $\top$ | |
| **if** (l1 < l2) ...; | 1 | 1 | 2 | $\top$ | 1 |
| **if** (l2 < l3) ...; | 1 | 1 | 2 | $\top$ | $\perp$ |
| **if** (l3 < p) ...; | 1 | 1 | 2 | 3 | $\perp$ |
| } | | | | | |

# State Versioning Output

- warnings on possibly inconsistent expressions
- displayed in their syntactical context
- warnings on same combination of versions are output only once



# Evaluation

- implementation of the analysis in the Bauhaus system
- able to handle larger programs
  - clamd: 66 KSLoC
  - full context sensitivity needs 15 min
  - 6,667 warnings
- number of warnings
  - precision in data flow relation important
  - flow-insensitive points-to information
  - recognition of reference parameters not yet implemented
- future work
  - increase precision in data flow representation
  - determine cut-off strategy for data flow chains

# Conclusion

- new analysis algorithm to detect inconsistent uses
- can find error patterns that data race detectors cannot
- can deal with atomic accesses
- generates higher quality warnings, easier to validate
- future work to deal with precision