Session-based Programming for Parallel Algorithms

Expressiveness and Performance

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Aim of this work

Investigate benchmark examples of session types to compare productivity, safety and performance with other communications programming languages.

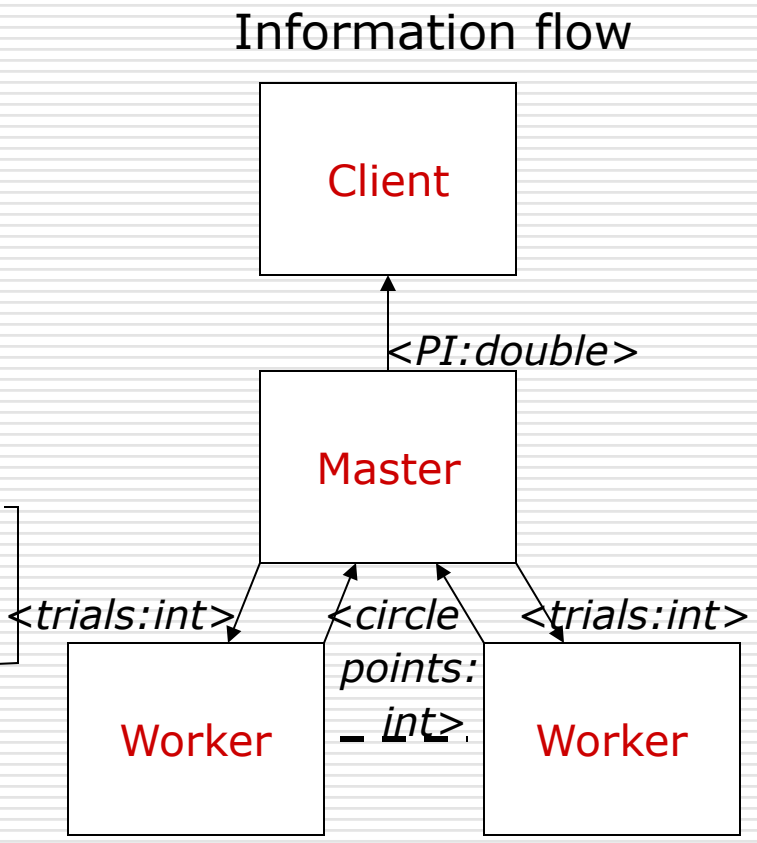
- Benchmark examples:
  - Monte Carlo Pi Approximation,
  - Jacobi solution of the Poisson Discrete Equation, and
  - a Simulation of the *n*-body Problem
- Session types: **SJ**, the first full object-oriented language to incorporate session types for type-safe concurrent and distributed programming.
- Other communications prog. lang. : **MPI** and **MPJ Express**

Monte Carlo π Approximation

```
protocol workerToMaster{
      sbegin.
            ?(int).
            !<int>
}

protocol masterToWorker{
      cbegin.
            !<int>.
            ?(int)
}
```

Safety (freedom from communication errors)

Duality of types: For each `send`(!) with a message type A corresponds a `receive`(?) with the same type.



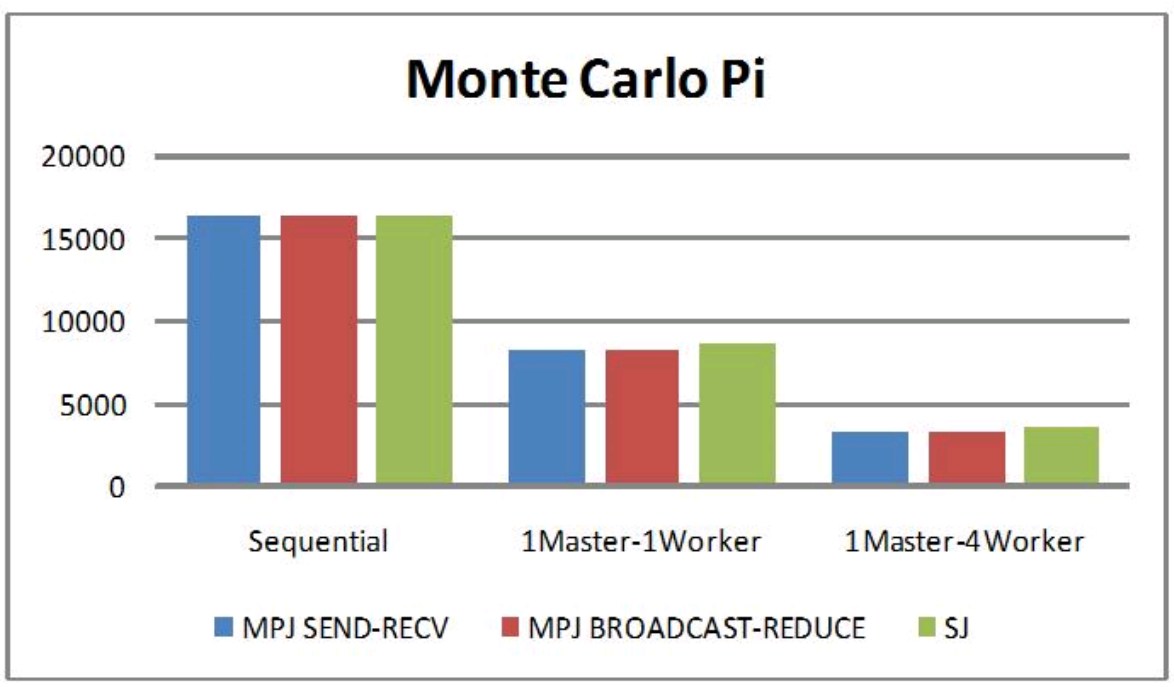
Monte Carlo π Approximation

Productivity

```
// Workers run the simulation.
int trials = s_wm.receive();
                                    //?(int)
for (int i = 0; i < trials; i++)
    if (hit()) hits++;
s_wm.send(hits); // !<int>
```

```
// Master controls the Workers.
<s_mw1, s_mw2>.send(trials);
                                    // Multicast.
int totalHits =
    s_mw1.receive() +
    s_mw2.receive(); // Collect the
                        results.
```

Performance Results

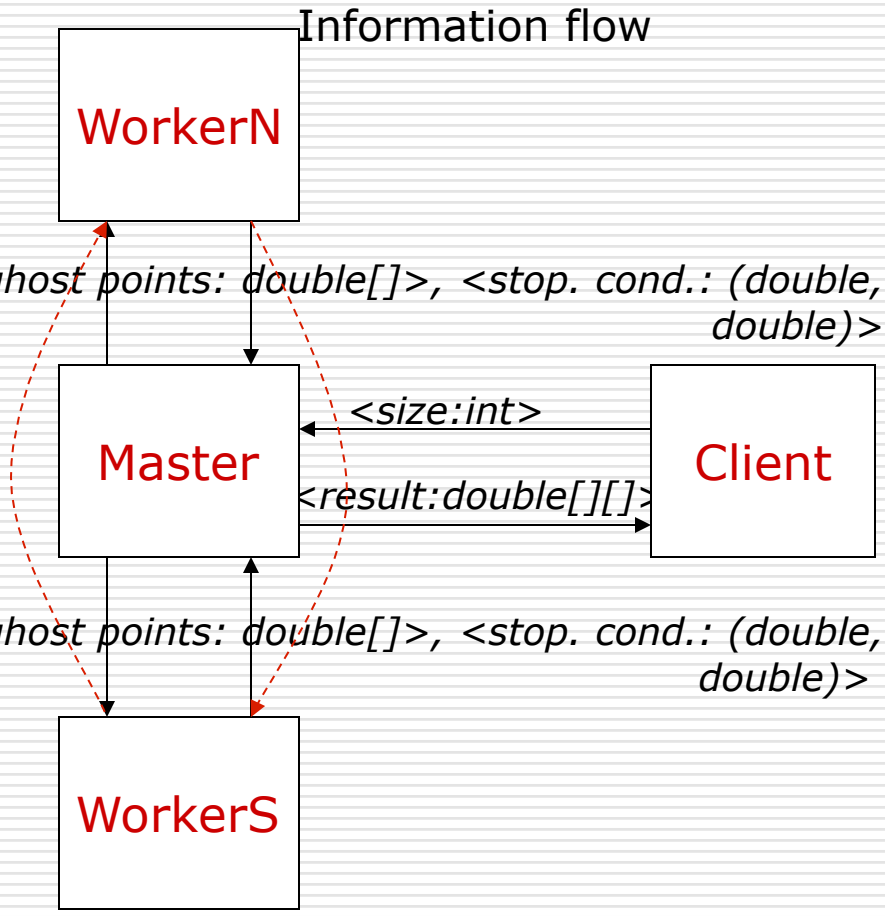


Client, Master and Workers run on different machines.

- Increasing the number of Workers reduces the time to complete the algorithm proportionally.
- MPJ Express implementation is 5-6% faster than the SJ implementation.

Jacobi Solution of the Discrete Poisson Equation

```
protocol masterToWorker {
  cbegin. // Request the Worker service.

    !<int>. // Send the size of the matrix.

    ![ // Enter scope of main algorithm
         iteration (check term. cond.).

      !<double[]>.?(double[]). // Send
           our boundary values; get Worker's
           updated ghost points.

      ?(double).?(double) // Receive the
       convergence data for Worker's subgrid.

    ]*. // After the last iteration...

    ?(double[][]) // ...get the final results.
}
```



Jacobi Solution of the Discrete Poisson Equation

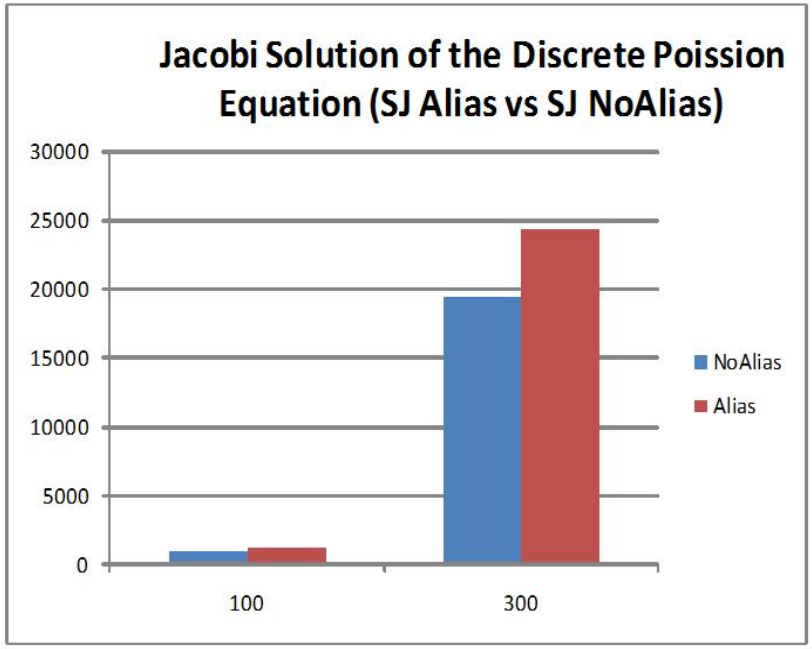
Productivity + Safety

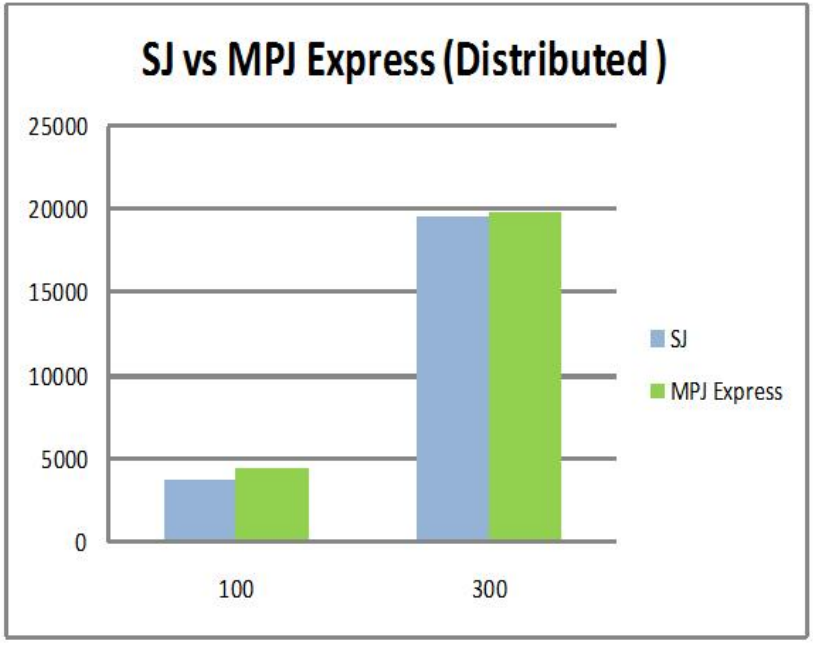
```
// Master controls iteration condition.                    // Workers obey the Master.

<mw1, mw2>.outwhile( // ![...                               <wm>.inwhile() { // ?[...
  !accurateEnough(...)
  && iters < MAX_ITERS){

    ... // Main                                  n.                ... /* Main body of the algorithm.*/

} // ...]*                                                    } // ...]*
```

Zero-copy message passing (when run on same VM)

```
// Array containing our boundary values (ghost points for the Master) declared as noalias.
noalias double[] ghostPoints = ...; // Update and prepare our boundary values for sending.

s_wm.send(ghostPoints); // Zero-copy send, as directed by types: !<noalias double[]>.

... // ghostPoints variable becomes null.
```

Performance Results

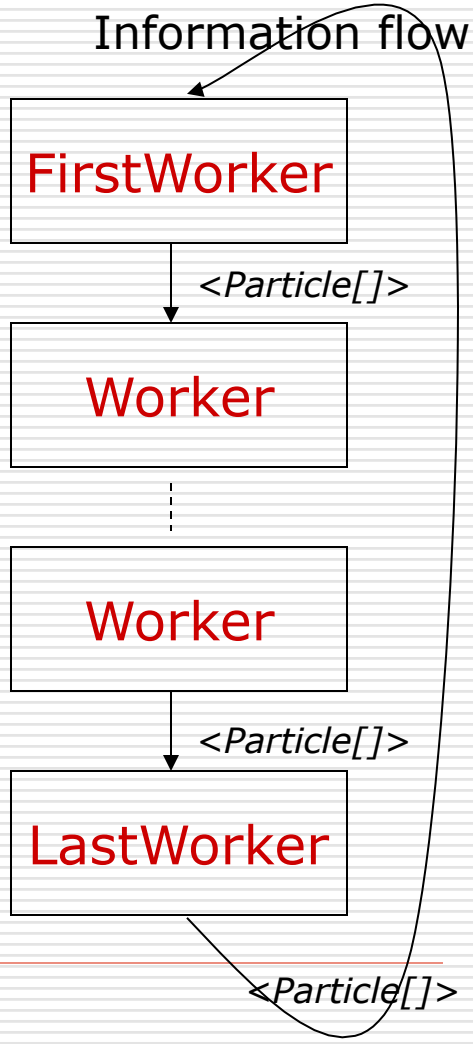




- The noalias version is approximately 20% faster than the ordinary one.
- The SJ implementation performs better than the MPJ Express one by 6% on average.

The *n*-Body Problem

```
protocol serverSide { // Interaction with the left
                      neighbour.
    sbegin. // Accept connection from left neighbour.

        !<int>. // Forward on the ring initialisation token.

        ?[ // Main simulation loop (iteration flag received
           from the left).

            ?[  // Inner iterations within each simulation
                step.

                ?(Particle[]) // Particle data forwarded
                              through pipeline.
            ]*
        ]*
}
```



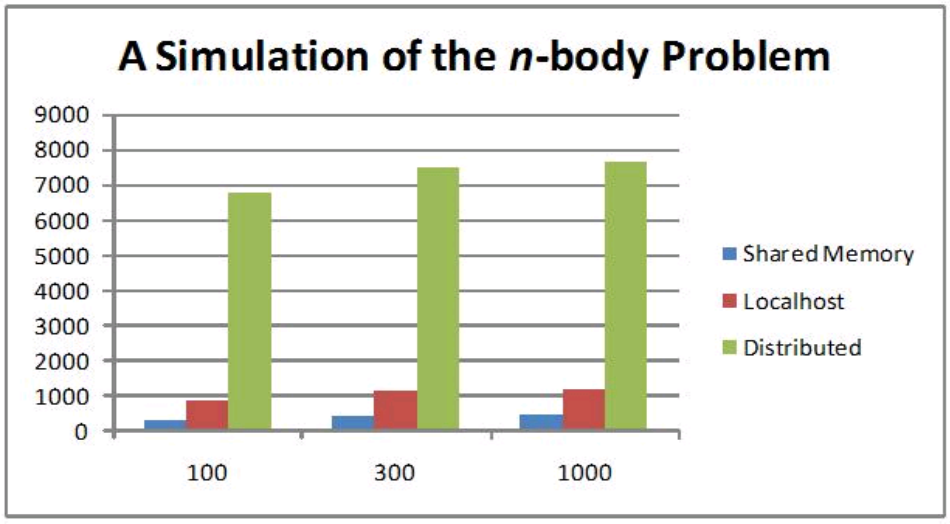
The *n*-Body Problem

Productivity + Safety

```
s_r.outwhile(s_l.inwhile()) { // Synch. with our two n'bours for each  sim. step. s_l: ?[..
    noalias Particle[] current = ...; // Prepare our own particle data for sending.
    s_r.outwhile(s_l.inwhile()) { // Inner iters. within each simulation step. s_l: ?[..
        s_r.send(current); // (i) Forward the current data set. s_r: !<Particle[]>.
        ...                // (ii) Add the current data to the running calculation.
        rrent = (Particle[]) s_l.receive(); // (iii) Receive next data set. s_l:
                                               ?(Particle[]).
    ..]*
    ... // Calculate the final results for this sim. step and update our own particle data.
} // s_l: ..]*
```

Zero-copy message passing (when run on same VM)

Performance Results



2 pipeline Workers

- Thread version faster than Localhost
  - 27% for size 100
  - 24% for size 300
  - 10% for size 1000
- Thread version faster than Distributed
  - 34% for size 100
  - 27% for size 300
  - 12% for size 1000

Comparing SJ with MPI

- Common MPI errors recognized by the community.
  - Doing things before `MPI_Init` and after `MPI_Finalize`
    - Runtime exceptions
  - Unmatched `MPI_Send` and `MPI_Recv` or matched `MPI_Broad` with `MPI_Recv`.
    - Deadlock
    - Broken invariants
    - Messages lost
  - Incorrect access of a shared communicator by separate threads.
    - Broken causalities
- ***SJ programs are guaranteed free from all of the above errors*** by the semantics of session communication and static session type checking.

Comparing SJ with MPI

- High-level message types.
  - In parallel algorithms, a common message structure is array.
  - In MPI, the programmer has to know the precise length of the array sent in order to read the data contained in it (e.g. in the MPI version of *n*-body).
  - In SJ, the length of the array is set by the runtime. At the application level arrays are considered as normal objects.
- Transparent zero-copy message passing.
  - Language support for zero-copy message passing in shared memory environment through `noalias` type.

Future Work

- Expanding the set of SJ operations and constructs, e.g. with session typed equivalents of MPI functions and features that are not yet directly supported.
- Compare SJ to PGAS languages such as X10.
- Extending SJ with full multiparty session types.
  - To express richer topologies such as rings and 2D-mesh
  - To enable performance improvements through massive parallelism

Conclusion

- SJ is an evolving framework, recent extensions
  - multicast output operations (<s_mw1, s_mw2>.send(trials);)
  - advanced iteration structures (<mw1, mw2>.outwhile(…), s_r.outwhile(s_l.inwhile()))
  - the Abstract Transport (use the same program to make use of the best transport available)
- SJ programs are guaranteed free from type and communication errors.
- In certain cases, SJ programs can out-perform their counterparts implemented
  - in communication-safe systems such as RMI
  - lower-level, non communication-safe message passing systems such as MPJ Express

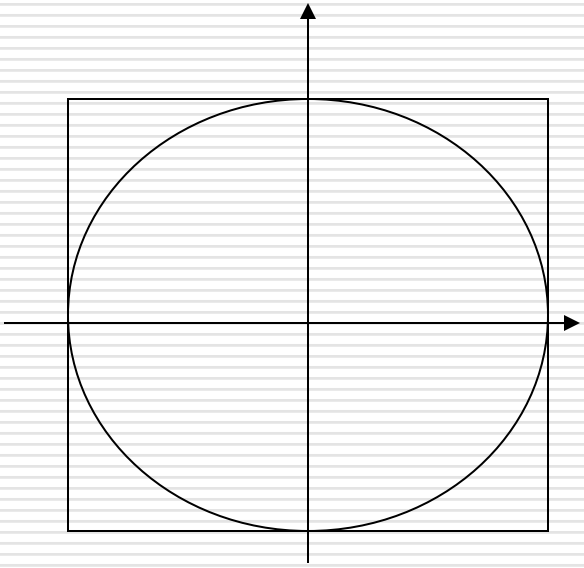
References

- Full implementation of the parallel algorithms in **SJ** and **MPJ Express**: http://www.doc.ic.ac.uk/~ab406/parallel_algorithms.htm
- **SJ** homepage: http://www.doc.ic.ac.uk/~rhu/sessionj.html
- **MPJ Express** homepage: http://mpj-express.org/
- William Gropp et al. *Using MPI: Portable Parallel Programming with the Message-Passing Interface* (1999).
- Session types:
  - Kaku Takeuchi et al. *An interaction-based language and its typing system* (PARLE 94).
  - Kohei Honda et al. *Language primitives and type discipline for structured communication-based programming* (ESOP 98).
  - Raymond Hu et al. *Session-based distributed programming in Java* (ECOOP 08).
  - Kohei Honda et al. *Multiparty asynchronous session types* (POPL 08).

Monte Carlo π Approximation

- Square area = 4 unit^2
- Circle area = π unit^2
- t = Circle area/Square area, π = 4*t

- Generate points (x, y) in [-1, 1] and check if they fall inside the circle ($x^2 + y^2 <= 1$)



Jacobi Solution of the Discrete Poisson Equation

- A partial differential equation with applications in heat flow, electrostatics, gravity and climate computations.

- The discrete two-dimensional Poisson equation for a $m \times n$ grid:

  $u_{i\,j} = 1/4\ (u_{i-1,\,j} + u_{i+1,\,j} + u_{i,\,j-1} + u_{i,\,j+1} - dx^2 g_{i,\,j})$

  where $2 \le i \le m-1$, $2 \le j \le n-1$, and $dx = 1/(n+1)$.

- Jacobi's Method converges on a solution by repeatedly replacing each element of the matrix u by an average of its four neighbours and $dx^2 g_{i,\,j}$; for this example, we set g to 0.

  $u_{i\,j}^{k+1} = 1/4\ (u_{i-1,\,j}^{k} + u_{i+1,\,j}^{k} + u_{i,\,j-1}^{k} + u_{i,\,j+1}^{k})$

- Parallelism:
  - The grid is divided into three sub-grids
  - Jacobi iteration over each subgrid

The *n*-Body Problem

- Find the movements of *n* particles following the Newton Laws of Motion and law of universal gravitation when the force between particles is present.
- The force between particles is defined by adding the forces between all pairs of particles.
- Parallelism
  - The particles are distributed among different processes
  - The force of the local particles is calculated.
  - The particles from every other process are gathered and the force between the local ones and the gathered ones is calculated.
  - The solution in this work uses a ring topology, where several worker processes form a pipeline, to gather the particles.