

CS 5/6110, Software Correctness Analysis, Spring 2021

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Overview of Lecture 19

- Projects
 - Please fix meeting this week (schedule online) to
 - Select/Refine projects
 - Seek resources
 - Projects will be the central aspect of your class
- Today's topic : Cache Coherence

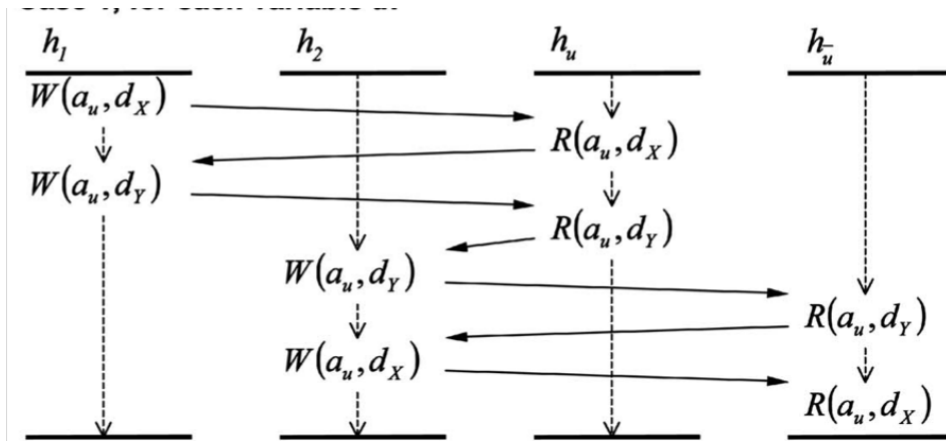
What is cache coherence?

- With shared-memory multiprocessors being the norm, we need a notion of sharing memory “as if it were one common area”
 - What does this mean?
 - Every write by P_i is readable by P_i as well as P_j where $i \neq j$
 - This is not precise-enough
 - A program can write more times to a location than once 😊
 - There could be multiple readers of a line
- So,
 - Formally define when write-events are observable by read-events that match

What is cache coherence?

- To define memory views as shared by multiple processors, we need to define a formal shared memory consistency model
- Coherence is one of the basic models
 - Each location has a latest data that every reader agrees on
 - Also known as “per-location sequential consistency”
- There are some interesting complexity results that help us understand coherence
 - Given a “finished execution trace”, checking coherence is NP-Complete
 - Very insightful proof by Jason Cantin et al
 - <https://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=1435343>

How a programmer sees coherence (Cantin paper)



Given four processes (or hardware threads) and reads/writes

Per location (“a_u” in this case) explain read-value outcomes.

Here we explain as if this interleaving took place.

The inability find such an explanation means the system is incoherent

Cool piece of encoding by Cantin: Given a 3SAT formula, he generates a shared memory execution such that the formula is SAT iff the execution is coherent!

If you are looking forward to challenging yourself in your growth as a professional CS researcher, you should not pass up such opportunities (follow such proofs). I can help if you are interested!

When you finish this, you’ll feel a faint glow around your head ;-)

ASIDE: There is a panel on “how to become a faculty” tomorrow. I’d say that solving these kinds of puzzles can help you!

i.e. before you get out of the SoC, try to get the union of knowledge of the SoC faculty

* Getting the intersection is a bad idea → you’ll get close to the null set ☺

Implementing coherence

- Snoopy-bus protocols (still present at smaller scales)
- Directory-based protocols (more scalable)
- See <https://www.morganclaypool.com/doi/pdf/10.2200/S00962ED2V01Y201910CAC049> for Thu's colloq speaker's book

Coherence Verification

- Given the complexity of coherence protocols, formal methods (model-checking mainly) is essential
- Let us take a look at an academic protocol called The German Protocol
- How does coherence verification scale?
 - Not well – today, large protocols take days to cover for one bit of data and 3 processors
 - Solutions
 - Derive cutoff bounds - Emerson and Kahlon
 - The bounds are large (7-8) and automatically computing bounds is not practical for large protocols
 - Do a parametric verification
 - Prove coherence for all "N" - N is the number of cores/threads
 - This involves modeling 2-3 nodes explicitly and involves a manual abstraction/refinement loop - called CEGAR
 - Counter-Example Guided Abstraction Refinement
 - Involves designer input of non-interference lemmas
 - Do formal synthesis
 - Dr. Nagarajan will be presenting this on Thu

Basics about Transition Systems

- Before we study the German protocol and how the parametric verification method I'm going to present works, let us discuss basic concepts about formal transition systems

Almost all specs for safety property checking look like this

- Based on Guarded Commands

Rule1: $g1 \implies a1$

Rule2: $g2 \implies a2$

...

RuleN: $gN \implies aN$

Invariant P

- Supported by tools such as Murphi (Stanford, Dill's group)
- Presents the behavior declaratively
 - Good for specifying "message packet" driven behaviors
 - Sequentially dependent actions can be strung using guards
- "Rule Sets" can specify behaviors across axes of symmetry
 - Processors, memory locations, etc.
- Simple and Universally Understood Semantics

Let us understand how we may safely transform such rule-based specifications (this is what we have to do in the parametric verification approach to be presented). The method is called the CMP method named after its inventors at Intel.

The name of the game - “invariants” !!

- Much like loop invariants, except
 - These are invariants pertaining to formal state-transition systems
- We are really talking about inductive invariants
 - Invariants P such that
 - They are true in the initial state
 - When held at a state, every transition rule preserves it
- This is a hugely important topic (invariant discovery)

Let us understand how we may safely transform such rule-based specifications. The first few will be warmups. Then the real thing!

- Observation: **Weakening a guard is sound**
- Suppose we add a disjunct as below (Cond1) and still manage to show that P is an invariant, then without adding Cond1, the result must still hold
 - Rule1: $g1 \vee \text{Cond1} \implies a1$**
 - Rule2: $g2 \implies a2$**
 - Invariant P**
- Reason: Rule1 fires more often with Cond1 added!
- **May get false alarms (P may fail if Rule1 fires spuriously)**
- For many “weak properties” P, **we can “get away” by guard weakening**
 - This is a standard abstraction, first proposed by Kurshan (E.g. removing a module that is driving this module, letting inputs “dangle”)
- BUT in the CMP method, we won’t do this - **rather we will do guard strengthening!**
- Except it is useful to know this disjunction property in thinking about certain steps of CMP

But... Guard Strengthening is, by itself, Unsound

- Strengthening a guard is not sound

Rule1: $g1 \wedge \text{Cond1} \implies a1$

Rule2: $g2 \implies a2$

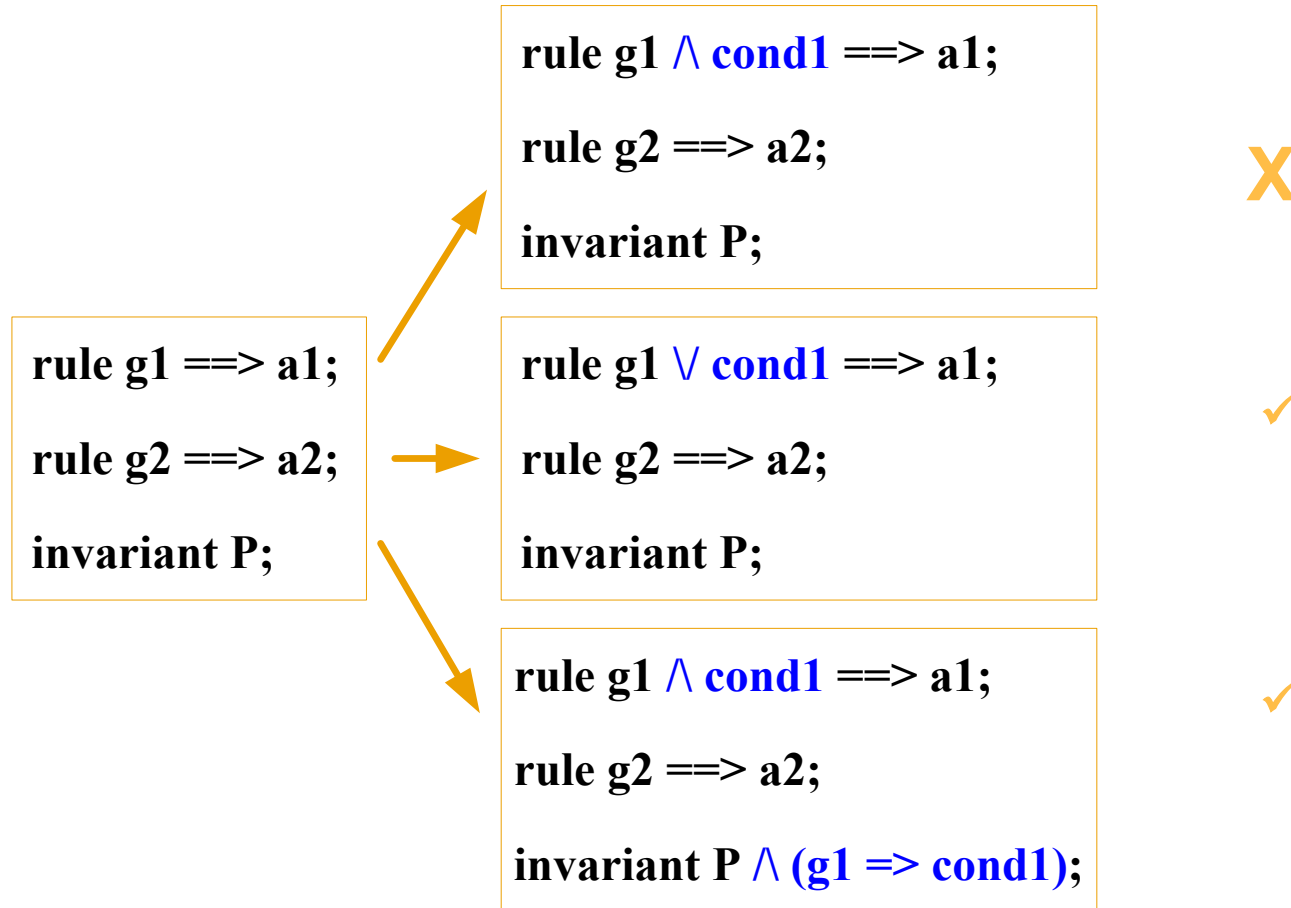
Invariant P

- Reason: Rule1 fires only when $g1 \wedge \text{Cond1}$
- So, less behaviors examined in checking P
 - Thus, verifying `_with_ Cond1` means nothing for verification without `Cond1`
- But hang on, there is more in the CMP method 😊

Guard Strengthening can be made sound, if the conjunct is implied by the guard

- This is sound
 - Rule1: $g1 \wedge \text{Cond1} \implies a1$
 - Rule2: $g2 \implies a2$
 - Invariant $P \wedge (g1 \implies \text{Cond1})$
- Reason: Rule1 fires only when $g1 \wedge \text{Cond1}$
- BUT, Cond1 is always implied by $g1$; we are showing $g1 \rightarrow \text{Cond1}$ is an invariant also, so no real loss of states over which Rule1 fires...
 - Call this “Guard Strengthening Supported by Lemma”
- Except, you are showing the invariant in the same modified system!
 - This is fine:
 - Initial state satisfies P , and also $(g1 \rightarrow \text{Cond1})$. Thus, whenever $g1$ is true in the initial state, Cond1 is an implied fact. So $g1 \wedge \text{Cond1}$ is like $g1$ by itself.
 - Thus “ $a1$ ” can be conducted in the initial state, to obtain the next set of states. (No change wrt $g2$ and $a2$, so they are like before.)
 - In general
 - At state t (by induction over time), we have P true and $(g1 \rightarrow \text{Cond1})$ true.
 - Thus, $g1$, when true, implies Cond1 at time t . Thus $g1 \wedge \text{Cond1}$ is like $g1$ (same truth status) at time t
 - Thus we can obtain the state at $t+1$ safely via “ $a1$ ”

Summary of Transformations so far (checkmark shows what's safe)



The CMP Approach

- Weaken to the Extreme
- Then Strengthen Back Just Enough (to pass all properties)

Weaken to the Extreme sounds crazy at first!

Rule1: $g1 \vee \text{True} \implies a1$

Rule2: $g2 \implies a2$

Invariant P

The transition system above

can be transformed to the one below without any issues

(except the proof of P being an invariant might not go through) – but that will be fixed momentarily

Rule1: $\text{True} \implies a1$

Rule2: $g2 \implies a2$

Invariant P

Strengthen Back Some

Rule1: $\text{True} \wedge C1 \implies a1$

Rule2: $g2 \implies a2$

Invariant P $\wedge (g1 \implies C1)$

*“Not Enough!” may be
the outcome of strengthening.
That is, while we added C1 back,
it may not be strong-enough.*

How to pick C1 will be discussed soon.

Strengthen Back More...

Rule1: $\text{True} \wedge C1 \implies a1$

Rule2: $g2 \implies a2$

Invariant $P \wedge g1 \implies C1$

“Not Enough!”



Rule1: $\text{True} \wedge C1 \wedge C2 \implies a1$

Rule2: $g2 \implies a2$

Invariant $P \wedge (g1 \implies C1) \wedge (g1 \implies C2)$

“OK, just right!”

A Variation of Guard Strengthening Supported by Lemma: Doing it in a meta-circular manner (i.e., the temporal induction I alluded to earlier...)

```
rule g1 ==> a1;  
rule g2 ==> a2;  
invariant P;
```



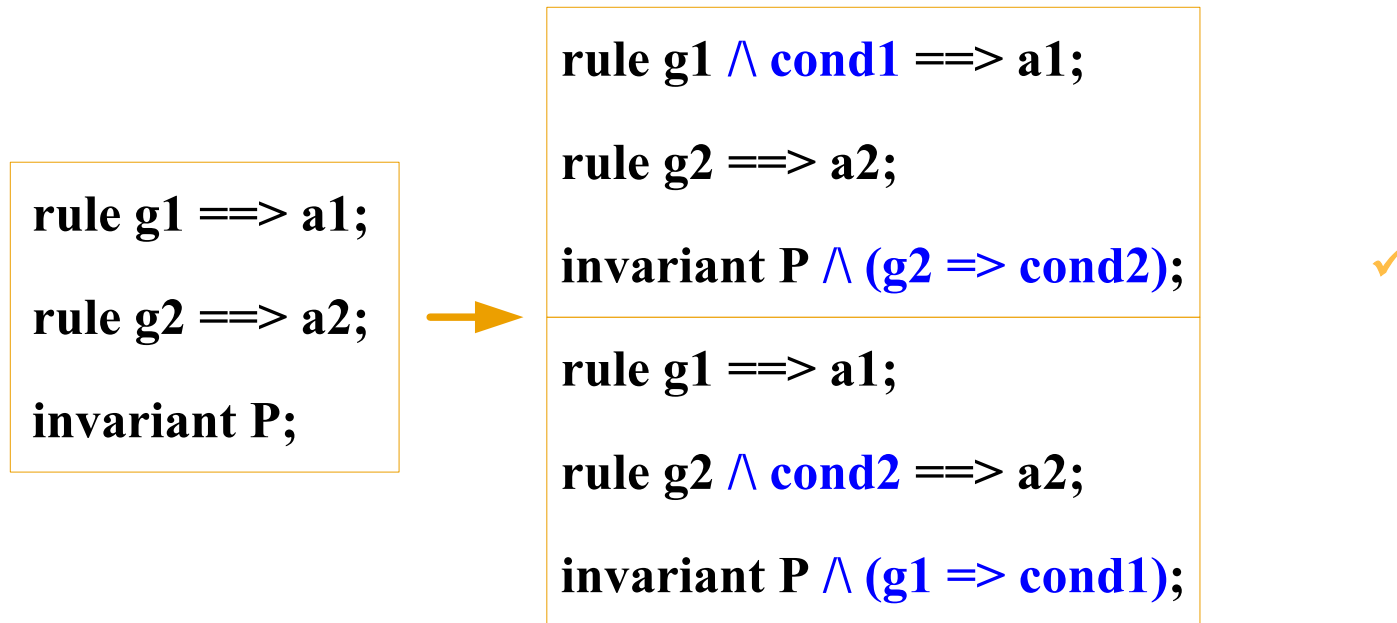
```
rule g1 ∧ cond1 ==> a1;  
rule g2 ==> a2;  
invariant P ∧ (g2 ==> cond2);  
rule g1 ==> a1;  
rule g2 ∧ cond2 ==> a2;  
invariant P ∧ (g1 ==> cond1);
```



This is the approach in our work

Now the secret: in the CMP method, the designer decouples all nodes beyond k (typically 2) explicitly modeled nodes. Then, brings back the $N-k$ nodes, but in ‘spirit’ - i.e., in terms of the non-interference conditions they must obey (note that “ N ” is a free parameter).

The C_i are thus the non-interference lemmas. Each is discovered upon seeing a counterexample, and then added back into the system! If the coherence invariant is proved (usually this happens), then you ended up having used a model-checker to prove a parametric theorem - which is a big deal!



This is the approach in our work

This method has been perfected at Intel and in production use!

- See <https://www.cs.utexas.edu/~hunt/FMCAD/FMCAD09/slides/talupur.pdf>
- <https://dl.acm.org/doi/pdf/10.5555/1517424.1517434>
- Designers write “protocol flow” diagrams as part of standard documentation
 - These are mined to obtain the non-interference lemmas
- See http://formalverification.cs.utah.edu/presentations/fmcad04_tutorial2/chou/ctchou-tutorial.pdf for details of how this is done
- NOTE the table-style specification recommended in the above tutorial at fmcad04 !!

We will now present highlights of the German Protocol to tell you how coherence protocols look like (but this is like a “hello world” of cache protocols)

- See `german.m` , `german.pdf` , and `abs-german.pdf` in the class directory
- We will note down some highlights in the coming slides

CMP highlights from paper of C-T Chou

abs-german.m

Mon Nov 1 20:00:47 2004

1

```
const ---- Configuration parameters ----
```

```
    NODE_NUM : 2;
```

```
    DATA_NUM : 2;
```

```
type ---- Type declarations ----
```

```
    NODE : scalarset(NODE_NUM);          -- NODE now consists of
```

```
                                           -- only concrete nodes
```

```
    DATA : scalarset(DATA_NUM);
```

```
    ABS_NODE : union {NODE, enum{Other}}; -- ABS_NODE consists of both
```

```
                                           -- concrete and abstract nodes
```

```
-----
```


CMP highlights from paper of C-T Chou

```
rule "ABS_RecvInvAck"  
  CurCmd != Empty & ExGntd = true  
==>  
  ExGntd := false; undefine MemData;  
end;
```

```
rule "ABS_RecvInvAck"  
  CurCmd != Empty & ExGntd = true &  
  forall j : NODE do  
    Cache[j].State != E & Chan2[j].Cmd != GntE  
  end  
==> ... end;
```

CMP highlights from paper of C-T Chou

which says that if home is ready to receive an `InvAck` from node `i` (note that the antecedent is simply the precondition of `RecvInvAck` plus the condition `ExGntd = true`, which is the only case when the `InvAck` is to have any effect in `ABS_RecvInvAck`), then every other node `j` must not have cache state `E` or a `GntE` in transit to it. (We are looking ahead a bit here: if the part about `GntE` is omitted from `Lemma_1`, the next counterexample will compel us to add it.) If `Lemma_1` is indeed true in `GERMAN`, then we will be justified to *refine* the offending abstract ruleset `ABS_RecvInvAck` as follows:

CMP highlights from paper of C-T Chou

We now do the model checking, which produces the following counterexample to **CtrlProp**: node n_1 sends a **ReqE** to home; home receives the **ReqE** and sends a **GntE** to node n_1 ; node n_1 receives the **GntE** and changes its cache state to **E**; node n_2 sends a **ReqS** to home; home receives the **ReqS** and is about to send an **Inv** to node n_1 ; but suddenly home receives a bogus **InvAck** from **Other** (via **ABS_RecvInvAck**), which causes home to reset **ExGntd** and send a **GntS** to node n_2 ; node n_2 receives the **GntS** and changes its cache state to **S**, which violates **CtrlProp** because node n_1 is still in **E**. The bogus **InvAck** from **Other** is clearly where things start to go wrong: if there is a node in **E**, home should not receive **InvAck** from any other node. We can capture this desired property as a *noninterference lemma*:

```
invariant "Lemma_1"
  forall i : NODE do
    Chan3[i].Cmd = InvAck & CurCmd != Empty & ExGntd = true ->
      forall j : NODE do
        j != i -> Cache[j].State != E & Chan2[j].Cmd != GntE
      end
  end end;
```

German protocol

```
const -- configuration parameters --
NODE_NUM : 6;
DATA_NUM : 2;

type -- type decl --

NODE : scalarset(NODE_NUM);
DATA : scalarset(DATA_NUM);

CACHE_STATE : enum {I, S, E};
CACHE : record State : CACHE_STATE; Data : DATA; end;

MSG_CMD : enum {Empty, ReqS, ReqE, Inv, InvAck, GntS, GntE};
MSG : record Cmd: MSG_CMD; Data : DATA; end;
```

German protocol

```
var -- state variables --

Cache : array [NODE] of CACHE;      -- Caches

Chan1 : array [NODE] of MSG;         -- Channels for Req*
Chan2 : array [NODE] of MSG;         -- Channels for Gnt* and Inv
Chan3 : array [NODE] of MSG;         -- Channels for InvAck

InvSet : array [NODE] of boolean;    -- Nodes to be invalidated
ShrSet : array [NODE] of boolean;    -- Nodes having S or E copies
ExGntd : boolean;                   -- E copy has been granted
CurCmd : MSG_CMD;                  -- Current request command
CurPtr : NODE;                     -- Current request node
MemData : DATA;                    -- Memory data
AuxData : DATA;                    -- Latest value of cache line
```

German protocol

```
-- Initial States --  
  
ruleset d : DATA do startstate "init"  
--  
-- All nodes: init all cmd channels to be empty, Cache States I,  
-- the set of nodes to be invalidated is empty  
-- and nodes having S or E copies empty  
--  
  for i : NODE do  
    Chan1[i].Cmd := Empty;  
    Chan2[i].Cmd := Empty;  
    Chan3[i].Cmd := Empty;  
    Cache[i].State := I;  
    InvSet[i] := false;  
    ShrSet[i] := false;  
  end;  
  ExGntd := false;  
  CurCmd := Empty;  
  MemData := d;  
  AuxData := d;  
end end;
```

German protocol

```
-- State Transitions --
-----
ruleset i : NODE do
-- Any node with cmd req channel empty and cache I can request ReqS
  rule "SendReqS"
    Chan1[i].Cmd = Empty &
    Cache[i].State = I
    ==>
    Chan1[i].Cmd := ReqS; -- raises "ReqS" semaphore
  end
end;
```

German protocol

```
-----  
ruleset i : NODE do  
-- Any node with cmd req channel empty and cache I/S can request ReqE  
rule "SendReqE"  
  Chan1[i].Cmd = Empty &  
  (Cache[i].State = I |  
   Cache[i].State = S)  
  ==>  
  Chan1[i].Cmd := ReqE; -- raises "ReqE" semaphore  
end  
end;
```


German protocol

```
-----
ruleset i : NODE do
-- For any node that is waiting with ReqS requested, with CurCmd Empty
-- we set CurCmd to ReqS on behalf of node i (setting CurPtr to point to it).
-- Then void Chan1 empty.
-- Now Set the nodes to be invalidated to the nodes having S or E copies.
  rule "RecvReqS" -- prep action of dir ctrlr
    CurCmd = Empty &
    Chan1[i].Cmd = ReqS
    ==>
    CurCmd := ReqS;
    CurPtr := i; -- who sent me ReqS
    Chan1[i].Cmd := Empty; -- drain its cmd
    for j : NODE do InvSet[j] := ShrSet[j] end; -- inv = nodes with S/E
  end
end;
```

German protocol

```
-----
ruleset i : NODE do
-- For any node that is waiting with ReqE requested, with CurCmd Empty
-- we set CurCmd to ReqE on behalf of node i (setting CurPtr to point to it).
-- Then void Chan1 empty.
-- Now Set the nodes to be invalidated to the nodes having S or E copies.
  rule "RecvReqE"
    CurCmd = Empty &
    Chan1[i].Cmd = ReqE
    ==>
    CurCmd := ReqE;
    CurPtr := i; -- who sent me ReqE
    Chan1[i].Cmd := Empty; -- drain its cmd
    for j : NODE do InvSet[j] := ShrSet[j] end; -- inv = nodes with S/E
  end
end;
```

German protocol

```
-----
ruleset i : NODE do
-- For every node with Chan2 Cmd empty and InvSet true (node to be invalidated)
-- and if CurCmd is ReqE or (ReqS with ExGnt true), then
-- void Chan2 Cmd to Inv, and remove node i from InvSet (invalidation already set out)
rule "SendInv"
  Chan2[i].Cmd = Empty &
  InvSet[i] = true & -- Gnt* and Inv channel
  ( CurCmd = ReqE | -- DC: curcmd = E
    CurCmd = ReqS & ExGntd = true ) -- DC: curcmd = S & ExGntd
==>
  Chan2[i].Cmd := Inv; -- fill Chan2 with Inv
  InvSet[i] := false;
end
end;
```

German protocol

```
-----  
--  
-- When a node gets invalidated, it acks, and when it was E  
-- then the node (i) coughs up its cache data into Chan3  
-- Then cache state is I and undefine Cache Data  
--  
ruleset i : NODE do  
  rule "SendInvAck"  
    Chan2[i].Cmd = Inv &  
    Chan3[i].Cmd = Empty  
    ==>  
    Chan2[i].Cmd := Empty;  
    Chan3[i].Cmd := InvAck;  
    if (Cache[i].State = E) then Chan3[i].Data := Cache[i].Data end;  
    Cache[i].State := I; undefine Cache[i].Data;  
  end  
end;
```

German protocol

```
-----  
ruleset i : NODE do  
  rule "RecvInvAck"  
    Chan3[i].Cmd = InvAck &  
    CurCmd != Empty  
    ==>  
    Chan3[i].Cmd := Empty;  
    ShrSet[i] := false;  
    if (ExGntd = true) then ExGntd := false;  
    MemData := Chan3[i].Data;  
    undefine Chan3[i].Data end;  
  end  
end;
```

German protocol

```
-----  
ruleset i : NODE do  
  rule "SendGntS"  
    CurCmd = ReqS &  
    CurPtr = i &  
    Chan2[i].Cmd = Empty &  
    ExGntd = false  
    ==>  
    Chan2[i].Cmd := GntS;  
    Chan2[i].Data := MemData;  
    ShrSet[i] := true;  
    CurCmd := Empty;  
    undefine CurPtr;  
  end  
end;
```

German protocol

```
-----
ruleset i : NODE do
  rule "SendGntE"
    CurCmd = ReqE &
    CurPtr = i &
    Chan2[i].Cmd = Empty &
    ExGntd = false &
    forall j : NODE do ShrSet[j] = false end -- nodes having S or E status
    ==>
    Chan2[i].Cmd := GntE;
    Chan2[i].Data := MemData;
    ShrSet[i] := true;
    ExGntd := true;
    CurCmd := Empty;
    undefine CurPtr;
  end
end;
```

German protocol

```
-----  
ruleset i : NODE do  
  rule "RecvGntS"  
    Chan2[i].Cmd = GntS  
    ==>  
    Cache[i].State := S;  
    Cache[i].Data := Chan2[i].Data;  
    Chan2[i].Cmd := Empty;  
    undefine Chan2[i].Data;  
  end  
end;
```


German protocol

```
-----  
ruleset i : NODE do  
  rule "RecvGntE"  
    Chan2[i].Cmd = GntE  
    ==>  
    Cache[i].State := E;  
    Cache[i].Data := Chan2[i].Data;  
    Chan2[i].Cmd := Empty;  
    undefine Chan2[i].Data;  
  end  
end;
```

German protocol

```
-----  
ruleset i : NODE;          -- for every node i  
    d : DATA              -- for every data d  
do  
    rule "Store"  
        Cache[i].State = E -- if node is in E  
        ==>  
        Cache[i].Data := d; -- store d into Cache[i].Data  
        AuxData := d;       -- Also update latest cache line value  
    end                    -- The node in E can get any "D" value  
end;  
-----
```

Invariants of the German protocol

---- Invariant properties ----

invariant "CtrlProp"

forall i : NODE do

forall j : NODE do

i!=j ->

(Cache[i].State = E -> Cache[j].State = I) &

(Cache[i].State = S -> Cache[j].State = I |
Cache[j].State = S)

end

end;

invariant "DataProp"

(ExGntd = false -> MemData = AuxData) &

forall i : NODE

do Cache[i].State != I ->

Cache[i].Data = AuxData

end;
