Session Types
Towards safe and fast reconfigurable programming
HEART 2012

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Motivation

- Parallel and heterogeneous architectures
  - Combines parallelism and specialisation, eg FPGA
  - Efficient use of computing resources
  - Difficult to program (correctly)
- One source of error of parallelising
  - Communication mismatch (send-receive)
  - Communication deadlocks
Message passing communication

- scalable, commonly used

MPI (Message-Passing Interface)
- common for communication in parallel computers

Communication mismatch and deadlocks
- lead to program error
Motivating example

```c
if (rank == 0) {
    // Program 0
    MPI_Send(a, 5, MPI_INT, 1, TAG, MPI_COMM_WORLD);
    MPI_Recv(b, 5, MPI_INT, 1, TAG, MPI_COMM_WORLD);
} else if (rank == 1) {
    // Program 1
    MPI_Send(b, 5, MPI_INT, 0, TAG, MPI_COMM_WORLD);
    MPI_Recv(a, 5, MPI_INT, 0, TAG, MPI_COMM_WORLD);
}
```

Program 0        Program 1
<table>
<thead>
<tr>
<th>Send a</th>
<th>Send b</th>
</tr>
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<tbody>
<tr>
<td>Recv b</td>
<td>Recv a</td>
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**Figure:** Interaction of two processes with a deadlock.
Contributions

- An intuitive programming framework and toolchain
  - For message-passing parallel programming
  - Based on formal and explicit interaction protocol
- Advanced communication topologies for computer clusters
- Case study comparing framework with existing tools
Session Types [Honda et al. ESOP’98, POPL’08]

- Typing system for communication
- Ensure compatible communication (send-receive) by typing
  - Sequence of send and receive
  - Also types flow-control constructs (eg. loops, if-then-else)

Ideal to integrate into programming language

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Program 0

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Figure: Incompatible.

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Figure: Compatible.
Session C programming framework: Aims

- Minimal extension of C language to support Session Types
- General communication-based framework
  - Safe distributed parallel programming
  - High performance applications
- Focussed on computer cluster communication
Session C toolchain and key reasoning

1. Design protocol in global view
2. Automatic *projection* to endpoint protocol, algorithm preserves safety
3. Write program according to endpoint protocol
4. Check program conforms to protocol
5. $\Rightarrow$ Safe program by design
/* Global protocol */

protocol Simple
  (role P1, role P2, role P3) {
    int from P1 to P2;
    char from P3 to P1;
    float from P2 to P3
  }
/* Endpoint protocol for P2 */

protocol Simple at P2
  (role P1, role P3) {
    int    from P1;

    float to P3;
  }

- Projection of Simple with respect to P2
- Endpoint protocol from perspective of P2
Session C Architecture

- Endpoint Scribble protocol
- Session C source code

User input *protocol* and *C source code*
- Session C framework
  - Runtime/communication API
  - Session Type checker

Session type checker
- clang compiler

Runtime library
- Executable
Session C Architecture: Session Type checker

- Endpoint Scribble protocol
- Session C source code
- Session type checker
- clang compiler
- Runtime library
- Executable

- Static analyser for source code
- Verify source code conforms with protocol specification
- Protocol extracted based on usage of API
Example topologies in the framework

- Topology safe if can be described in framework
  - Subject to global protocol well-formedness conditions
- Examples: Ring topology and map-reduce
Topologies: Ring

```
protocol Ring {
    rec LOOP {
        datatype from Node0 to Node1;
        datatype from Node1 to NodeN;
        // Wrap back to Node0
        datatype from NodeN to Node0;
        LOOP;
    }
}
```
Topologies: Map-reduce

```
protocol MR {
  rec LOOP {
    datatype from Master to Worker0, Worker1;
    datatype from Worker0, Worker1 to Master;
    LOOP;
  }
}
```
Evaluation

- Comparing session-enhanced programming with MPI
- Strength: Protocol known (and safe) at implementation time
- Asynchronous operation re-ordering
  - Optimisation applied to implementations
  - Correctness ensured by Session Type checker
Heterogeneous Computing Node (HCN)

- CPU
- GPU
- FPGA
- RAM
- PCIe bus
- Ethernet
- Graphics memory
- FPGA memory

**Heterogeneous accelerators**
- Multicore CPU
- GPU
- FPGA

**Communication**
- Inter-node: Ethernet
- Inter-component: PCI
- Inter-FPGA: Infiniband
N-body simulation accelerated by FPGA (Java)

- Session Java comparable to MPJ Express (MPI in Java)
- FPGA overhead improves with larger input size
• Session C performance same as MPI
• Significant improvement with FPGA acceleration
Scalability: N-body simulation and K-means clustering

- Performance improve with number of nodes
- MPI and Session C converge as nodes increase
Evaluation: Summary

- Session-enhanced languages (Java and C)
  - Communication safety ensured
  - Negligible performance cost
  - FPGA acceleration improves performance
  - Solution scalable
Future work

- Extending approach to include eg GPU or other hardware
- MPI-compatible runtime for multiparty session programming
- Integrate with customisable communication framework [Denholm et al., ASAP’11]
Conclusion

- Introduced a programming and verification framework for communication in C
- Shown advanced communication topologies for computer clusters
- Performance evaluation of framework against existing tools
  - Competitive performance
Session C runtime and type-checker
http://sesscc.googlecode.com
Appendix
Related works

- MPI Deadlock detection by model checking techniques
  - ISP/DAMPI [Vo et al., PPoPP’09/SC’10]
  - TASS [Siegel et al., PPoPP’11]
- Our approach does not depend on testing or heuristics
  - Full guarantee of deadlock-freedom and communication-safety
Session C example: Protocol design

Description of protocol

```
protocol P (role A, role B) {
    int from A to B;
    int from B to A;
}
```

⇒ Description of a protocol for each endpoint

```
protocol P at A (role B) {
    int to B;
    int from B;
}
```

```
protocol P at B (role A) {
    int from A;
    int to A;
}
```
```c
#include <libsess.h>

int main() { // A session C program
    session *s; int ival, sum = 0;
    // Start a session that follows the protocol "Protocol_Endpoint"
    join_session (&argc, &argv, &s, "Protocol_Endpoint.spr");
    role Bob = s->get_role(s, "Bob"); // Get role handle

    send_int(Bob, 42); // Send int to Bob
    while (i < 3) {
        recv_int(Bob, &ival); //Recv int from Bob
        sum += ival;
    }
    send_int(Bob, sum); // Send int to Bob

    end_session(s); // End a session
    return 0;
}
```
Ring topology: full example
- Input segmented to $n$ parts
- Results shifted right until all nodes worked on all segments

```plaintext
protocol Nbody /* Global protocol */
( role Head, role Body, role Tail ) {
  rec NrOfSteps {
    rec SubCompute {
      particles from Head to Body;
      particles from Body to Tail;
      particles from Tail to Head;
      SubCompute; }
    NrOfSteps; }
}
```

$N$-node ring topology
N-body simulation: Ring topology (2)

/* Endpoint Protocol */

protocol Nbody at Body
  (role Head, role Tail) {
    rec NrOflters {
      rec SubCompute {
        particles from Head;
        particles to Tail;
        SubCompute;}
      NrOflters;}
  }

/* Implementation of Body worker */

particle_t *ps, *tmp_ps;
while (iterations ++ < ITERS_NR) {
  while (rounds++ < NODES_NR) {
    send_particles(Tail, tmp_ps);
    // Update velocities
    compute_forces(ps, tmp_parts ,...);
    recv_particles(Head, &tmp_ps);
  } // Update positions
  // by received velocities
  compute_positions(ps, pvs, ... );
}
Asynchronous reordering
Safe pipeline communication

- Some synchronous operations can be safely reordered [Mostrous et al., ESOP’09]
- Pipelines impossible in ‘strict’ multiparty session types, possible with asynchronous subtyping
- Safe pipeline improves performance, more scalable

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Figure: MPST.

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Figure: Asynchronous subtyping.
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![Figure: MPST.](image1)

![Figure: Asynchronous subtyping.](image2)
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