A Hardware Approach for Detecting, Tolerating and Exposing High Level Atomicity Violations.

Lois Orosa
João Lourenço

Euro-TM Short Term Scientific Mission
Departamento de informática
Faculdade de Ciências e Tecnologia
Universidade Nova de Lisboa

DMTM - January 22, 2014
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   • Detecting HLAVs
   • Exposing HLAVs
   • Tolerating HLAVs

3 Conclusions
**Introduction - Parallel Programming**

- **Multicore processors** are mainstream (Intel, AMD, IBM, etc.)
- **Shared memory** model (more intuitive than message passing)
- **Difficult** to program and debug
- Synchronization mechanisms can lead to **concurrent bugs**
Introduction - Concurrent Bugs

- Concurrent bugs are **difficult to detect** and reproduce
- It takes long time to debug them
- Several types:
  - Dealocks, Livelocks ...
  - Data Races
  - Order violations
  - Asymmetric (or low level) data races
  - High Level Atomicity Violations
- Other Tools (Deterministic replay, tools for code analisys, etc.)
- Hardware and Software approaches
Introduction - High Level Atomicity Violations (HLAV)

- All shared variables are protected by synchronization mechanisms (no data races).
- If one thread accesses data together in the atomic section and another thread accesses the same data separately in different atomic sections, a HLAV is reported.

```java
1 atomic void getA() {
2     return pair.a;
3 }
4 atomic void getB() {
5     return pair.b;
6 }
7 atomic void setPair (int a, int b) {
8     pair.a=a;
9     pair.b=b;
10 }
11 boolean areEqual() {
12     int a = getA();
13     int b = getB();
14     return a==b;
15 }
```
**Introduction - High Level Atomicity Violations (II)**

- **View**: addresses of memory locations accessed in an atomic region
- **Maximal view**: is not a subset of any views of that thread/core

### real HLAV

<table>
<thead>
<tr>
<th>new view</th>
<th>view1</th>
<th>view2</th>
<th>view3</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AB</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>core1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>core2</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### potential HLAV

<table>
<thead>
<tr>
<th>new view</th>
<th>view1</th>
<th>view2</th>
<th>view3</th>
</tr>
</thead>
<tbody>
<tr>
<td>AB</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>core1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>core2</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### HLAV: definition

There is an HLAV if the intersections of two views of one thread with the maximal view of another thread do not form an inclusion chain.
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Idea - Module of Bloom filters

- Windows of \( N \) views per core
- The new view replaces the older view in the window
- Maximal window to maintain maximal views from all cores
Idea - Description

In each core

- **Collection** of the addresses accessed in the atomic sections.
- Additional **Bloom filter** per core.
- At unlocks, the core **sends** the content of the Bloom filter to the module.

Module

- **Receives** the views of all cores.
- Core windows keep the last views of the cores
- Maximal window keeps the maximal views of all cores
  - Also maintains **additional information** from cores that can have a HLAV with this maximal view
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Idea - Detecting HLAVs (I)

New View

1. If a view is maximal, is inserted in the maximal window
2. If the intersection of the new view with a MV is subset of that MV, the new view is set as possible causative of a HLAV
3. If (2) and if there is another view in the same window that the new view that also matches (2), and this 2 views do not form a chain, HLAV is detected
Idea - Detecting HLAVs (II)

Example

```
core1
3 2 1
ABEF
Maximal Window
core2
EF CD AB
Maximal Window
```
Idea - Detecting HLAVs (II)

Example

```
core1
3 2 1
ABEF
Maximal Window CD
AB
```
Idea - Detecting HLAVs (II)

Example

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Idea - Detecting HLAVs (II)

Example

```
+-----+-----+-----+
| 3   | 2   | 1   |
+-----+-----+-----+
| core1 |     |     |
|       |     |     |
| core2 |     |     |
|       |     |     |
| Maximal Window |     |     |
| EF   | CD  | AB  |
| (core2) |     |     |
```

Maximal Window

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Idea - Detecting HLAVs (II)

Example

```
core1

3 2 1

ABEF

Maximal Window

AB
(core2)

core2

(1)

EF
CD
AB

(core2)
```
Idea - Detecting HLAVs (II)

Example

```
3 2 1
ABEF
Maximal Window
AB
(core2)
A
(1)
B

core1

core2

Maximal Window

EF CD AB
```
Idea - Detecting HLAVs (II)

Example

```
<table>
<thead>
<tr>
<th></th>
<th>3</th>
<th>2</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>core1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>core2</td>
<td>B</td>
<td>A</td>
<td></td>
</tr>
<tr>
<td>Maximal Window</td>
<td>EF</td>
<td>CD</td>
<td>AB</td>
</tr>
<tr>
<td>(core2)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
```

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Idea - Detecting HLAVs (II)

Example

```
<table>
<thead>
<tr>
<th></th>
<th>3</th>
<th>2</th>
<th>1</th>
</tr>
</thead>
<tbody>
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<tr>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximal Window</td>
<td>EF</td>
<td>CD</td>
<td>AB</td>
</tr>
</tbody>
</table>
```

HLAV
Contents

1 Introduction

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   • Detecting HLAVs
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   • Tolerating HLAVs

3 Conclusions
Idea - Exposing HLAVs (I)

- Tries to become the potential HLAVs into real HLAVs
- Forces the interleaving by stalling cores
- Timeout to avoid deadlocks
- Minimal hardware additions to support this feature
- Practical in the debugging process
Idea - Exposing HLAVs (II)

Example

```
core1
  5  4  3  2  1
core2
Maximal Window
  AB
```
### Idea - Exposing HLAVs (II)

#### Example

<p>| | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

#### core1

<p>| | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### core2

<p>| | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
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<th></th>
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</thead>
<tbody>
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<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>AB</td>
</tr>
</tbody>
</table>

#### Maximal Window

<p>| | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>CD</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>AB</td>
<td>AB</td>
</tr>
</tbody>
</table>

---

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Idea - Exposing HLAVs (II)

Example

```
core1
5 4 3 2 1
(core2)
core2
```

Maximal
Window

```
      5  4  3  2  1
core1

core2
          AB

Maximal
Window

CD
      AB
(core2)
```
### Idea - Exposing HLAVs (II)

#### Example

<table>
<thead>
<tr>
<th></th>
<th>5</th>
<th>4</th>
<th>3</th>
<th>2</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>core1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>core2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximal Window</td>
<td></td>
<td></td>
<td></td>
<td>CD</td>
<td>AB</td>
</tr>
</tbody>
</table>

**Maximal Window:** (core2)

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A Hardware Approach for Detecting, Tolerating and Exposing High Level Atomicity Violations

Idea - Exposing HLAVs (II)

Example

```
<table>
<thead>
<tr>
<th>5</th>
<th>4</th>
<th>3</th>
<th>2</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>B</td>
<td>A</td>
</tr>
<tr>
<td>core1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>core2</td>
<td></td>
<td></td>
<td>AB</td>
<td></td>
</tr>
<tr>
<td>Maximal Window</td>
<td></td>
<td></td>
<td>CD</td>
<td>AB</td>
</tr>
</tbody>
</table>
```

(core2)
Idea - Exposing HLAVs (II)

Example

<table>
<thead>
<tr>
<th></th>
<th>5</th>
<th>4</th>
<th>3</th>
<th>2</th>
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</tr>
</thead>
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<tr>
<td>core1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>core2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximal Window</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Potential HLAV

AB

(core2)
Idea - Exposing HLAVs (II)

Example

```
core1

5  4  3  2  1
.core2

B 1
A 1

Maximal Window

1 1
AB

(core2)

AB

CD

Exp
```
Idea - Exposing HLAVs (II)

Example

<table>
<thead>
<tr>
<th></th>
<th>5</th>
<th>4</th>
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<tr>
<td>core1</td>
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<td>B</td>
<td></td>
</tr>
<tr>
<td>core2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>AB</td>
</tr>
<tr>
<td>Maximal Window</td>
<td></td>
<td></td>
<td>CD</td>
<td></td>
<td>(core2) AB</td>
</tr>
</tbody>
</table>

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Idea - Exposing HLAVs (II)

Example

- Stall core1

```plaintext
core1

core2

Maximal Window

5 4 3 2 1

A 1
B 1
A
B
AB
CD
AB
Exp
```

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Example - Exposing HLAVs (II)

A Hardware Approach for Detecting, Tolerating and Exposing High Level Atomicity Violations

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Idea - Exposing HLAVs (II)

Example

<table>
<thead>
<tr>
<th>Core 1</th>
<th>Core 2</th>
<th>Maximal Window</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>B</td>
<td>CD</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>AB</td>
</tr>
</tbody>
</table>

(stall core 1)

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### Idea - Exposing HLAVs (II)

#### Example

<table>
<thead>
<tr>
<th></th>
<th>5</th>
<th>4</th>
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<tr>
<td>core1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>core2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximal Window</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **core1**
  - A
  - Exp

- **core2**
  - B
  - AB

- **Maximal Window**
  - CD
  - AB
  - (core2)
Idea - Exposing HLAVs (II)

Example

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Idea - Exposing HLAVs (II)

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   - Exposing HLAVs
   - Tolerating HLAVs

3 Conclusions
Idea - Tolerating HLAVs (I)

General Idea
- Useful in production runs
- Tries to avoid real HLAVs
- Uses information based on previous potential HLAV
- Uses transactions to protect regions that are suspect to be buggy

Additions
- Lock addresses are tracked, and used by the module
- Cores have a list of suspicious locks (to start Tx)
- The views in the module could be now in speculative state
Idea - Tolerating HLAVs (II)

Example
Idea - Tolerating HLAVs (II)

Example

A Hardware Approach for Detecting, Tolerating and Exposing High Level Atomicity Violations
Idea - Tolerating HLAVs (II)

Example

```
  5 4 3 2 1
core1
core2
Maximal
Window

AB
(CORE2)

#fff1

mutex
bloom filter

core1

mutex
bloom filter

core2
```
Idea - Tolerating HLAVs (II)

Example

A Hardware Approach for Detecting, Tolerating and Exposing High Level Atomicity Violations
Example

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Idea - Tolerating HLAVs (II)

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Example

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Idea - Tolerating HLAVs (II)

Example

```plaintext
A Hardware Approach for Detecting, Tolerating and Exposing High Level Atomicity Violations
```
A Hardware Approach for Detecting, Tolerating and Exposing High Level Atomicity Violations

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Idea - Tolerating HLAVs (II)

Example

![Diagram showing a three-core system with a maximal window and mutexes for detecting atomicity violations.]

- Core 1
- Core 2
- Maximal Window

- Core 1
- Core 2

- Mutex
- Bloom filter

- Example of detecting atomicity violations with a maximal window.
Idea - Tolerating HLAVs (II)

Example

<table>
<thead>
<tr>
<th></th>
<th>5</th>
<th>4</th>
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<th>2</th>
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<tbody>
<tr>
<td>core1</td>
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<td></td>
<td>B</td>
<td>A</td>
</tr>
<tr>
<td>core2</td>
<td></td>
<td></td>
<td></td>
<td>CD</td>
<td>AB</td>
</tr>
<tr>
<td>Maximal Window</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Tol
Idea - Tolerating HLAVs (II)

Example

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Example

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Example

A Hardware Approach for Detecting, Tolerating and Exposing High Level Atomicity Violations

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idea - tolerating hlav's (ii)

example

maximal window

mutex

bloom filter

# f1

# f2

# f3
tol

core1

core2

mutex

bloom filter

mutex

bloom filter

# f1

(core2)

A

# f2

B

# f3
tol

# f3

# f2

A

# f1

AB

Tx

aborts

core1

core2

5 4 3 2 1

AB

CD

AB

A

B

A

f1

f2

f3

f1

f2

f3
Idea - Tolerating HLAVs (II)

Example

<table>
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<td>A</td>
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<tr>
<td>core2</td>
<td></td>
<td></td>
<td></td>
<td>AB</td>
<td></td>
</tr>
<tr>
<td>Maximal Window</td>
<td></td>
<td></td>
<td></td>
<td>CD</td>
<td>AB</td>
</tr>
</tbody>
</table>

Tx aborts

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Idea - Tolerating HLAVs (II)

Example

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Idea - Tolerating HLAVs (II)

Example

A Hardware Approach for Detecting, Tolerating and Exposing High Level Atomicity Violations
Idea - Tolerating HLAVs (II)

Example

```
+----------+----------+----------+----------+----------+
| core1    | core2    | Maximal  | core1    | core2    |
|          |          | Window   |          |          |
| 5        | 4        | 3        | 2        | 1        |
|          |          |          |          |          |
| B        | AB       | CD       | A        | AB       |
| #fff3    | #fff1    |          | #fff2    | #fff1    |
|          |          |          |          |          |
| AB       |          |          |          |          |
| #fff2    |          |          |          | #fff3    |
|          |          |          |          |          |
| Tol      |          |          |          |          |
|          |          |          |          |          |
+----------+----------+----------+----------+----------+
```

Maximal Window:
- Core 1: B, A
- Core 2: AB, AB
- Maximal Window: CD, AB

Mutex blooming filter:
- Core 1: #fff2, #fff3
- Core 2: #fff2, #fff3

Transaction start (beginTx): A

Tolerating HLAVs (II)
Idea - Tolerating HLAVs (II)

Example

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Idea - Tolerating HLAVs (II)

Example

```
core1
core2
Maximal Window

5 4 3 2 1
AB
Maximal Window CD
5 4

core1
core2
mutex
bloom filter
mutex
bloom filter

# f1
AB
(core2)
A

# f2
B

# f3
Tol

# f3
# f2
# f1
AB

# f2
A
```
Idea - Tolerating HLAVs (II)

Example

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Example
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   - Tolerating HLAVs

3. Conclusions
Conclusions

- First **hardware approach** addressing the detection of **HLAVs**
- The module **Exposes** bugs
- The module **Tolerates** bugs in production runs
- Very **low performance overhead**
Thank you very much!

Questions?