ParTypes in Action

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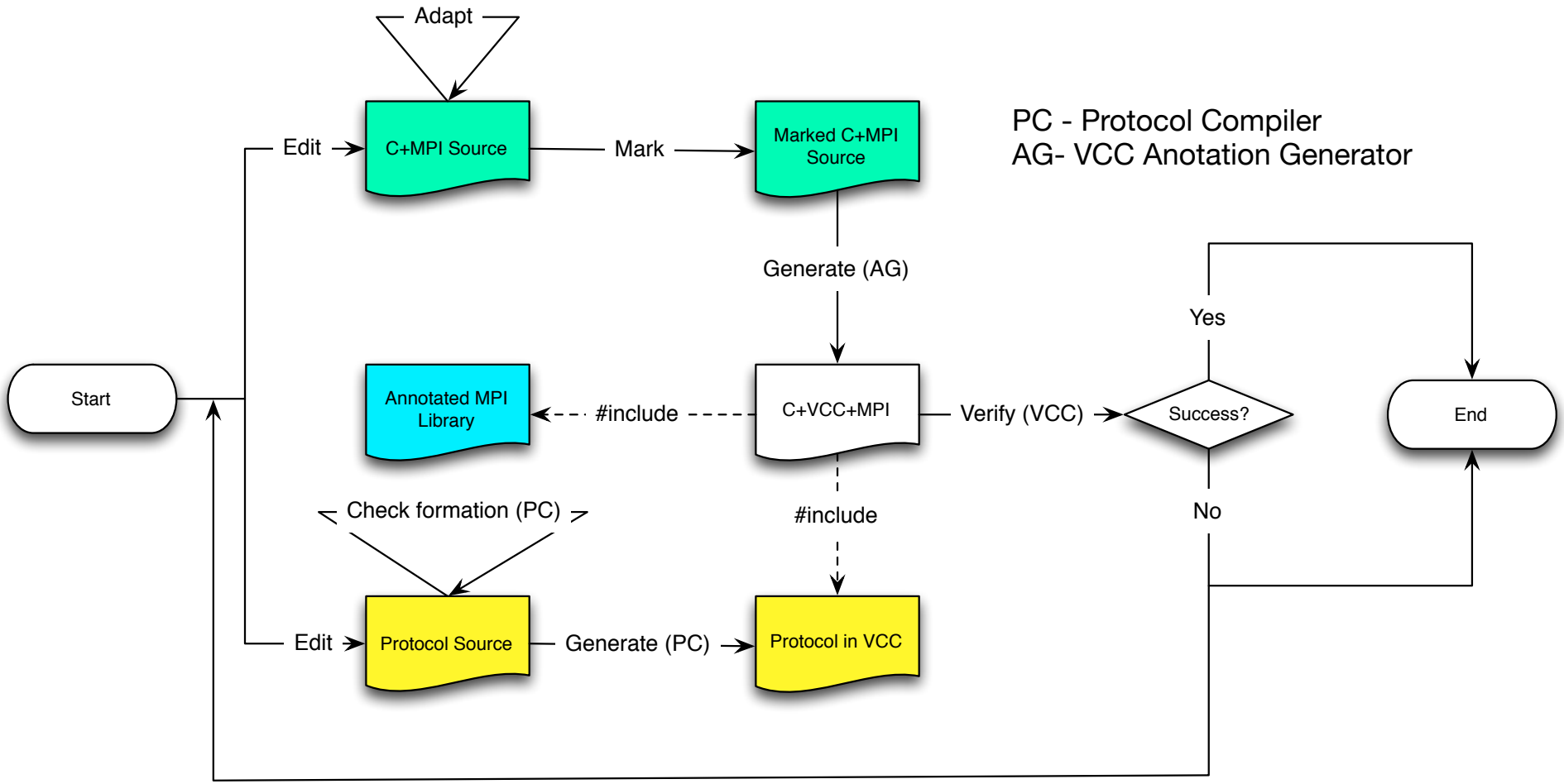
Betty meeting, March 18th, Valletta

Goal

Use (a variant of) MPST to verify that parallel C programs that use MPI (C+MPI) follow a specified protocol

Our approach



Crash course on MPI

- **C+MPI** adhere to the **Single Program Multiple Data** paradigm
  - The same program is deployed in every node
  - Distinct node behaviour is achieved by branching
- There are **hundreds of MPI primitives** for communication and synchronisation
  - This people care for performance
  - A broadcast is not a derived construct
    - Sending a message to every node is not the same as broadcasting a message to all nodes

MPI primitives we cover

- Start and stop MPI
  - **MPI_Init**
    - We start verifying the protocol
  - **MPI_Finalize**
    - We check that the protocol came to an end
- Obtain information about the environment
  - **MPI_Comm_rank**
    - Obtains the process id
  - **MPI_Comm_size**
    - Gives the number of participants in the run

MPI communication primitives

- Point-to-point communication
  - **MPI_Send** and **MPI_Recv** for direct communication between participants
- Collective communication
  - **MPI_Bcast**
  - **MPI_Scatter** and **MPI_Gatter**
  - **MPI_Reduce**
  - **MPI_All_reduce, MPI_All_gather**,…

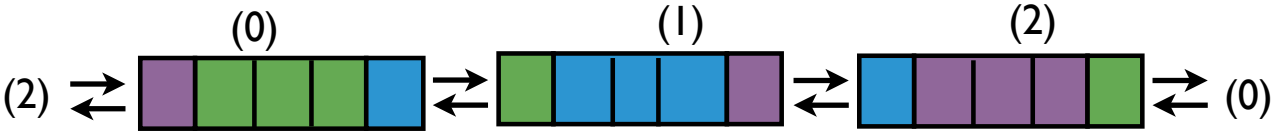
The Finite Differences (FD) example

Input data at rank 0

Scatter data for each participant

Each participant computes its finite differences

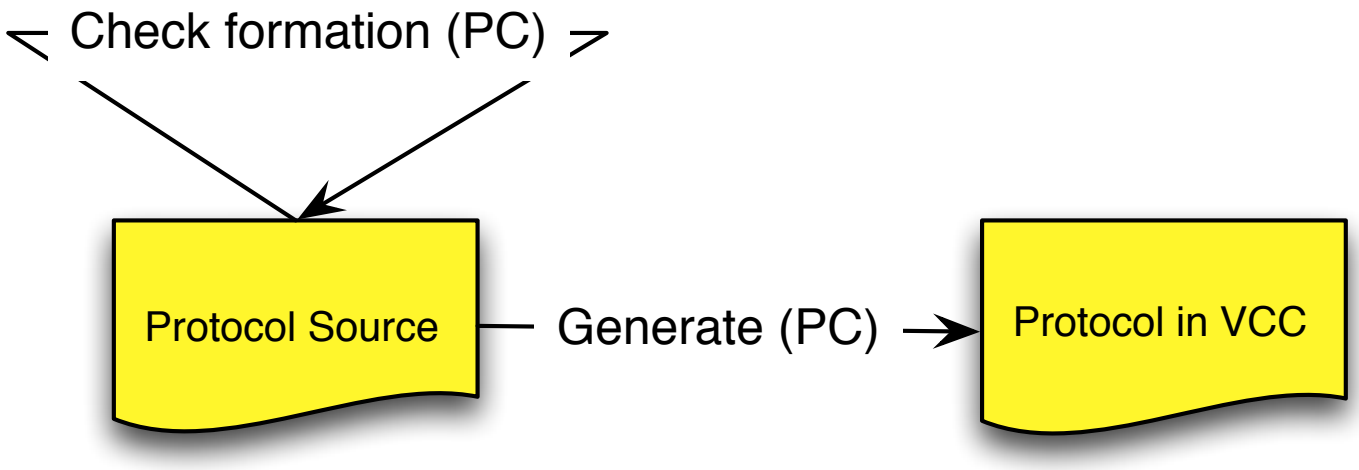
Send/recv boundary values to determine convergence



Perform global reduction (AllReduce) to compute the max error;
Loop if convergence criterion not met, up until to MAX_ITER

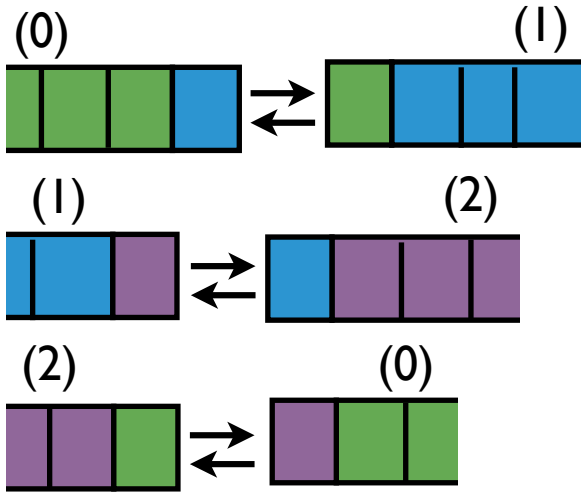
Gather the solution data at rank 0, if there was convergence.

First step: come up with a well-formed protocol



FD Protocol – Point-to-point comm.

message 0 1 **float**
message 1 0 **float**
message 1 2 **float**
message 2 1 **float**
message 2 0 **float**
message 0 2 **float**



Source rank

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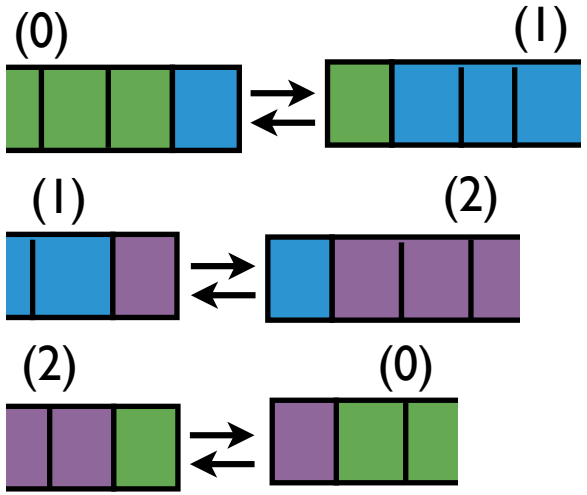


```
foreach i: 0 .. size-1 {
    // send right a floating point number
    message i (i=size-1 ? 0 : i+1) float
    // send left a floating point number
    message i (i=0 ? size-1 : i-1) float
}
```

Parameter of the protocol

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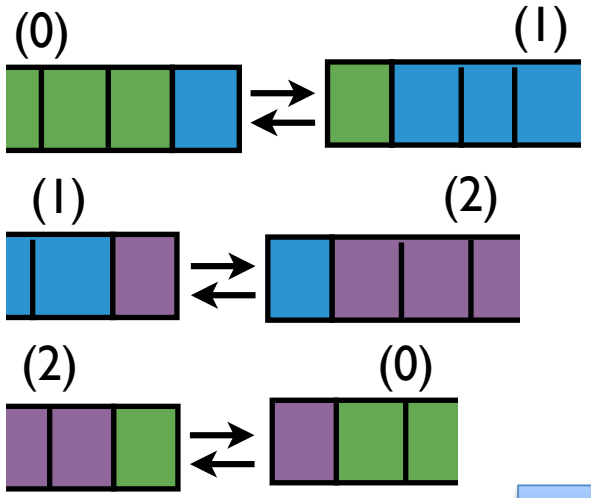


Parameter of the protocol

```
foreach iteration: 1 .. numIterations {
    foreach i: 0 .. size-1 {
        // send right a floating point number
        message i (i=size-1 ? 0 : i+1) float
        // send left a floating point number
        message i (i=0 ? size-1 : i-1) float
    }
}
```

FD Protocol – Collective comm.

Should be a multiple of the number of processes

// Process rank 0 divides the array among all processes
scatter 0 **float**[n]

… // point-to-point communication

// Each process proposes a floating point number;
// process rank 0 collects the max of these
reduce 0 **max float**
// Each process proposes its part of the solution,
// process rank 0 gathers these to form Xn, an array of length n
gather 0 **float**[n/**size**]

FD Protocol – Collective comm.

```
// The problem size must be a multiple of size, the number of processes
val numIterations: positive
// Process rank 0 broadcasts the maximum number of iterations
broadcast 0 n: {x: positive | x % size = 0}

// Process rank 0 divides the array among all processes
scatter 0 float[n]
...
ion

// Each process proposes a floating point number; process rank 0
// collects the max of these
reduce 0 max float
// Each process proposes its part of the solution,
// process rank 0 gathers these to form Xn, an array of length n
gather 0 float[n/size]
```

Introduces value **numIterations** in the protocol

Dependent Type specifying that **n** is a multiple of **size**

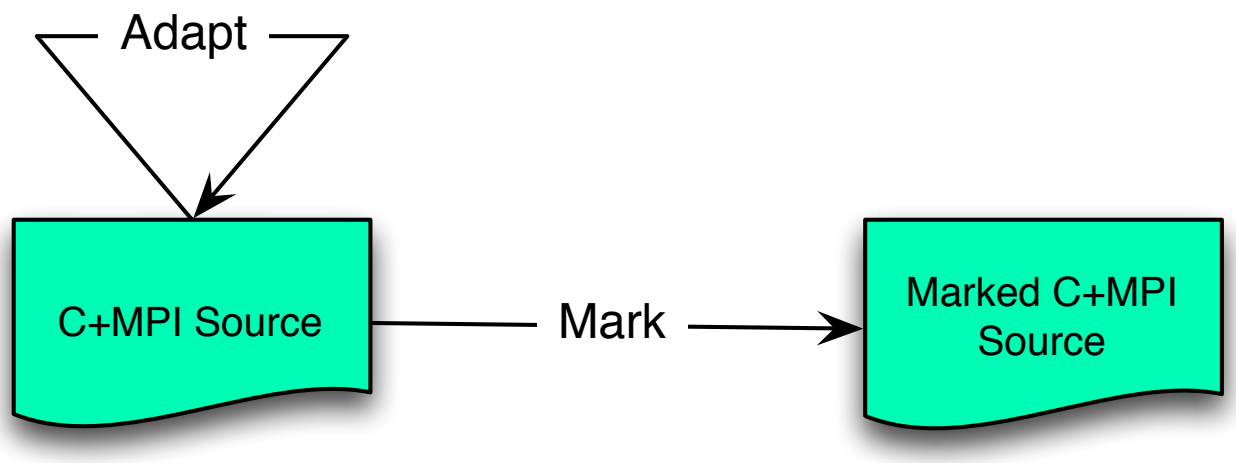
Demo time!

Let's play with an Eclipse plug-in that helps in writing well-formed protocol types

Also available online at:

http://gloss.di.fc.ul.pt/tryit/ParTypes

Second step:
Annotate the C+MPI code



Question:

- Does this C+MPI program follow the protocol?

Let's look at the code…

How do we annotate the code?!

1. We provide contracts for all MPI primitives
   - No need to annotate the primitives
2. We inject the Rank and the Size values
   - No need to explicit insert them in the protocol
3. Provide the actual value to insert for every val primitive
   - Annotate with _applyInt (or _applyIntArray…)

How do we annotate the code?!

4. Put a mark in the **for** loops that correspond to **foreach** in the protocol
   - The C language has only one for loop construct
   - The mark: _foreach
   - A tool expands it to VCC annotations
     - Clang LLVM plug-in not currently working ☹

Intuition about the for loop annotations

_foreach

```
for (iter=1; iter <= NUM_ITER; iter++) {
      // loop body
}
```

Expands to

```
_(ghost Cons _cfe0 = cons(_protocol, _rank))
_(ghost Protocol _fe0 = head(_cfe0))
_(assert foreachLower(_fe0) == 1)
_(assert foreachUpper(_fe0) == NUM_ITER)
_(ghost IntAbs _fe0Body = foreachBody(_fe0))
for (iter=1; iter <= NUM_ITER; iter++) {
    _(ghost _protocol = _fe0Body[iter])
    // loop body
    _(assert isSkip(_protocol,_rank))
 }
_(ghost _protocol = tail(_cfe0))
// Continuation of the program
```

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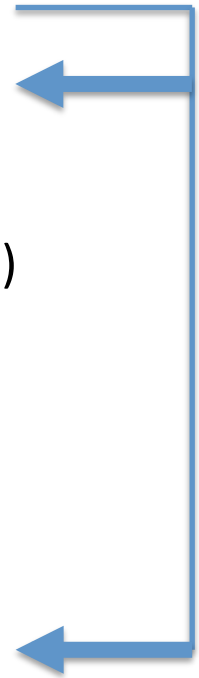

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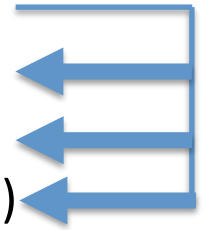

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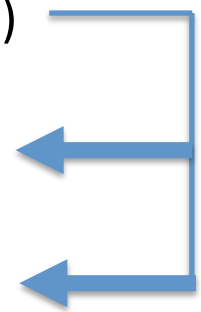
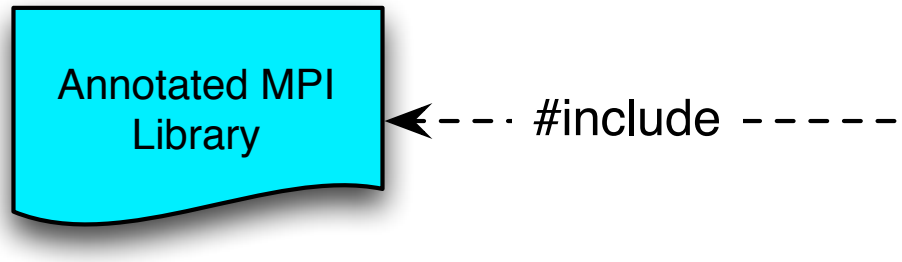


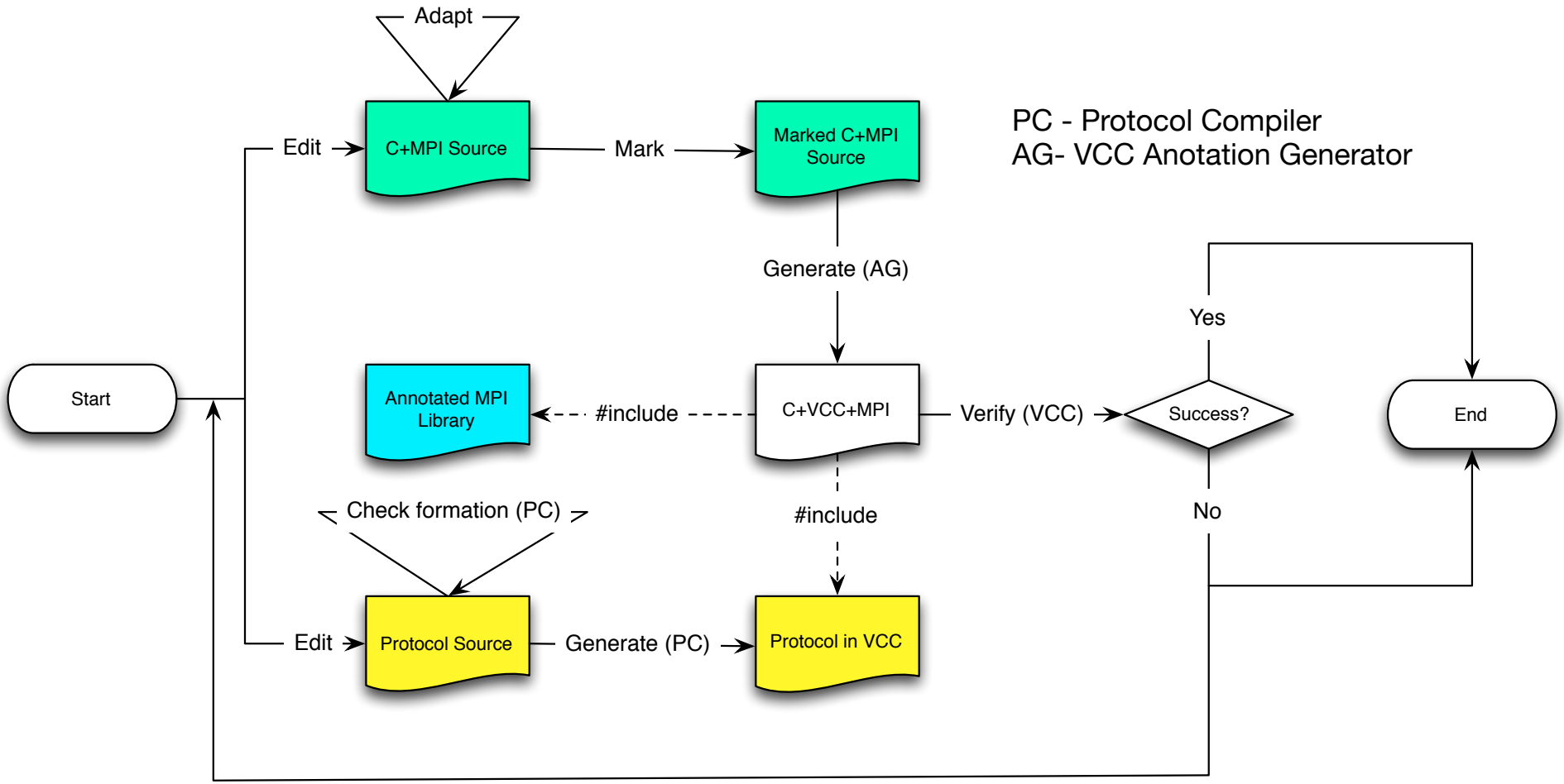
The ParTypes Theory



Eavesdrop VCC code

- MPI_InitAndFinalize.h
- MPI_CommRankAndSize.h
- MPI_SendAndRecv.h
- ParTypes.h

Our approach (Again)



Warning!

Beware of bugs in the above code; I have only proved it correct, not tried it.

Donald Knuth