Deductive Verification of Parallel Programs Using Why3

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Outline

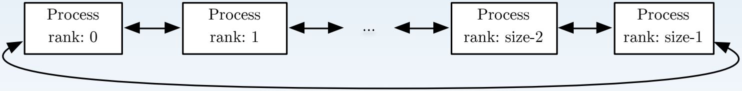
1. Introduction
2. Approach
3. Protocol language
4. Programming language
5. Results and conclusions

MPI

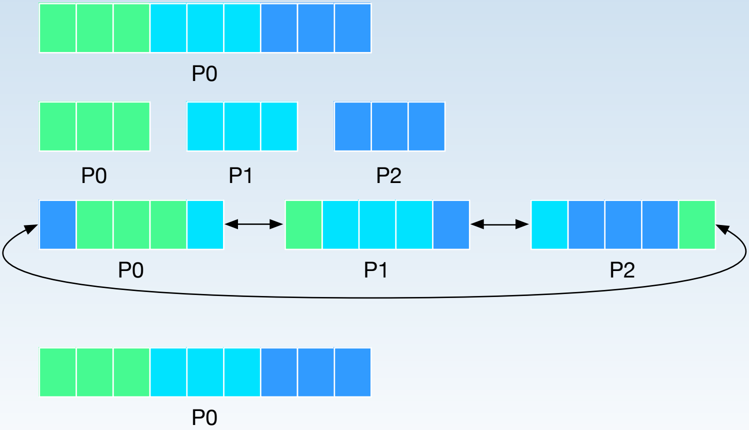
- Message-based specification for parallel computing
- Industry standard (C/Fortran libraries)
- Single-Program Multiple-Data (SPMD)
- Every process is issued a rank (process number)
- Point-to-point and collective communication
- Used for simulations that require a lot of computational power

Example: Finite differences

- Numeric method for solving differential equations
- The program starts with an initial solution X_0, and calculates X_1,X_2,X_3,... iteratively until a maximum number of iterations are executed
- Processes are organized in a ring topology



Example: Finite differences



Example: Finite differences

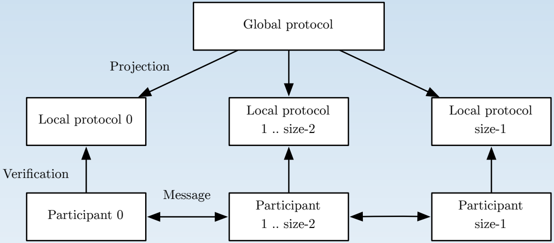
```c
int main(int argc, char** argv) {
    MPI_Init(&argc, &argv);
    MPI_Comm_rank(MPI_COMM_WORLD, &rank);
    MPI_Comm_size(MPI_COMM_WORLD, &size);
    MPI_Bcast(&n, 1, MPI_INT, 0, MPI_COMM_WORLD);
    MPI_Scatter(data, n/size, MPI_FLOAT, &local[1], n/size, MPI_FLOAT, 0, MPI_COMM_WORLD);
    int left = rank == 0 ? size - 1 : rank - 1;
    int right = rank == size - 1 ? 0 : rank + 1;
    for (iter = 1; i <= ITERATIONS; iter++) {
        MPI_Send(&local[1], 1, MPI_FLOAT, left, 0, MPI_COMM_WORLD);
        MPI_Send(&local[n/size], 1, MPI_FLOAT, right, 0, MPI_COMM_WORLD);
        MPI_Recv(&local[n/size+1], 1, MPI_FLOAT, right, 0, MPI_COMM_WORLD, &status);
        MPI_Recv(&local[0], 1, MPI_FLOAT, left, 0, MPI_COMM_WORLD, &status);
        // Computation is performed here, removed for simplicity
    }
    MPI_Reduce(&localErr, &globalErr, 1, MPI_FLOAT, MPI_MAX, 0, MPI_COMM_WORLD);
    MPI_Gather(&local[1], n/size, MPI_FLOAT, data, n/size, MPI_FLOAT, 0, MPI_COMM_WORLD);
    MPI_Finalize();
    return 0;
}
```

Does it deadlock? Is it communication type safe?

Challenges

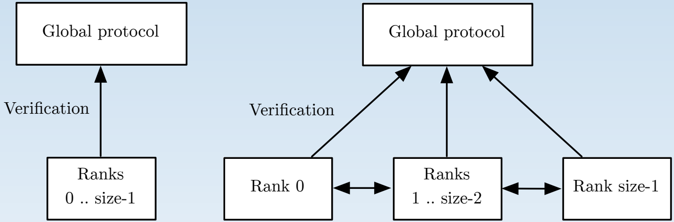
- Verifying parallel programs is difficult
  - State explosion problem
- Many verification tools only work at runtime
  - Dependent on the quality of the test set
  - Performance costs

Multi-party session types



- Theory for communication protocols
- Global protocol is projected for each process
- Properties guaranteed for program: absence of deadlocks and of communication errors
- Does not suffer from the state explosion problem

ParTypes

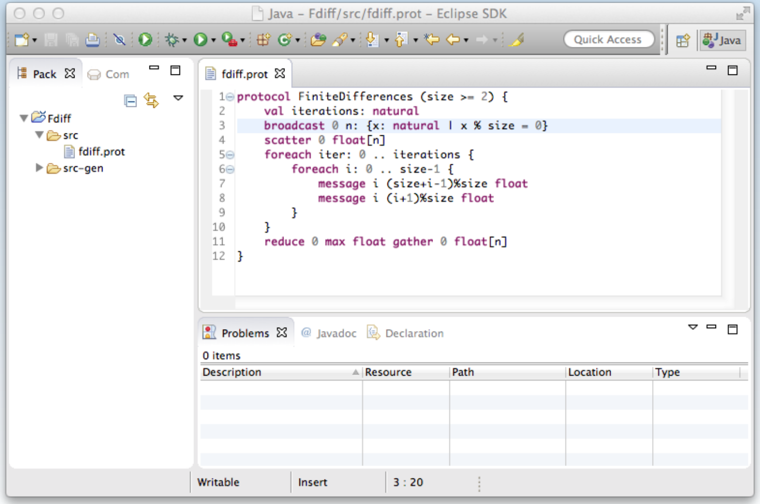


- Inspired by multi-party session types
- Point-to-point and collective communication, for loops and collective choices
- No separate projection step
- Can be used with both SPMD (like MPI) and MPMD programs

Protocol language

```
protocol FiniteDifferences (size >= 2) {
    val iterations: natural
    broadcast 0 n: {x: natural | x % size = 0}
    scatter 0 float[n]
    foreach iter: 0 .. iterations {
        foreach i: 0 .. size-1 {
            message i (size+i-1)%size float
            message i (i+1)%size float
        }
    }
    reduce 0 max float
    gather 0 float[n]
}
```

Protocol compiler (Eclipse plugin)



Foreach expansion

i	Loop body	Rank 0	Rank 1	...	Rank size-2	Rank size-1
0	message 0 size-1 message 0 1	send size-1 send 1	recv 0			recv 0
1	message 1 0 message 1 2	recv 1	send 0 send 2			
2	message 2 1 message 2 3		recv 2			
...						
size-2	message size-2 size-3 message size-2 size-1				send size-3 send size-1	recv size-1
size-1	message size-1 size-2 message size-1 0	recv size-1			recv size-1	send size-2 send 0

Example: Finite differences

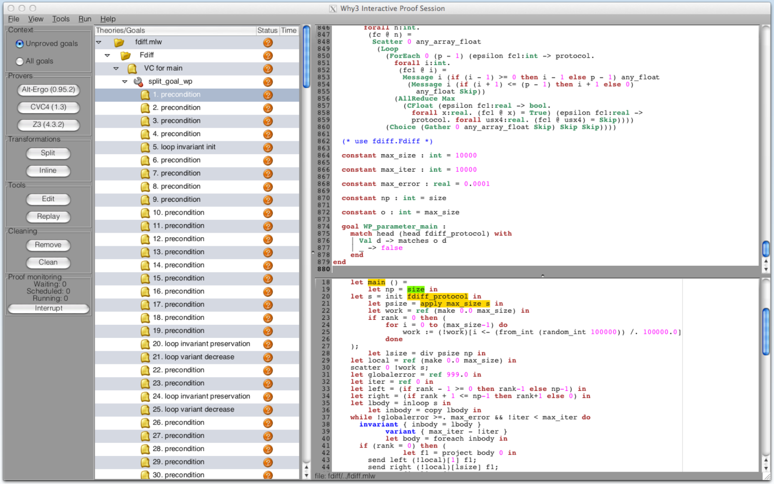
```
int main(int argc, char** argv) {
    MPI_Init(&argc, &argv);
    MPI_Comm_rank(MPI_COMM_WORLD, &rank);
    MPI_Comm_size(MPI_COMM_WORLD, &size);
    MPI_Bcast(&n, 1, MPI_INT, 0, MPI_COMM_WORLD);
    MPI_Scatter(data, n/size, MPI_FLOAT, &local[1], n/size, MPI_FLOAT, 0, MPI_COMM_WORLD);
    int left = rank == 0 ? size - 1 : rank - 1;
    int right = rank == size - 1 ? 0 : rank + 1;
    for (iter = 1; i <= ITERATIONS; iter++) {
        MPI_Send(&local[1], 1, MPI_FLOAT, left, 0, MPI_COMM_WORLD);
        MPI_Send(&local[n/size], 1, MPI_FLOAT, right, 0, MPI_COMM_WORLD);
        MPI_Recv(&local[n/size+1], 1, MPI_FLOAT, right, 0, MPI_COMM_WORLD, &status);
        MPI_Recv(&local[0], 1, MPI_FLOAT, left, 0, MPI_COMM_WORLD, &status);
        // Computation is performed here, removed for simplicity
    }
    MPI_Reduce(&localErr, &globalErr, 1, MPI_FLOAT, MPI_MAX, 0, MPI_COMM_WORLD);
    MPI_Gather(&local[1], n/size, MPI_FLOAT, data, n/size, MPI_FLOAT, 0, MPI_COMM_WORLD);
    MPI_Finalize();
    return 0;
}
```

This is going to deadlock

Why3

- Deductive software verification platform
- Specification language (Why) + programming language (WhyML)
- Verification conditions can be split in parts and proven with different SMT solvers (or with proof assistants such as Coq)
- Chosen to avoid the annotation overhead required for static verification of C/Fortran programs
- Experiment in programming methodology

Why3 IDE


Why3 Interactive Proof Session
File View Tools Run Help
Context
Unproved goals
All goals
Provers
Alt-Ergo (0.95.2)
CVC4 (1.3)
Z3 (4.3.2)
Transformations
Split
Inline
Tools
Edit
Replay
Cleaning
Remove
Clean
Proof monitoring
Waiting: 0
Scheduled: 0
Running: 0
Interrupt
Theories/Goals
Status
Time
fdiff.mlw
Fdiff
VC for main
split_goal_wp
1. precondition
5. loop invariant init
20. loop invariant preservation
21. loop variant decrease
constant max_size : int = 10000
constant max_iter : int = 10000
constant max_error : real = 0.0001
goal WP_parameter_main :
file: fdiff/../fdiff.mlw

Why3 theory for protocols

```
type protocol =
      Val datatype
    | Broadcast int datatype continuation
    | Scatter int datatype protocol
    | Gather int datatype protocol
    | Message int int datatype protocol
    | Reduce int op datatype protocol
    | Skip
    | AllGather datatype continuation
    | Foreach int int (cont int) protocol
    | AllReduce op datatype continuation
with
    op = Max | Min | Sum | ...
```

WhyML library

- Inspired by MPI
- Point-to-point and collective communication
- Primitives annotated with pre and post-conditions
- Verification guided by the protocol
- Requires program annotations for loops and choices

Finite differences in WhyML

```
let main () =
    let s = init fdiff_protocol in
    let iterations = apply 100000 s in
    let n = broadcast 0 input s in
    let local = scatter 0 work s in
    let left = (if rank > 0 then rank-1 else size-1) in
    let right = (if rank < size-1 then rank+1 else 0) in
    let inbody = expand (foreach s) rank in (* Annotation *)
    for iter = 1 to iterations do
        (* Loop body *)
    done;
    globalerror := reduce 0 Max !localerror s;
    gather 0 local s;
    isSkip s; (* Annotation *)
```

Fixed communication

```
let body = foreach inbody in (* Annotation *)
if (rank = 0) then (
   let f1 = expand body 0 in (* Annotation *)
   send left local[1] f1;
   send right local[n/size] f1; isSkip f1; (* Annotation *)
   let f2 = expand body 1 in (* Annotation *)
   local[n/size+1] <- recv right f2; isSkip f2; (* Annotation *)
   let f3 = expand body (np-1) in (* Annotation *)
   local[0] <- recv left f3; isSkip f3); (* Annotation *)
else if (rank = size-1) then (
   let f1 = expand body 0 in (* Annotation *)
   local[lsize+1] <- recv right f1; isSkip f1; (* Annotation *)
   let f2 = expand body (np-2) in (* Annotation *)
   local[0] <- recv left f2; isSkip f2; (* Annotation *)
   let f3 = expand body (np-1) in (* Annotation *)
   send left local[1] f3;
   send right local[lsize] f3; isSkip f3); (* Annotation *)
else (
   ...
isSkip inbody; (* Annotation *)
(* Computation is performed here, removed for simplicity *)
```

Fixed communication

```
let body = foreach inbody in (* Annotation *)
if (rank = 0) then (
    let f = expand body [size-1, 0, 1] in (* Annotation *)
    send left local[1] f;
    send right local[n/size] f;
    local[n/size+1] <- recv right f;
    local[0] <- recv left f;
    isSkip f); (* Annotation *)
else if (rank = size-1) then (
    let f = expand body [size-2, size-1, 0] in (* Annotation *)
    local[lsize+1] <- recv right f;
    local[0] <- recv left f;
    send left local[1] f;
    send right local[lsize] f;
    isSkip f); (* Annotation *)
else (
    ...
isSkip inbody; (* Annotation *)
(* Computation is performed here, removed for simplicity *)
```

Results: Annotation effort and verification time

Program	Why3 LOC	Why3 Anot	Ratio	VCC LOC	VCC Anot	Why3/VCC
Pi	33	6	18%	42	10	23%
Finite differences	86	29	33%	128	49	38%
Parallel dot	61	11	18%	99	30	30%

Program	Why3 Sub-Proofs	Why3 Time (s)	VCC Time (s)	Why3/VCC
Pi	27	1,6	2,4	66,7%
Finite differences	374	14,9	16,1	92,5%
Parallel dot	298	7.9	7,4	106,7%

Conclusions

- Our approach does not suffer from the state-explosion problem, typical of model checking
- Nor does it require any sort of runtime verification
- Results comparable with the closest tool, with less annotations and more verification options
- Many program annotations still required
- ... but can be simplified
- Protocols have the advantage of also serving as documentation

Future work

- Larger subset of MPI primitives (e.g. non-blocking, wildcard receive)
- Reduce annotation effort
- Adapt work for industry use
- Cover real-world applications

Thank you!

Questions?