# Easy Parameterized Verification of Biphase Mark and 8N1 Protocols

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[1]Some of this work was performed while this author was at the NASA Langley Research Center.

# Prelude

- This paper was published in TACAS, 2006.
- Extensions to this work were presented at DCC, 2006.
- This paper is an *application* of SMT possibly of interest to the PDPAR community because
  - It is a real-world verification with an 2-3 orders-of-magnitude simpler proof than previously-published proofs.
  - It demonstrates the power of SMT-enabled infinite-state induction.

*Warning: not a theory paper.*

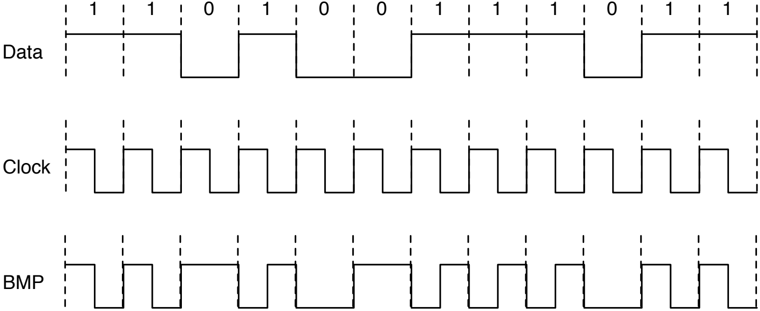
# Application: Biphase Mark and 8N1 Protocols

- Biphase Mark Protocol (BMP)

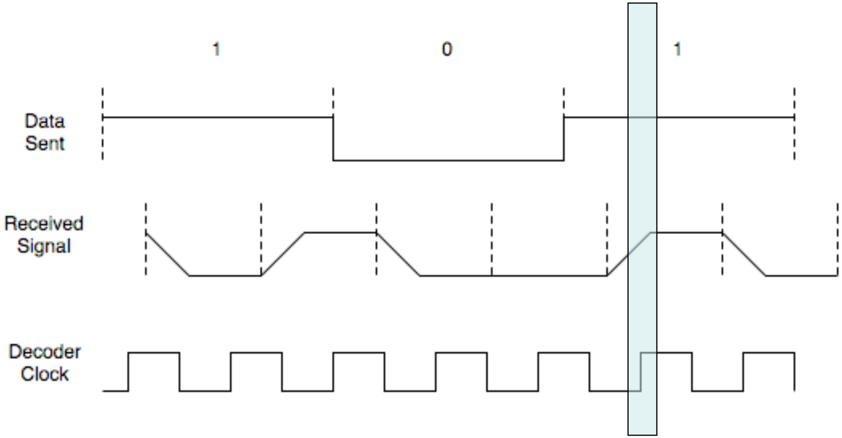
  Used for data transmission in CDs and ethernet, for example.
- 8N1 Protocol

  Used in UARTs.

# Biphase Mark Protocol (BMP)



# Unreliable Sampling



# What Makes This Hard?

- We're crossing clock domains.
  - . . . With different phases, frequencies, and settling times and stable periods
  - . . . And error in these parameters due to jitter, signal skew, distortion, etc.
- And we want a *parameterized* verification.
- So we want to prove correct behavior under general constrains on the parameters.

# An Informal Comparison to the Past

- One PVS effort required 37 invariants and 4000 individual proof directives (before "optimizing" the proofs).
- Ours required five invariants, each of which is proved automatically by SAL.
- In the other PVS effort, it takes 5 hours for PVS to *check* the manually-generated proof scripts.
- Ours requires just a few minutes to *generate* the proofs.
- J. Moore reports the BMP verification as one of his "best ideas" in his career.[2]
- Our initial effort in SAL took a couple days.
  ...And we found a significant bug in a UART application note.

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[2] http://www.cs.utexas.edu/users/moore/best-ideas/

# What's Needed for Easy Parameterized Verification?

Induction via infinite-state bounded model-checking

- Expressive modeling language (SAL)
- Easy generation of invariants
  - *k*-induction
  - Disjunctive invariants

# Induction (over Transition Systems)

Let $\langle S, S^0, \rightarrow \rangle$ be a transition system.

For safety property $P$, show

- **Base**: If $s \in S^0$, then $P(s)$;
- **Induction Step**: If $P(s)$ and $s \rightarrow s'$, then $P(s')$.

Conclude that for all reachable $s$, $P(s)$.

# $k$-Induction Generalization

Generalize from single transitions to trajectories of fixed length.

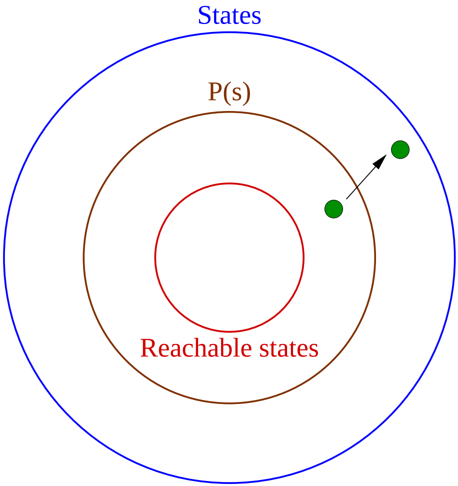
For safety property $P$, show

- **Base**: If $s_0 \in S^0$, then for all trajectories $s_0 \rightarrow s_1 \rightarrow \ldots \rightarrow s_k$, $P(s_i)$ for $0 \leq i \leq k$;
- **IS**: For all trajectories $s_0 \rightarrow s_1 \rightarrow \ldots \rightarrow s_k$, If $P(s_i)$ for $0 \leq i \leq k-1$, then $P(s_k)$.

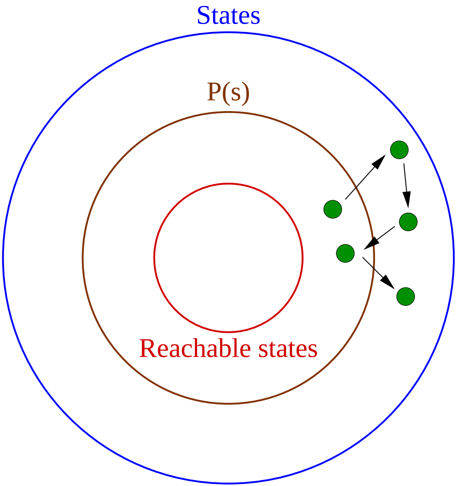
Conclude that for all reachable $s$, $P(s)$.

Induction is the special case when $k = 1$.

# Induction



# $k$-Induction



# $k$-Induction

```
counter1: MODULE =
  BEGIN
    LOCAL cnt : INTEGER
    LOCAL b   : BOOLEAN
    INITIALIZATION
      cnt = 0;
      b = TRUE
    TRANSITION
      [       b --> cnt' = cnt + 2;
                    b' = NOT b
        [] ELSE --> cnt' = cnt - 1;
                    b' = NOT b
      ] END;

 Thm1 : THEOREM counter1 |- G(cnt >= 0);
```

Circuit behavior:

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| b = | T | F | T | F | T | F | ... |
| cnt = | 0 | 2 | 1 | 3 | 2 | 4 | ... |

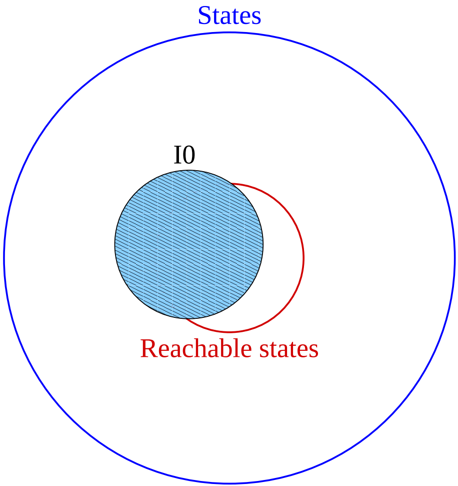
Thm1 fails for $k = 1$, succeeds for $k = 2$ (why?).

# Disjunctive Invariants

*Disjunctive Invariants* to weaken safety properties until they become invariant.

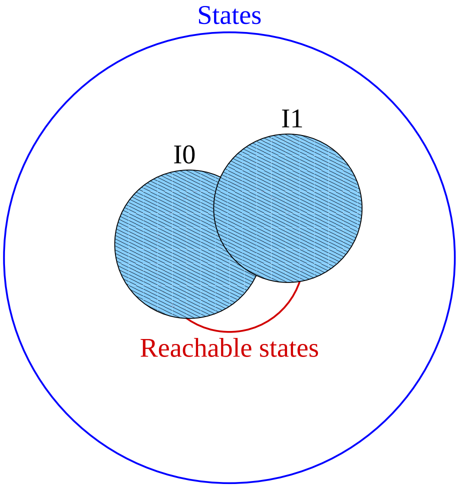
- General and interactive.
- Developed by Pneuli & Rushby, independently.
- A disjunctive invariant can be built iteratively to cover the reachable states from the counterexamples returned by SAL for the hypothesized invariant being verified.

# Initial Attempt



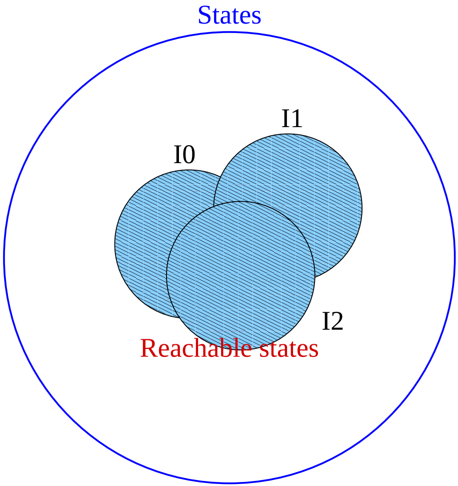

$I0$ Not invariant...

# Generalization




$I0 \vee I1$ Almost...

# Invariant




$I0 \vee I1 \vee I2$ There we go!

# Disjunctive Invariants

```
counter1: MODULE =
  BEGIN
    LOCAL cnt : INTEGER
    LOCAL b   : BOOLEAN
    INITIALIZATION
      cnt = 0;
      b = TRUE
    TRANSITION
      [       b --> cnt' = (-1 * cnt) - 1;
                    b' = NOT b
        [] ELSE --> cnt' = (-1 * cnt) + 1;
                    b' = NOT b
      ] END;

 Thm2a : THEOREM counter2 |- G(b AND cnt >= 0);
```

Circuit behavior:

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| b = | T | F | T | F | T | F | ... |
| cnt = | 0 | -1 | 2 | -3 | 4 | -5 | ... |

Thm2a is our initial approximation ...

# Disjunctive Invariants

... And fails

SAL's output:

```
  Counterexample:

Step 0:
--- System Variables (assignments) ---
cnt = 0
b = true
------------------------

Step 1:
--- System Variables (assignments) ---
cnt = -1
b = false
------------------------
```

```
   Thm2b : THEOREM counter2 |- G(   (b AND cnt >= 0)
                                 OR (NOT b AND cnt < 0));
```

Thm2b succeeds.

# Paper Addendum and Challenge

- We were able to complete fully-parameterized proofs of both BMP and the 8N1 Protocol.
- We leave it as a challenge to the real-time model-checking communities, including TReX, HyTech, and Uppal, to reproduce these results for both protocols.

# Current Work: Temporal Refinement in SAL

Infinite-state *k*-induction is great, but...

It's not compositional (between the real-time protocols and synchronous hardware). Idea:

- Start with a finite-state model of the cross-domain protocol.
- Prove safety properties over the finite-state model (using SMC).
- Prove that the real-time model is an implementation of the finite-state one.
  - Abadi-Lamport style refinement over the guarded transitions.[3]
  - Relatively easy for this class of protocols – show refinement of the guards of the guarded transitions.

[3] The Existence of Refinement Mappings, *Theor. Comp. Sci.*, 82(2), 1991.

# Final Thoughts on Real-Time Verification Using SMT

We use what Leslie Lamport calls an *explicit-time* model[4] for real-time verification without a real-time model-checker.
Some benefits:

- No new languages and simple semantics.
- SMT is extensible (the theory of arrays, lists, uninterpreted functions, etc.)
- Compositional with non real-time specifications.

[4] *CHARME, 2005*

# Getting our Specifications and SAL

## BMP and 8N1 Specs & Proofs

`http://www.cs.indiana.edu/~lepike/pub_pages/bmp.html`

Google: Brown Pike BMP 8N1

## SRI's SAL

`http://sal.csl.sri.com`

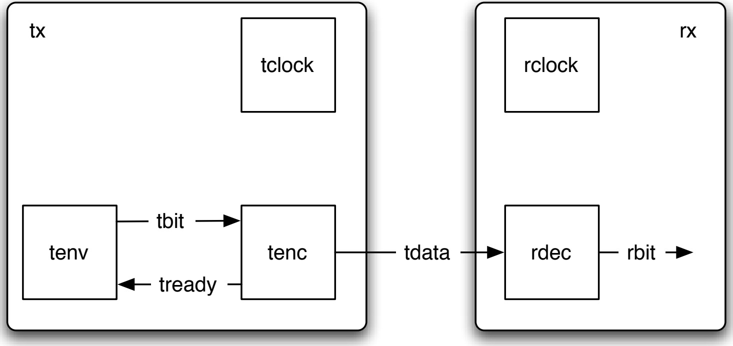
Google: SRI SAL

. . .More coming (email if interested).

Thanks to John Rushby, Leonardo de Moura, and our TACAS referees for their comments.

# Appendix.

# General System Architecture




Just the encoder (`tenc`), decoder (`rdec`), and constraints are protocol-specific.

# Timeout Automata[5] (Semantics)

An *explicit* real-time model.

Construct a transition system $\langle S, S^0, \rightarrow \rangle$:

- A set of states $S$, mapping state variables to values.
- A set of initial states $S^0 \subseteq S$.
- A partition on the state variables for $S$, and associated with each partition is a timeout $t \in \mathbb{R}$.
- A set of transition relations, such that $\rightarrow_t$ associated with timeout $t$ and is enabled if for all timeouts $t'$, $t \leq t'$ ($\rightarrow$ is the union of $\rightarrow_t$ for all $t$.)

[5] B. Dutertre and M. Sorea. Timed systems in SAL. *SRI TR*, 2004.

# Parameterized Timing Constraints

SMT allows for *parameterized* proofs of correctness. The following are the parameters from the BMP verification:

```
TIME : TYPE = REAL;

TPERIOD      :     { x : REAL | 0 < x };
TSETTLE      :     { x : REAL | 0 <= x AND x < TPERIOD };
TSTABLE      :     TIME = TPERIOD - TSETTLE;

RSCANMIN :  { x: TIME | 0 < x };
RSCANMAX :  { x: TIME | RSCANMIN <= x AND x < TPERIOD - TSETTLE};
RSAMPMIN :  { x : TIME | TPERIOD + TSETTLE < x };
RSAMPMAX :  { x : TIME | RSAMPMIN <= x AND
                         x < 2 * TPERIOD - TSETTLE - RSCANMAX };
```

# SAL's Language

- Typed with predicate subtypes.
- Infinite types (e.g., `INTEGER` and `REAL`).
- Synchronous (lock-step) and asynchronous (interleaving) composition (`||` and `[]`, respectively).
- Quantification (over finite types).
- Recursion (over finite types).