Seven Obstacles in the Way of Parallel SystemC Simulation

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Thoughts on the next generation of SystemC

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Goals

• Truly parallel simulation of SystemC models
  – High speed due to parallel execution on multi/many core hosts
  – Compliant to the IEEE 1666 standard
• Identify the main obstacles in the way of standard-compliant parallel SystemC
  – And propose potential solutions
• Technical review and evaluation of
    • IEEE Std 1666™-2011 (Revision of IEEE Std 1666-2005)
  – Accellera open source proof-of-concept library (v2.3.1)

Warning: Controversial Content Ahead!
  – Evolve SystemC to true parallelism (major revision)
  – Let’s have a good discussion!

Discrete Event Simulation (DES)

• Traditional DES
  – Concurrent threads of execution
  – Managed by a central scheduler
  – Driven by events and time advances
    • Delta-cycle
    • Time-cycle
  ➢ Partial temporal order with barriers
• Sequential Reference Simulator
  – SystemC standard IEEE 1666-2011
  ➢ A single thread is active at any time
  ➢ Cannot exploit parallelism
  ➢ Cannot utilize multiple cores
Parallel Discrete Event Simulation (PDES)

- Parallel DES
  - Threads execute in parallel \textit{iff}
    - in the same delta cycle, \textit{and}
    - in the same time cycle
  \> Significant speed up!

Obstacle 1: Co-Routine Semantics

- Fact: IEEE 1666-2011 requires co-operative multitasking
  \> Quotes from Section “4.2.1.2 Evaluation phase” (pages 17, 18):

Since process instances execute without interruption, only a single process instance can be running at any one time, […] A process shall not pre-empt or interrupt the execution of another process. This is known as \textit{co-routine semantics} or co-operative multitasking.

[…] The scheduler is not pre-emptive. An application can assume that a method process will execute in its entirety without interruption, and a thread or clocked thread process will execute the code between two consecutive calls to function wait without interruption.

- Problem: Uninterrupted execution guarantee

An implementation running on a machine that provides hardware support for concurrent processes may permit two or more processes to run concurrently, provided that the behavior appears identical to the co-routine semantics defined in this subclause. In other words, the implementation would be obliged to analyze any dependencies between processes and to constrain their execution to match the co-routine semantics.
Parallel Discrete Event Simulation (PDES)

- Parallel DES
  - Threads execute in parallel \textit{iff}
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    - in the same time cycle
  - Significant speed up!

- SystemC LRM Requirement:
  “The scheduler is not pre-emptive.”

- SystemC: guaranteed safe!
- PDES: not safe! (race condition)

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    - The scheduler is \textit{not pre-emptive}. An application can assume that a method process will execute in its entirety without interruption, and a thread or clocked thread process will execute the code between two consecutive calls to function \textit{wait} without interruption.

- Problem: Uninterrupted execution guarantee
  - An implementation running on a machine that provides hardware support for concurrent processes may permit two or more processes to run concurrently, provided that the behavior appears identical to the co-routine semantics defined in this subclause. In other words, the implementation would be obliged to analyze any dependencies between processes and to constrain their execution to match the co-routine semantics.

- Proposal: Explicitly allow parallel execution, preemption
  - Process instances at the same time \( (t,\delta) \) may execute in parallel
    - Model designer must write thread safe code, avoid race conditions
  - Parallel systems, parallel models, parallel programming
Obstacle 2: Simulator State

- Fact: Discrete Event Simulation (DES) is presumed
  - Example from IEEE 1666-2011, page 31: `sysc/kernel/sc_simcontext.h`

```cpp
bool sc_pending_activity_at_current_time();
bool sc_pending_activity_at_future_time();
bool sc_pending_activity();
bool sc_time_to_pending_activity();
```

- Problem: Parallel Discrete Event Simulation (PDES) is different from sequential DES
  - After elaboration, there may be multiple running threads
  - Scheduling may happen while some threads are still running
- Proposal: Carefully review simulator state primitives and revise as needed for PDES
  - Adapt the functions and APIs for parallel execution semantics
  - The general notion of shared state needs attention…

Obstacle 2: Simulator State

- Fact: Discrete Event Simulation (DES) is presumed
- Problem: Parallel Discrete Event Simulation (PDES) is different from sequential DES
- Proposal: Carefully review simulator state primitives and revise as needed for PDES
  - The general notion of shared state needs attention
  - Special consideration for very strict semantics, e.g. debugging:
    - Quote from IEEE 1666-2011, Section “4.2.1.2 Evaluation phase” (page 17):
      - Strict DES can remain valid as a special case of PDES
        - While PDES typically runs up to \( n \) threads in parallel, where \( n = \) number of cores on the host, we can set \( n = 1 \) to mimic the classic DES case

The order in which process instances are selected from the set of runnable processes is implementation defined. However, if a specific version of a specific implementation runs a specific application using a specific input data set, the order of process execution shall not vary from run to run.
Obstacle 3: Lack of Thread Safety

- Fact: Primitives are generally not multi-thread safe
  - Suspicious example from IEEE 1666-2011, page 194:
    ```
    sc_length_param length10(10);
    sc_length_context cntxt10(length10);  // length10 now in context
    sc_int_base    int_array[2];        // Array of 10-bit integers
    ```
- Problem: Parallel execution may lead to race conditions
  - Race conditions result in non-deterministic/undefined behavior
  - Explicit protection (e.g. by mutex locks) is cumbersome
  - Identifying problematic constructs is difficult
    - Example: `class sc_context`, commented as "co-routine safe"
- Proposal: Require all primitives to be multi-thread safe
  - Carefully revise the proof-of-concept SystemC library
    - Encouraging item: `async_request_update` is thread-safe!
    - See "5.15 sc_prim_channel", IEEE 1666-2011, page 121

Obstacle 4: Class sc_channel

- Fact: `sc_channel` is an alias type for `sc_module`
  - IEEE 1666-2011, Section "5.2.23 sc_behavior and sc_channel" (page 56):
    ```
    typedef sc_module sc_channel;
    typedef sc_module sc_behavior;
    ```
  - The typedefs `sc_behavior` and `sc_channel` are provided for users to express their intent.
    - `systemc-2.3.1/include/sysc/kernel/sc_module.h`
    - There is no distinction between a `behavior` and a hierarchical channel other than a difference of intent. Either may include both ports and public member functions.
- Problem: Alias type is only another name, no new type
  - Language does not distinguish modules and channels
  - No separation of communication and computation
    - Breaks a key system-level design principle...
- Proposal: Class `sc_channel`, derived from `sc_module`
  - Module encapsulates computation (hosts threads/processes)
  - Channel encapsulates communication (implemented interfaces)
Obstacle 4: Class sc_channel

- Proposal: Class sc_channel, derived from sc_module
  - Module encapsulates computation (hosts threads/processes)
  - Channel encapsulates communication (implemented interfaces)
  - Q: Why do we need channels? A: Thread safe communication!
    - Example: Blocking write in primitive channel sc_fifo.h

  ```c++
  template <class T> inline
  void sc_fifo<T>::write( const T& val_ )
  {
    while( num_free() == 0 ) {
      sc_core::wait( m_data_read_event );
    }
    m_num_written ++;
    buf_write( val_ );
    request_update();
  }
  ``

  - Race condition between num_free and m_num_written
  - Prevented by locking m_mutex of this channel instance
    - Channel acts as a monitor for multi-thread safe communication

Obstacle 5: TLM-2.0

- Fact: Channel concept has disappeared
    Presentation by David Black, Doulos, at DAC’15 Training Day

- Problem: Where is the channel?
Obstacle 5: TLM-2.0

• Fact: Channel concept has disappeared

• Problem:
  Where is the channel?
  – Interface methods are well-defined, but not contained
  – Separation of concerns “Computation ≠ Communication” principle is broken

• Proposal:
  Encapsulate communication methods in channels

Initiator and Target Sockets

Channels encapsulate communication on fw and bw paths
Obstacle 6: Sequential Mindset

- Fact: SC_METHOD is preferred over SC_THREAD, context switches are considered overhead
  - IEEE 1666-2011, Section 5.2.11 on threads (page 44):
    - Each thread or clocked thread process requires its own execution stack.
    - As a result, context switching between thread processes may impose a simulation overhead when compared with method processes.
  - Problem: Sequential modeling is encouraged
    - However, systems are parallel by nature, so should be models
    - Avoiding context switches is the wrong optimization criterion
  - Proposal: Use actual threads, eliminate SC_METHOD, identify dependencies among threads
    - Promote parallel mindset, with true thread-level parallelism
      - Speed due to parallel execution, not due to fewer context switches
    - Explicitly express task relations (use e.notify(), wait(e))
      - Synchronize, communicate through events and channels

Obstacle 7: Temporal Decoupling

- Fact: TD is designed to speed up sequential DES
  - IEEE 1666-2011, Section 12.1 on “TLM-2.0 global quantum” (page 453):
    - Temporal decoupling permits SystemC processes to run ahead of simulation time for an amount of time known as the time quantum and is associated with the loosely-timed coding style. Temporal decoupling permits a significant simulation speed improvement by reducing the number of context switches and events.
    - Abstraction trades off accuracy for higher simulation speed
  - Problem: PDES is a different foundation than DES
    - TD design assumptions are not necessarily true for PDES
    - Global time quantum is a technical obstacle (race condition)
  - Proposal: Reevaluate costs/benefits, redesign if needed
    - Analyze TD idea for PDES, adopt advantages, drop drawbacks
      - Avoid tlm_global_quantum, promote wait(time)
    - Consider the use of a compiler to optimize scheduling, timing
      - Out-of-Order PDES is one solution (fully automatic, accurate)
Concluding Remarks

- Towards *standard-compliant parallel SystemC*
  - Higher simulation speed on multi/many core hosts
- Overcome the identified IEEE 1666-2011 obstacles
  - Move up from DES to PDES
  - Adopt a parallel mindset, expose and exploit parallelism
  - Apply the principle of separation of concerns
    - Modules encapsulate computation
    - Channels encapsulate communication
  - Simulate models faster with parallel execution semantics
- SystemC must evolve in a major revision (3.x)
  - C++11 already has built-in support for multithreading
  - SystemC must embrace true parallelism
    - Otherwise it will go down the same path as the dinosaurs…

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