Temporal Constraints for Concurrent Object Synchronisation

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What does Inheritance do, after all?

class Buffer {
    void put(Object v) { ....; }
    void get() { ....; }
    ....
}

class Lock {
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    void unlock() { ....; }
}
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Influence Buffer inheriting behaviour from Lock.

class LockableBuffer extends Buffer, Lock{
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Do you expect a Buffer which is locked/unlocked via Lock?
Objects and Concurrency

**Objects**: A fundamental, state-of-the-art concept for engineering complex software systems. (Design Patterns, Refactoring, …)

**Concurrency**: A fundamental technology to meet today’s demands on software functionalities. (Internet, Mobile and Embedded Devices, Software Agents, …)

Alas, a difficult marriage

Synchronisation of concurrent activities and inheritance do not mix:

Inheritance Anomaly (Yonezawa [1987])

So bad to justify banning inheritance from OO languages! (America [1991])

The plan

Explain the phenomenon via examples;

Illustrate the driving lines of the main existing approaches;

Design and implementation of the programming language Jeeg.
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- Design and implementation of the programming language Jeeg.
The problem: $x := 0; ( x := x + 1 \| x := x + 2 )$. Then, $x \in \{1, 2, 3\}$.
Concurrency and Interference

The problem: \( x := 0; ( x := x + 1 \parallel x := x + 2 ) \). Then, \( x \in \{1, 2, 3\} \).

The solutions:

- **Operational Mechanisms**: Semaphores and Locks, …
- **Linguistic Constructs**: Critical Regions and Monitors, …
- **Alternative Models**: Message Passing, Resource-Based, …

Their relevance: In the end the problem is in the concurrency model.
public class Buffer {
    protected Object[] buf;
    protected int MAX, current = 0;

    Buffer(int max) {
        MAX = max;
        buf = new Object[MAX];
    }

    public synchronized Object get() throws Exception {
        while (current <= 0) wait();
        Object ret = buf[--current];
        notifyAll();
        return ret;
    }

    public synchronized void put(Object v) throws Exception {
        while (current >= MAX) wait();
        buf[current++] = v;
        notifyAll();
    }
}
In **sequential programming**, clients can be asked to behave well. E.g., don’t **get** unless you have **put**. *(Synchronisation code and Business code.)*
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In **concurrency**, the resource must contain synchronisation code. This results essentially in methods **not being available** at certain moments in time.

Concurrent object oriented programs in common programming languages consist of business code **inextricably interwoven** with synchronisation code.
Inheritance Anomaly: Adding a new method morally unrelated, forces the redefinition of all other methods of a class.
**The Inheritance Anomaly**

**Inheritance Anomaly:** Adding a new method *morally* unrelated, forces the redefinition of all other methods of a class.

```java
class Buffer {
    ...
    void put(Object el) {
        if ("buffer not full") ...
    }
    Object get() {
        if ("buffer not empty") ...
    }
}
```
The Inheritance Anomaly

Inheritance Anomaly: Adding a new method morally unrelated, forces the redefinition of all other methods of a class.

class Buffer {
  ...
  void put(Object el) {
    if ("buffer not full") ...
  }
  Object get() {
    if ("buffer not empty") ...
  }
}

Add a method freeze.

Chances are that the synchronisation code in Buffer must be totally rewritten for that.

All approaches to the anomaly so far consist of disentangling business and synchronisation code. None is very successful.
Partitioning of States

**State Partition**: Introduce an explicit partition of the object’s state, and explicit enabling conditions for methods.

**Example**: In the case of *Buffer*, choose *empty*, *partial*, *full* and the declarations:

- **put**: requires not full
- **get**: requires not empty
Partitioning of States

**State Partition:** Introduce an explicit partition of the object’s state, and explicit enabling conditions for methods.

**Example.** In the case of Buffer, choose empty, partial, full and the declarations:

```java
put: requires not full
get: requires not empty
```

Then

```java
Object get() {
    ... 
    if ("buffer is now empty") become empty;
    else become partial;
    return res;
}
```
Partition of States

This solves the problem only very partially.
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Consider adding \texttt{get2} which retrieves \texttt{two} elements at once. Then, the partition \texttt{empty} and \texttt{full} is not enough anymore.

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Consider adding `get2` which retrieves two elements at once. Then, the partition empty and full is not enough anymore.

Need to distinguish those states where there is exactly one element: `single`.

Correspondingly, refine it to be:

`get2: requires not empty or single`

```java
Object get() {
    ... 
    if ("buffer is now empty") become empty;
    else if ("buffer is singleton") become single;
    else become partial;
    return res;
}
```
History-Sensitiveness of Acceptable States

When methods’ enabling depends on the history of objects, we have a form of the anomaly so-called history-sensitive.

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For instance, a method withdraw available only after a method authenticate has been completed.

To exemplify, we want to add to Buffer a method gget enabled only if the last method invoked of Buffer was other than get.
public class HistoryBuffer extends Buffer {
    boolean afterGet = false;
    public HistoryBuffer(int max) super(max);
    public synchronized Object get() throws Exception {
        while (current <= 0 || afterGet) wait();
        Object ret = buf[--current]; afterGet = false;
        notifyAll();
        return ret;
    }
    public synchronized Object get() throws Exception {
        while (current <= 0) wait();
        Object ret = buf[--current]; afterGet = true;
        notifyAll();
        return ret;
    }
    public synchronized void put(Object v) throws Exception {
        while (current>=MAX) wait();
        buf[current++] = v; afterGet = false;
        notifyAll();
    }
}
public class HistoryBuffer extends Buffer {
    boolean afterGet = false;
    public HistoryBuffer(int max) { super(max); }

    public synchronized Object get() throws Exception {
        while (current <= 0 || afterGet) wait();
        afterGet = false;
        return super.get();
    }

    public synchronized Object get() throws Exception {
        Object o = super.get();
        afterGet = true;
        return o;
    }

    public synchronized void put(Object v) throws Exception {
        super.put(v);
        afterGet = false;
    }
}

History Buffer, again
Modification of Acceptable States

Anomaly when mix-in classes are used to add behaviour to object via multiple inheritance.

```java
class Lock {
    ...
    void lock() { ...; }
    void unlock() { ...; }
}
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Trying to influence the enabling conditions of a class, by inheritance.

```java
class LockableBuffer extends Buffer, Lock{
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**Modification of Acceptable States**

Anomaly when *mix-in classes* are used to add behaviour to object via multiple inheritance.

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Of course, this does no much towards having a lockable buffer, in any language I know of.

**Question:** Is the Inheritance Anomaly nonsense or a genuine problem? If you look at it from the OO standpoint, it is genuine.
Jeeg tackles the (History-Sensitive) Inheritance Anomaly. It is:

- an aspect-oriented superimposition of two separate languages
- Java (no synchronized(), wait(), notify(), and notifyAll() for business code);
- Linear Time Temporal Logic for synchronisation code (method guards).
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```java
public class MyClass {
    sync {
        m : φ;
        ....
    }
    // Standard Java class definition
}
```

m is a method id and φ, the guard, is a formula in a given constraint language. When m is invoked, the thread is kept on hold unless φ. When the condition is true, all waiting threads are awaken. m is implicitly synchronized.
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If `φ` is a boolean expression, this is just a declarative version of Java concurrency.
The logic

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Linear temporal logic (past tense)

\[ \phi ::= AP \mid \neg \phi \mid \phi \Rightarrow \phi \mid \text{Previous } \phi \mid \phi \text{ Since } \phi \]

AP are pure boolean expressions with no:

- side-effects,
- references to objects,
- method invocations,
- and it only refers to private/protected fields of the class it belongs to.

Derived connectives:

\[ \phi \&\& \psi \triangleq \neg !!(\phi \Rightarrow \psi) ; \quad \text{Sometime } \phi \triangleq \text{true Since } \phi ; \quad \text{Always } \phi \triangleq \neg \text{Sometime } \neg \phi . \]
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This yield a rather expressive language CL, yet easy to implement.
An Object’s History

A generic computation $\pi$ from $o$’s perspective.

$$h_0^0 \cdots h_{j_0}^0 o.m_1 h_0^1 \cdots h_{j_1}^1 o.m_2 h_0^2 \cdots h_{j_2}^2 \cdots$$
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\[ h_0^0 \cdots h_j^0 o.m_1 h_0^1 \cdots h_j^1 o.m_2 h_0^2 \cdots h_j^2 \cdots \]

Here only the part of $h_j^k$ containing the values of private/protected, non-reference variables of $o$, say $\sigma_k$, can affect evaluation. Therefore, we take

\[ \mathcal{H}_o(\pi) \equiv \sigma_0 \xrightarrow{m_1} \sigma_1 \xrightarrow{m_2} \sigma_2 \xrightarrow{m_3} \sigma_3 \cdots \]
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Here only the part of $h_{j_k}^k$ containing the values of private/protected, non-reference variables of $o$, say $\sigma_k$, can affect evaluation. Therefore, we take

$$H_o(\pi) \equiv \sigma_0 \xrightarrow{m_1} \sigma_1 \xrightarrow{m_2} \sigma_2 \xrightarrow{m_3} \sigma_3 \cdots$$

We think of $H_o(\pi)$ as

$$H_o \equiv \sigma_0 \sigma_1 \sigma_2 \sigma_3 \cdots$$

where $\sigma_i$ binds the special identifier event to (a value representing method) $m_i$. 
Concurrent Objects’ Histories
Interpretation of Formulae on Object Histories

Let $\Sigma$ denote $\mathcal{H}_o(\pi)$. For all indexes $k$ in $\Sigma$, we define $\Sigma_k \models \phi$, that is $\phi$ holds at time $k$, by structural induction on $\phi$ as follows.

$\Sigma_k \models p$ iff $\sigma_k \models p$ ($p$ is true at $\sigma_k$)

$\Sigma_k \models \neg \phi$ iff $\neg \Sigma_k \models \phi$

$\Sigma_k \models \phi \lor \psi$ iff $\Sigma_k \models \phi$ or $\Sigma_k \models \psi$

$\Sigma_k \models \text{Previous } \phi$ iff $k > 0$ and $\Sigma_{k-1} \models \phi$

$\Sigma_k \models \phi \text{ Since } \psi$ iff $\Sigma_j \models \psi$ for some $j \leq k$, and $\Sigma_i \models \phi$ for all $j < i \leq k$

Finally, we convene that $\Sigma \models \phi$ iff $\Sigma_0 \models \phi$. 
public class Buffer {
    sync {
        put : current < MAX;
        get : current > 0;
    }
    protected Object[] buf;
    protected int MAX, current = 0;
    Buffer(int max) {
        MAX = max; buf = new Object[MAX];
    }

    public Object get() throws Exception {
        Object ret = buf[--current];
        return ret;
    }

    public void put(Object v) throws Exception {
        buf[current++] = v;
    }
}
public class HistoryBuffer extends Buffer {
    sync {
        gget: Previous (event != get) && current > 0;
    }

    public HistoryBuffer(int max) {
        super(max);
    }

    public Object gget() throws Exception {
        Object ret = buf[--current];
        return ret;
    }
}

History Buffer in JEEG
public interface Lock {
    public void lock();
    public void unlock();
}

public class LockBuf extends Buffer implements Lock {
    sync {
        get : super.getConstr && !Previous (event == lock);
        put : super.putConstr && !Previous (event == lock);
        lock : !Previous (event == lock);
        unlock : true;
    }

    public LockBuf(int max) { super(max); }
    public void lock() { }
    public void unlock() { }
}
Expressiveness of JEESG

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Expressiveness of LTL: A set of state sequences $X$ is the set of all $\Sigma$s that satisfy a given $\phi$ if and only if $X$ is a star-free regular language. (Zuck [1986])

Star-free Regular Languages:

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State for $C$: $p \in A_C \subseteq AP$; Sequence of states: $P \in A_C^*$. $(\Sigma \models P$ iff $\Sigma_k \models P_k)$

Theorem (Characterizing CL). For $\phi$ a formula on $C$, $X = \{\Sigma \mid \Sigma \models \phi\}$ iff there exists $re$ on $A_C$ such that $\Sigma \in X$ iff $\Sigma \models P$ for some $P \in re$. 
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Special case: Only atomic propositions of the kind event $= m$.

Then CL would capture precisely those sequences of events which are star-free regular languages (i.e., enforce synchronisation policies so expressible).
Examples

**HistoryBuffer**: the temporal constraint

Previous event \( \neq \) get

can be expressed by the following star-free regular expressions.

\[ \neg (A^* \cdot \text{get}) \quad \text{where } A^* \triangleq \varepsilon + \neg \varepsilon. \]

The temporal constraint

Sometime \( m \triangleq \text{true Since } m. \)

corresponds to

\[ A^* \cdot m \cdot A^*. \]
Limitations of LTL: No Counting

```java
public class SharedResource {
    sync {
        request: true;
        release: true;
    }
    public void request() { ... }
    public void release() { ... }
    ...
}
```

Define a class `SeizableResource` which allows exclusive access to the shared resource: An additional method `exclusiveRequest` must be provided.

Clearly, this leads to identify a pattern of events such as:

\[ M ::= \epsilon \mid \text{request } M \text{ release } \mid MM \mid \ldots \]

It is well known that this language is not regular. Methods `request` and `release` will have to be redefined. The anomaly surfaces again here.
Runtime Evaluation of CL Expressions

Given a finite trace $\Sigma$ and a LTL formula $\phi$, does $\Sigma \models \phi$?

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Given a finite trace $\Sigma$ and a LTL formula $\phi$, does $\Sigma \models \phi$?


- Build the syntax tree of the formula;
- Associate variables $\text{before}$ and $\text{now}$ to every node, initially set to $\text{false}$;
- Visit the tree depth-first and simultaneously assign $\phi.\text{before} := \phi.\text{now}$ and $\phi.\text{now}$ as follows.

<table>
<thead>
<tr>
<th>previous</th>
<th>now := $\phi_0.\text{before}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>since</td>
<td>now := $\phi_1.\text{now} \lor (\text{before} \land \phi_0.\text{now})$</td>
</tr>
<tr>
<td>or</td>
<td>now := $\phi_0.\text{now} \lor \phi_1.\text{now}$</td>
</tr>
<tr>
<td>not</td>
<td>now := not $\phi_0.\text{now}$</td>
</tr>
<tr>
<td>AP</td>
<td>now := eval($\phi$)</td>
</tr>
</tbody>
</table>

![Diagram of syntax tree](image)
Example: Let us consider the evaluation of the temporal formula

$$\text{Previous}(x == 1)$$

<table>
<thead>
<tr>
<th>Previous</th>
<th>Previous</th>
<th>Previous</th>
<th>Previous</th>
</tr>
</thead>
<tbody>
<tr>
<td>now = false</td>
<td>now = false</td>
<td>now = true</td>
<td>now = false</td>
</tr>
<tr>
<td>before = false</td>
<td>before = false</td>
<td>before = false</td>
<td>before = true</td>
</tr>
</tbody>
</table>

$$x == 1$$

now = false  before = false

$$x = 0$$ \(\text{inc}()\) $$x = 1$$ \(\text{inc}()\) $$x = 2$$ \(\text{dec}()\) $$x = 1$$
The Synchronisation Manager

Formulae must be evaluated after every method execution. This is done by a synchronization manager via Method Call Interception. It

- takes control at method call and checks (not evaluates) the constraint for the method.

- If it holds, control goes to the method code; otherwise the synchronization manager performs a wait(), putting the object to sleep.

- After the method execution, control shifts back to the manager, which now re-evaluates the synchronization constraints.

- After updating the formulae logic value, the manager issues a notifyAll() statement. Blocked methods may then attempt to proceed again.

To have access to private/protected fields, the synchronization manager an inner class of the object it manages.
Benchmarks: Object Creation

Object creation triggers the creation of data structures for formulas.
Method calls trigger the evaluation of formulas
Benchmarks: Details of Method Call

Machine 2

Machine 3

Formulae evaluation triggers mutual exclusion protocols
Benchmarks: Comparison

However, synchronisation must be performed also in Java!
**Performance Evaluation**

Testing shows that:

- **Under low-load** (below 70 threads) even complex synchronization constraints yield little performance overhead.

- **Low-end** machines face worse scalability problems due object locking: The slower the evaluation algorithm, the longer a large number of threads are kept waiting.
Conclusion

Jeeg

- Synchronization constraints written in LTL and specified in a aspect-oriented, declarative manner.
- CL is helpful in treating the inheritance anomaly.
- Characterisation of CL in terms of regular languages
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Future Work:

- Quantified linear temporal logic (QLTL) or monadic second order logic (MSOL), ‘second order’ variations of LTL of greater expressiveness.
- Optimizing the LTL evaluation procedure by using ad-hoc static-analysis techniques.