Proving Safety of a Distributed Program

GEOFF MOORES

Way Ahead:

Program Orientation

Proof Structure + Methods

Lessons Learned + Takeaways

Code Inspection + Questions

Other Resources

Program Orientation

“Dining” Distributed Lock

State:
Thinking,
Hungry,
or Eating

To eat, a node must hold the fork.
Hungry nodes (waiting to eat, without fork) send ‘R’ request and wait for fork.
Thinking nodes must release fork on receipt of ‘R’.

Desired Safety Property: Two nodes should never ‘eat’ at the same time

Program Orientation

“Dining” Distributed Lock

```
    Node: State, Fork, Req, Done

    acquire () #eat
        if not Fork: State <- Hungry; send Req; Req <- False
        wait for Fork: State <- Eat

    release ()
        state <- Thinking
        if Req: send Fork; Fork <- False

recv_msg()
    while not Done: msg <- FIFO channel
    msg = Fork: Fork <- True
     “    = Req: Req <- True ; if Thinking: send Fork; Fork <- False
     “    = End: Done <- True
```

Assume atomicity of these rules. All state changes in acq, rel, and recv_msg will happen without any other state changes interfering.

Proof Structure

Represent a World with two Nodes in Coq

Capture all relevant state

Define the possible state transitions via atomic rules

Identify a set of Invariant Assertions:

- hold for every reachable state
- imply Safety:
  - Invariant(~ (Node A eating /\ Node B eating))

Proof Structure

Represent a World with two Nodes in Coq

Capture all relevant state

Define the possible state transitions via atomic rules

Identify a set of Invariant Assertions:

- ○ Number of forks (World) = 1
- ○ Node X Eating -> X has Fork
- ○ imply Safety:
    - ○ Invariant(~ (Node A eating /\ Node B eating))

Coq Methods

```
Definition initState (n: node) : nodeState :=
match n with
  | a => { --> 10 } & { S --> 0 ; F --> 1 ; R --> 0 ; D --> 0 ; W --> 0 }
  | b => { --> 10 } & { S --> 0 ; F --> 0 ; R --> 1 ; D --> 0 ; W --> 0 }
end.
```

```
Inductive msg : Type :=
  | req : msg
  | fork : msg
  | endm : msg
  | nullm : msg.
```

```
Inductive input : Type :=
  | acq : input
  | rel : input
  | endi : input
  | nulli : input.
```

```
Inductive world : Type :=
| spawn (l : localState) (inFlightMsgs : list packet) (trace : list externalEvent).
```

Coq Methods

```
Definition processInput (n : node)(i : input)(s : nodeState) : response :=
match (s W),(s D) with
  | 1,_ => r(s, ( [ ] ) )  (* Accept / process no input if the node is waiting *)
  | _,1 => r(s, ( [ ] ) )  (* Accept / process no input if the node is ended *)
  | _,_ =>
 match i with
   | acq => match (s F) with
          | 1 => r( (s & { S --> 2 }), ( [ ] ) )
          | _ => r( (s & { S --> 1 ; R --> 0 ; W --> 1 }), ( p((neighbor n),req) :: [ ] ) )
        end
   | rel => match (s F),(s R) with
      | 0, _ => r(s, ( [ ] ) ) (* Do nothing, invalid user call (rel without fork) *)
      | 1, 1 => r((s & { F --> 0 ; S --> 0 }), ( p((neighbor n),fork) :: [ ] ))
      | 1, _ => r((s & { S --> 0 }), ( [ ] ))
      | _ , _ => r(s, ( [ ] ) ) (* Do nothing, invalid node state *)
     end
   | endi => r((s & { D --> 1 }), ( p((neighbor n),endm) :: [ ] ))
   | nulli => r(s, ( [ ] ) )  (* nothing placeholder for our null input *)
 end
end.
```

Coq Methods

```
Definition processMsg (n : node)(m : msg)(s : nodeState) : response :=
match m with
  | req => match (s S),(s F) with
          | 0,1 => r( (s & { F --> 0 ; R --> 1 }), ( p((neighbor n),fork) :: [ ] ) )  (* comment *)
          | _,_ => r( (s & { R --> 1 }), ( [ ] ) )                                  (* optimization + proofing *)
       end
  | fork => (processInput n acq (s & { F --> 1 ; W --> 0 }))
  | endm => match s D with
          | 0 => r((s & { D --> 1 }), ( [ ] ))
          | _ => r(s, ( [ ] ) )
       end
  | nullm => r(s, ( [ ] ) )   (* nothing placeholder for our null message *)
end.
```

Coq Methods

```
Inductive reliable_step : world -> world -> Prop :=
 | step_input :  forall w i n st' ms,
     processInput n i ((localSt w) (key n)) = r(st', ms) ->
     reliable_step w
      ( W ( ((localSt w) & {(key n) --> st'}),  ( ms ++ (inFlightMsgs w)),
        ( (trace w) ++ [e(n, i)] ) ) )

 | step_msg :  forall w m n st' ms,
     nextMessage n (inFlightMsgs w) = (p(n,m)) ->
     processMsg n m ((localSt w) (key n)) = r(st', ms) ->
     reliable_step w
      ( W(  ((localSt w) & {(key n) --> st'}),  ( ms ++ ( pop (inFlightMsgs w) (p(n,m)) )),
        ( trace w ) ) ).

Definition reliable_step_star := clos_refl_trans_n1 _ reliable_step.

                        Definition reachable (w : world) : Prop := reliable_step_star initWorld w.
```

Coq Methods

```
Theorem bool_vars_bool : forall w, reachable w ->
  check_binvars_bin w bool_vars = true.     (* Comment on setup of world state *)

Theorem one_fork : forall w, reachable w -> forks w = 1.

Theorem eating_imp_fork : forall w N, reachable w ->
  N = A \/ N = B ->
  localSt w N S = 2 -> localSt w N F = 1.

Theorem one_eater : forall w, reachable w ->
  ~(localSt w A S = 2 /\ localSt w B S = 2).
```

Code Inspection + Questions

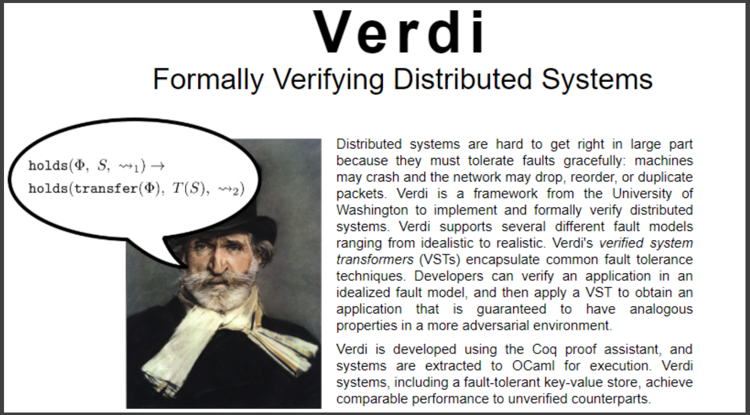
Other Resources: Verdi

"framework from the University of Washington to implement and formally verify distributed systems"

http://verdi.uwplse.org/

Open source, nice blog intros

Verified System Transformers – prove safety under certain conditions, will transform an application into another which holds under a different environment.



Verdi

Formally Verifying Distributed Systems

$\mathtt{holds}(\Phi,\ S,\ \leadsto_1) \rightarrow$
$\mathtt{holds}(\mathtt{transfer}(\Phi),\ T(S),\ \leadsto_2)$

Distributed systems are hard to get right in large part because they must tolerate faults gracefully: machines may crash and the network may drop, reorder, or duplicate packets. Verdi is a framework from the University of Washington to implement and formally verify distributed systems. Verdi supports several different fault models ranging from idealistic to realistic. Verdi's *verified system transformers* (VSTs) encapsulate common fault tolerance techniques. Developers can verify an application in an idealized fault model, and then apply a VST to obtain an application that is guaranteed to have analogous properties in a more adversarial environment.

Verdi is developed using the Coq proof assistant, and systems are extracted to OCaml for execution. Verdi systems, including a fault-tolerant key-value store, achieve comparable performance to unverified counterparts.