A CSP Model for Java Threads (and Vice-Versa)

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The Real World and Concurrency

Computer systems - to be of use in this world - need to model that part of the world for which it is to be used.

If that modeling can reflect the natural concurrency in the system … it should be simpler.

Yet concurrency is thought to be an advanced topic, harder than serial computing (which therefore needs to be mastered first).
This tradition is WRONG!

… which has (radical) implications on how we should educate people for computer science …

… and on how we apply what we have learnt …

What we want from Parallelism

- A powerful tool for simplifying the description of systems.

- Performance that spins out from the above, but is not the primary focus.

- A model of concurrency that is mathematically clean, yields no engineering surprises and scales well with system complexity.
Most objects are dead - they have no life of their own.

All methods have to be invoked by an external thread of control - they have to be caller oriented …

… a somewhat curious property of so-called object oriented design.

The object is at the mercy of any thread that sees it.

Nothing can be done to prevent method invocation …

… even if the object is not in a fit state to service it. The object is not in control of its life.
Objects Considered Harmful

Each single thread of control snakes around objects in the system, bringing them to life *transiently* as their methods are executed.

Threads cut across object boundaries leaving spaghetti-like trails, *paying no regard to the underlying structure*.

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Java Monitors - CONCERNS

- Easy to learn - but very difficult to apply … safely …

- Monitor methods are *tightly interdependent* - their semantics compose in *complex ways* … the whole skill lies in setting up and staying in control of these complex interactions …

- Threads have no structure … there are no *threads within threads* …

- Big problems when it comes to scaling up complexity …
Almost all multi-threaded codes making direct use of the Java monitor primitives that we have seen (including our own) contained race or deadlock hazards.

Sun’s Swing classes are not thread-safe … why not?

One of our codes contained a race hazard that did not trip for two years. This had been in daily use, its sources published on the web and its algorithms presented without demur to several Java literate audiences.

“ If you can get away with it, avoid using threads. Threads can be difficult to use, and they make programs harder to debug. ”

“ Component developers do not have to have an in-depth understanding of threads programming: toolkits in which all components must fully support multithreaded access, can be difficult to extend, particularly for developers who are not expert at threads programming. ”
It is our basic belief that extreme caution is warranted when designing and building multi-threaded applications ... use of threads can be very deceptive ... in almost all cases they make debugging, testing, and maintenance vastly more difficult and sometimes impossible. Neither the training, experience, or actual practices of most programmers, nor the tools we have to help us, are designed to cope with the non-determinism ... this is particularly true in Java ... we urge you to think twice about using threads in cases where they are not absolutely necessary ...”

So, Java monitors are not something with which we want to think - certainly not on a daily basis.

If we have to think with them at all, we want some serious help!

The first step in getting that help is to build a formal model of what we think is happening ...
Communicating Sequential Processes (CSP)

A mathematical theory for specifying and verifying complex patterns of behaviour arising from interactions between concurrent objects.

CSP has a formal, and *compositional*, semantics that is in line with our informal intuition about the way things work.

**Claim**

Why CSP?

- Encapsulates fundamental principles of communication.
- Semantically defined in terms of structured mathematical model.
- Sufficiently expressive to enable reasoning about *deadlock* and *livelock*. Process semantics are in terms of its *traces*, *failures* and *divergences*.
- Abstraction and refinement central to underlying theory.
- Robust *and commercially supported* software engineering tools exist for formal verification.
Why CSP?

- CSP libraries available for Java (JCSP, CTJ).
- Ultra-lightweight kernels* have been developed yielding sub-hundred-nano-second overheads for context switching, process startup/shutdown, synchronized channel communication and high-level shared-memory locks.
- Easy to learn and easy to apply (WYSIWYG) …

* not yet available for JVMs

So, what is CSP?

CSP deals with processes, networks of processes and various forms of synchronisation / communication between processes (events).

Processes are active entities - they perform (internal) computations and engage in events. Each process, \( P \), is registered for a particular set of events in which it might engage - this set is called its alphabet, \( \alpha(P) \).

Events are barriers. If one process tries to engage in an event, all processes (whose alphabets include that event) must engage in it before the engagement will complete.
So, what is CSP?

Channels are special kinds of events, usually in the alphabets of just two processes - the sender and the receiver. Channels communicate values. Each \(<channel.value>\) pair represents a different event.

Processes may be combined in sequence \((P; Q)\), in parallel \((P||Q)\), by internal choice \((P\cap Q)\) and by external choice \((P\&Q)\).

If \(a\) is an event and \(P\) is a process, then \((a\rightarrow P)\) is a process meaning: engage in \(a\), then become \(P\).

\textbf{SKIP} is a process that starts, does nothing and terminates.

Java Monitors

The key Java primitives for thread synchronisation are:

- \textbf{synchronized} methods and blocks;
- the methods \texttt{wait}, \texttt{notify} and \texttt{notifyAll} from the \texttt{Object} superclass.

We will only be concerned with how running threads interact in this paper. We will not be concerned, therefore, with starting threads (\texttt{Thread.start}) or waiting for them to terminate (\texttt{Thread.join}).

We have no intention of considering the deprecated thread control methods (\texttt{Thread.start}, \texttt{Thread.suspend} and \texttt{Thread.resume}).
Java Monitors

The key Java primitives for thread synchronisation are:

- synchronized methods and blocks;
- the methods wait, notify and notifyAll from the Object superclass.

We will also not be dealing with Thread.interrupt in this paper - nor with the InterruptedException that might be thrown by the wait() method.

And we’re not going to deal with timeouts either!

Nor priorities!!

A CSP Model of Java Monitors

Let Objects be an enumeration of all Java objects. For any particular system, this can be restricted to just those on which a synchronized action is performed. For example:

Objects = {0, 1, 2}

Let Threads be an enumeration of all Java threads. For any particular system, this can be restricted to just those threads that are created and started. For example:

Threads = {0, 1}
A CSP Model of Java Monitors

Define the following set of channels:

channel claim, release, waita, waitb, notify, notifyAll
: Objects. Threads

This introduces six families of channel - each family is indexed by an object and a thread. For example:

claim.o.t

where o is in Objects and t is in Threads.

Modeling the Monitor Interface

Claiming and releasing a monitor lock:

synchronized (o) {
    ... some process P
}

This maps to:

claim.o.me → P; release.o.me → SKIP

where me is the thread executing the above code.

Note that this also gives us the model for synchronized methods.
Modeling the Monitor Interface

Formally, entry and exit to a synchronized block or method is modeled by the processes:

\[
\begin{align*}
\text{STARTSYNC}(o, me) &= \text{claim} \cdot o \cdot me \rightarrow \text{SKIP} \\
\text{ENDSYNC}(o, me) &= \text{release} \cdot o \cdot me \rightarrow \text{SKIP}
\end{align*}
\]

where \(o\) is the monitor object being synchronised and \(me\) is the thread doing the synchronising.

Running in parallel with all user processes will be system processes \(\text{MONITOR}(o)\), one for each object \(o\) being used as a monitor. This has the above \(\text{claim} \cdot o \cdot me\) event in its alphabet and, if the lock is held by another thread, will refuse to engage in it. That will block entry to the monitor by the \(me\) thread.

The \(\text{o.wait()}\) method is modeled by the process:

\[
\begin{align*}
\text{WAIT}(o, me) &= \text{wait}a \cdot o \cdot me \rightarrow \text{release} \cdot o \cdot me \rightarrow \\
&\quad \text{wait}b \cdot o \cdot me \rightarrow \text{claim} \cdot o \cdot me \\
&\quad \rightarrow \text{SKIP}
\end{align*}
\]

where \(o\) is the monitor object whose lock has to be held and \(me\) is the thread that is doing the waiting.
The \texttt{o.wait()} method is modeled by the process:

\begin{align*}
\text{WAIT}(o, me) &= \text{waita}.o.me \rightarrow \text{release}.o.me \\
&\quad \rightarrow \text{waitb}.o.me \rightarrow \text{claim}.o.me \\
&\quad \rightarrow \text{SKIP}
\end{align*}

Again, the system process, \texttt{MONITOR(o)}, ensures the above semantics.

The \texttt{o.notify()} method is modeled by the process:

\begin{align*}
\text{NOTIFY}(o, me) &= \text{notify}.o.me \rightarrow \text{SKIP}
\end{align*}

The \texttt{o.notifyAll()} method is modeled by the process:

\begin{align*}
\text{NOTIFYALL}(o, me) &= \text{notifyAll}.o.me \rightarrow \text{SKIP}
\end{align*}

Again, the system process, \texttt{MONITOR(o)}, interacts with the above user process actions to arrange the exit from the wait set of some waiting user process (or processes) and its (their) reclaim of the monitor lock.
Summary of the Monitor Interface

\[
\begin{align*}
\text{STARTSYNC}(o, \text{me}) &= \text{claim}.o.\text{me} \rightarrow \text{SKIP} \\
\text{ENDSYNC}(o, \text{me}) &= \text{release}.o.\text{me} \rightarrow \text{SKIP} \\
\text{WAIT}(o, \text{me}) &= \text{waita}.o.\text{me} \rightarrow \text{release}.o.\text{me} \rightarrow \\
&\quad \text{waitb}.o.\text{me} \rightarrow \text{claim}.o.\text{me} \rightarrow \\
&\quad \text{SKIP} \\
\text{NOTIFY}(o, \text{me}) &= \text{notify}.o.\text{me} \rightarrow \text{SKIP} \\
\text{NOTIFYALL}(o, \text{me}) &= \text{notifyAll}.o.\text{me} \rightarrow \text{SKIP}
\end{align*}
\]

... where the blue events above may cause the user threads engaging in them to block (because \text{MONITOR}(o) has those events in its alphabet and may refuse to engage).

The Monitor Processes

Every Java object can be used as a monitor. In our model, there will be a monitor process, \text{MONITOR}(o), for each \textit{o} in \textit{Objects}. This process is itself the parallel composition of two processes:

\[
\text{MONITOR}(o) = \text{MLOCK}(o) \parallel \text{MWAIT}(o,\{\})
\]

The \text{MLOCK}(o) process controls the locking of the monitor associated with object \textit{o} - i.e. it deals with \textit{synchronized}.

The \text{MWAIT}(o,\{\}) process controls the (initially empty) \textit{wait-set} of threads currently stalled on this monitor - i.e. it deals with \textit{wait()}, \textit{notify()} and \textit{notifyAll()}. 
The Monitor Processes

Every Java object can be used as a monitor. In our model, there will be a monitor process, $\text{MONITOR}(o)$, for each $o$ in $\text{Objects}$. This process is itself the parallel composition of two processes:

$$\text{MONITOR}(o) = \text{MLOCK}(o) \ || \ \text{MWAIT}(o,\{\})$$

The alphabet of $\text{MONITOR}(o)$ is just the union of the alphabets of its component processes.

This will be the case for all parallel process compositions in this paper.

Locking the Monitor

Each $\text{MLOCK}(o)$ is basically a binary semaphore. Once claimed by a thread, only a release from that same thread will let it go - meanwhile it refuses all other claims.

If this were all it had to do, it could be simply modelled:

$$\text{MLOCK}(o) = \text{claim}.o.t \rightarrow \text{release}.o.t \rightarrow \text{MLOCK}(o)$$

Where the alphabet of $\text{MLOCK}(o)$ is:

$$\{\text{claim}.o.t, \text{release}.o.t \mid t \text{ in Threads}\}$$
However, a constraint in Java is that `o.wait()`, `o.notify()` and `o.notifyAll()` are only allowed if the invoking thread has the monitor lock on `o`.

Therefore, we extend the alphabet of `MLOCK(o)` to:

{claim.o.t, release.o.t, waita.o.t,

    notify.o.t, notifyAll.o.t | t in Threads}

In its initial unlocked state, `MLOCK(o)` refuses all the extra events. In its locked state, `MLOCKED(o)` accepts those extra events suffixed by the locking thread, but these have no impact on its state.

The `MLOCK(o)` process then becomes:

\[
MLOCK(o) = \text{claim.o?t} \rightarrow MLOCKED(o,t)
\]

where:

\[
MLOCKED(o,t) = \text{release.o.t} \rightarrow MLOCK (o)
\]

\[
\begin{align*}
    &\text{waita.o.t} \rightarrow MLOCKED(o,t) \\
    &\text{notify.o.t} \rightarrow MLOCKED(o,t) \\
    &\text{notifyAll.o.t} \rightarrow MLOCKED(o,t)
\end{align*}
\]

So, `MLOCK(o)` prevents any `o.wait() / o.notify() / o.notifyAll()`. `MLOCKED(o)` allows them, but only by the locking thread.
Managing the Wait-Set

The $\text{MWAIT}(o, ws)$ process controls the wait-set, $ws$, belonging to the monitor object $o$. Its alphabet contains just the wait and notify events:

$$\{\text{wait}.o.t, \text{waitb}.o.t,$$
$$\text{notify}.o.t, \text{notifyAll}.o.t \mid t \in \text{Threads}\}$$

In its initial state, $\text{MWAIT}(o, ws)$ listens for a $\text{waita}.o?t$, $\text{notify}.o?t$ or $\text{notifyAll}.o?t$, from any thread $t$.

It releases a waiting thread, by communicating on some $\text{waitb}.o.s$ - but only in response to a $\text{notify}.o.t$ or $\text{notifyAll}.o.t$.

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Managing the Wait-Set

$\text{MWAIT}(o, ws) =$

- $\text{waita}.o?t \rightarrow \text{MWAIT}(o, ws \text{ union } \{t\})$

- $\text{notify}.o?t \rightarrow$

  - if $|ws| > 0$ then
    $$\bigcap \limits_{s \in ws} \text{waitb}.o!s \rightarrow \text{MWAIT}(o, ws \text{ minus } \{s\})$$
  - else
    $$\text{MWAIT}(o, \{\})$$

- $\text{notifyAll}.o?t \rightarrow \text{RELEASE } (o, ws)$

Releases one thread, chosen non-deterministically
### Managing the Wait-Set

\[
\text{RELEASE}(o, ws) = \begin{cases} 
\text{if } |ws| > 0 \text{ then} & \bigcap \text{wait.b.o!s} \rightarrow \text{RELEASE}(o, ws \text{ minus } \{s\}) \\
\text{else} & \text{MWAIT}(o, \{\})
\end{cases}
\]

\text{RELEASE}(o, ws) \text{ follows a notifyAll.o?t.} \text{ It must release all the waiting threads (if any) in some non-deterministic order.}

### The Monitor Processes

Each arrow represents an array of channels, one for each thread, \( t \), that synchronizes on this monitor, \( o \). The shared channels are broadcasters - both sub-processes must input.
Putting CSP into practice ...

http://www.cs.ukc.ac.uk/projects/ofa/jcsp/
Synchronised Communication

A may write on c at any time, but has to wait for a read.
B may read from c at any time, but has to wait for a write.

Synchronised Communication

Only when both A and B are ready can the communication proceed over the channel c.
public class One2OneChannel {
    private Object channelHold; // data in transit
    private boolean channelEmpty; // sync flag

    ... public sync Object read ()
    ... public sync void write (Object mess)

    }

public synchronized Object read ()
throws InterruptedException {
    if (channelEmpty) {
        // first to rendezvous
        channelEmpty = false;
        wait (); // wait for the writer
        notify (); // schedule writer to finish
    } else {
        // second to rendezvous
        channelEmpty = true;
        notify (); // schedule waiting writer
    }
    return channelHold;

}
The JCSP One2OneChannel

```java
public synchronized void write (Object mess) throws InterruptedException {
    channelHold = mess;
    if (channelEmpty) { // first to rendezvous
        channelEmpty = false;
        wait (); // wait for the reader
    } else { // second to rendezvous
        channelEmpty = true;
        notify (); // schedule waiting reader
        wait (); // let reader regain lock
    }
}
```

Synchronised Communication

THEOREM:
For any processes A and B, the above CSP network …
**Synchronised Communication**

\[ \text{THEOREM (cont.):} \]

\[ \ldots \text{is equivalent to this one!} \]

**Parallel Introduction**

*Gratuitous* introduction of parallel processes can be done anywhere. Suppose \( X \) contains a serial process including one or more instances of \( P \) \( \ldots \)
Then, \textit{x} is equivalent to the parallel composition of the above two processes. \textit{X'} is \textit{x} with all instances of \textit{P} replaced by (\textit{ping} \rightarrow \textit{pong} \rightarrow \textit{SKIP}). \textit{Xb'} is a \textit{buddy} process that just performs \textit{P} on its behalf.

If the process being delegated accesses and modifies the state of \textit{x} …
Parallel Introduction

Then, ping and pong become channels through which the state and update results are passed, as well as retaining their synchronisation roles between $X'$ and $Xb'$.

Synchronised Communication

LEMMA:

$\langle A' || Ab' \rangle = A$ and $\langle B' || Bb' \rangle = B$
LEMMA:

\[(A' || A_j') = A_j \] and \[(B' || B_j') = B_j\]

Synchronised Communication

**LEMMA:**

The above process (that hides the internal channel \(c\) and just provides two ping-pong interfaces) is equivalent to …
Synchronised Communication

LEMMA: ... the above process (that also hides all internal channel \( c \) and just provides two ping-pong interfaces).

Summary - I

- A CSP model for the Java monitor mechanisms \( \text{synchronized, wait, notify, notifyAll} \) has been built.
- This enables any Java threaded system to be analysed in CSP terms - e.g. for formal verification of freedom from deadlock/livelock.
- Confidence gained through the formal proof of correctness of the JCSP channel implementation:
  - a JCSP channel is a non-trivial monitor - the CSP model for monitors transforms this into an even more complex system of CSP processes and channels;
  - using FDR, that system has been proven to be a refinement of a single CSP channel and vice versa - Q.E.D.
Summary - II

- Extending the model to deal with re-acquisition of a monitor lock by a thread already holding it (easy).
- Extending the model to deal with interrupts and the exception raised by \texttt{wait()} - (OK, but not so easy).
- Analysing published Java multithreaded codes and looking for trouble!
- Verifying (hopefully) the implementation of the rest of the JCSP primitives - especially those concerning Alternation, where earlier undetected race hazards were a real shake to our confidence …
**ALTing Communication**

```
A0
Hold (c0)
Empty (c0)
MONITOR (c0)
Alt (c0)

State (alt)
MONITOR (alt)
Selected (alt)
Index (alt)

A1

B
Hold (c1)
Empty (c1)
MONITOR (c1)
Alt (c1)
```

---

**ALTing Communication**

```
A0

A1

B
c0

c1
```
Summary - III

- Using parallel introduction in the same way gives the model checker something on which to bite.
- FDR, after working through around 48000 states, confirms that the two networks are equivalent.
- FDR revealed the deadlock trace in the CSP network representing the original implementation within seconds. That deadlock had taken 2 years to reveal itself in practice!
- This has only verified a 2-way ALT. FDR could probably manage a 3-way one … but an n-way?
- Nevertheless, a huge confidence boost for JCSP.

Final Thought …

- A CSP model of Java's multithreading puts it on a solid engineering foundation.
- Systems can be analysed for refinement, equivalence, deadlock, livelock and race hazards.

“So, Bill, you sold your system without really knowing whether it was deadlock-free ... and you never even tried these standard procedures that might have found out?!! Disclaimer notices notwithstanding, would you say that that shows a lack of due care or a lack of diligence towards your customer?”