Formal Verification of LabVIEW Programs with ACL2: Progress Report on Handling State

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OUTLINE

- Background
- The problem of state
- Hierarchy (work in progress)

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- **Background**
  - **Brief history**
  - **ACL2 representation**
  - **Main verification idea**
- The problem of state
- Hierarchy (work in progress)

BRIEF HISTORY

- Jeff Kodosky started playing around in 2004 with the idea of verifying a LabVIEW program.
- Warren Hunt and J Moore met on occasion with Jeff and Jacob Kornerup over several years, culminating with NI engaging Grant Passmore as an intern in 2005.
- Grant developed an approach to prove Gauss's theorem that the sum of the integers from 1 to n is n*(n+1)/2.
- Summer 2007: Matt Kaufmann developed an alternate approach to model LabVIEW programs, including loop structures, directly as ACL2 functions. Grant updated the infrastructure accordingly.
- Fall 2007: Grant transferred infrastructure support to Mark Reitblatt, NI intern from UT CS. Mark has worked with Matt on further automating the loop verification.
- Since then: Matt has been working on extending the previous work to handle LabVIEW diagrams with state. Also, Mark has looked into applying model checking.

ACL2 REPRESENTATION, p. 1

- Every module, primitive or not, takes and returns a single alist that we call a *record*, by calling `S*`, “set”.
- Every wire returns a LabVIEW data value, obtained by applying `G`, “get”, to a record.

```
    |----------------------------------- n
    |                                   |
    |        |---N0       |----N1       |
x --|-- X0 --|   |        |    |        |
    |        | + |-- W0 --| 1+ |-- Z0 --|-- z
y --|-- Y0 --|   |        |    |        |
    |        |---|        |----|        |
    |-----------------------------------|
```

ACL2 REPRESENTATION, p. 2

```
    |----------------------------------- n
    |                                   |
    |        |---N0       |----N1       |
x --|-- X0 --|   |        |    |        |
    |        | + |-- W0 --| 1+ |-- Z0 --|-- z
y --|-- Y0 --|   |        |    |        |
    |        |---|        |----|        |
    |-----------------------------------|
```

```
(DEFUN X0 (IN) (G  :X IN))
(DEFUN Y0 (IN) (G  :Y IN))
(DEFUN N0 (IN) (S* :T0 (+ (X0 IN) (Y0 IN))))
(DEFUN W0 (IN) (G  :T0 (N0 IN)))
(DEFUN N1 (IN) (S* :T0 (1+ (W0 IN))))
(DEFUN Z0 (IN) (G  :T0 (N1 IN)))
```

MAIN VERIFICATION IDEA

- An assertion is simply a Boolean-valued wire that can be checked at runtime.
- Goal: prove that each assertion is true
- Earlier focus: For-loops and while-loops

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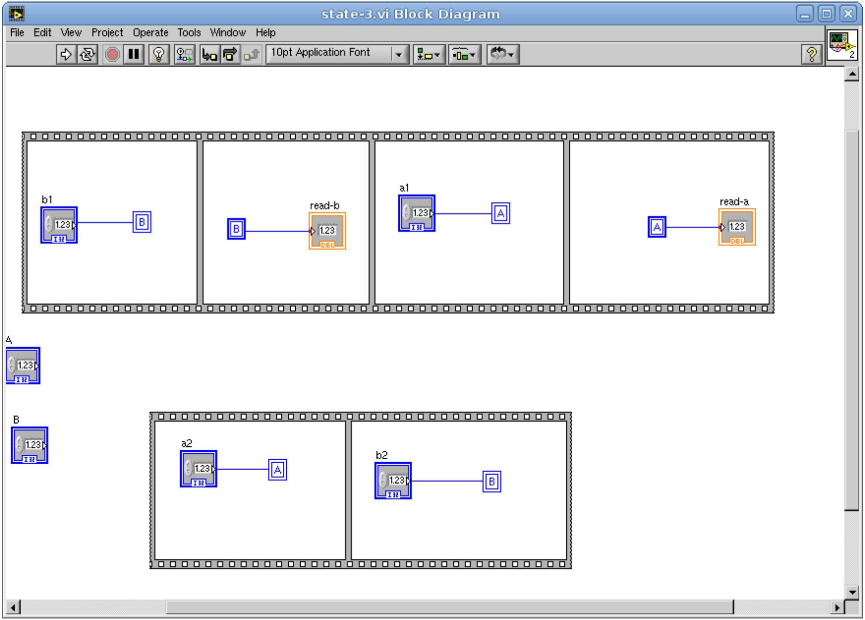
- **The problem of state**:
  - **Producer-consumer scenario**
  - **Valid traces**
  - A simple producer-consumer example using global variables
  - A simple producer-consumer example using a feedback loop
  - Atomic read-modify-write using sub-VIs
- Hierarchy (work in progress)

Producer-consumer scenario (p. 1)



Producer-consumer scenario (p. 2)

```
N1: Wr B, 1        N5: Wr A, 2
N2: Rd B           N6: Wr B, 2
N3: Wr A, 1
N4: Rd A
```

We want to prove the following.

- N4 reads 1 or 2 for A.
- If N2 reads 2 for B, then N4 reads 1 for A.

Valid traces (p. 1)

For "If N2 reads 2 for B, then N4 reads 1 for A": This theorem will be stated as a property of all valid computation *traces* — node sequences.

```
N1: Wr B, 1      N5: Wr A, 2
 ^                ^
N2: Rd B   >?    N6: Wr B, 2
 ^
N3: Wr A, 1
 ^
N4: Rd A
```

Valid traces (p. 1)

For “If N2 reads 2 for B, then N4 reads 1 for A”: This theorem will be stated as a property of all valid computation *traces* — node sequences.

```
N1: Wr B, 1       N5: Wr A, 2
 ^                 ^
N2: Rd B   >?     N6: Wr B, 2
 ^
N3: Wr A, 1
 ^
N4: Rd A
```

We specify node pairs (N . N’) such that N must fire before N’:

```
(valid-tracep-setup st1
                    ((n1 . n2)
                     (n2 . n3)
                     (n3 . n4)
                     (n5 . n6)))
```

Valid traces (p. 2)

Generated by above `valid-tracep-setup` call:

```
(DEFUN ST1$VALID-TRACEP (LST)
  (AND (NO-DUPLICATESP-EQUAL LST)
       (PREC-LST (ST1$PREC-REL) LST)))
```

Examples:

```
ACL2 !>(st1$valid-tracep (reverse '(n1 n2 n3 n4 n5 n6)))
T
ACL2 !>(st1$valid-tracep (reverse '(n1 n5 n2 n3 n6 n4)))
T
ACL2 !>(st1$valid-tracep (reverse '(n1 n5 n2)))
T
ACL2 !>(st1$valid-tracep (reverse '(n4 n5 n6)))
NIL
ACL2 !>(st1$valid-tracep (reverse '(n2 n1)))
NIL
ACL2 !>
```

Valid traces (p. 3)

Consider:

```
:trans1 (valid-tracep-setup st1
                            ((n1 . n2)
                             (n2 . n3)
                             (n3 . n4)
                             (n5 . n6)))
```

Here we edit away some output. Note that some hints use functional instantiation.

Valid traces (p. 4)

```
(PROGN (DEFUN ST1$PREC-REL ()
         '((N1 . N2)
           (N2 . N3)
           (N3 . N4)
           (N5 . N6)))
       (DEFUN ST1$VALID-TRACEP (LST)
         (AND (NO-DUPLICATESP-EQUAL LST)
              (PREC-LST (ST1$PREC-REL) LST)))
       (DEFTHM ST1$VALID-TRACEP-FORWARD-TO-NO-DUPLICATESP-EQUAL
         (IMPLIES (ST1$VALID-TRACEP TRACE)
                  (NO-DUPLICATESP-EQUAL TRACE))
         :RULE-CLASSES :FORWARD-CHAINING)
       (DEFTHM ST1$VALID-TRACEP-FORWARD-TO-PREC-N1-N2
         (IMPLIES (AND (ST1$VALID-TRACEP TRACE)
                       (MEMBER-EQUAL 'N2 TRACE))
                  (MEMBER-EQUAL 'N1
                                (MEMBER-EQUAL 'N2 TRACE)))
         :RULE-CLASSES :FORWARD-CHAINING)
       ... ; similarly for N2-N3, N3-N4, N5-N6
       (DEFTHM ST1$VALID-TRACEP-FORWARD-TO-PREC-N1-N2$2
         (IMPLIES (AND (ST1$VALID-TRACEP TRACE)
                       (EQUAL 'N2 (CAR TRACE)))
                  (MEMBER-EQUAL 'N1 (CDR TRACE)))
         :RULE-CLASSES :FORWARD-CHAINING)
       ... ; similarly for N2-N3$2, N3-N4$2, N5-N6$2
       (IN-THEORY (DISABLE ST1$VALID-TRACEP))
       (DEFTHM ST1$VALID-TRACEP-CDR
         (IMPLIES (ST1$VALID-TRACEP TRACE)
                  (ST1$VALID-TRACEP (CDR TRACE))))
       (DEFTHM ST1$VALID-TRACEP-MEMBER-EQUAL
         (IMPLIES (ST1$VALID-TRACEP TRACE)
                  (ST1$VALID-TRACEP (MEMBER-EQUAL NODE TRACE))))
       (DEFCONST *ST1$NODES* '(N1 N5 N6 N2 N3 N4)))
```

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- **The problem of state**:
  - Producer-consumer scenario
  - Valid traces
  - **Producer-consumer with global variables**
  - Producer-consumer with a feedback loop
  - Atomic read-modify-write using sub-VIs
- Hierarchy (work in progress)

DISCLAIMER

- We're skipping most technical detail (time limitations).
- See `.lisp` files (certified books) for details, including some interesting technical challenges. I'm happy to serve as tour guide.

Producer-consumer with global variables (p. 1)

We return to the example already presented:

```
N1: Wr B, 1        N5: Wr A, 2
N2: Rd B           N6: Wr B, 2
N3: Wr A, 1
N4: Rd A
```

We want to prove the following.

- N4 reads 1 or 2 for A.
- If N2 reads 2 for B, then N4 reads 1 for A.

The next slides illustrate our translation.

Producer-consumer with global variables (p. 2)

Basic node and wire functions are based on the state at the time the node or wire gets its value, e.g.:

```
; Node N3 does a write, so returns nothing:
(defun n3@ (in st)
  nil)

; Node N4 returns a record with the value of A.
(defun n4@ (in st)
  (s* :t0 (g :a st)))

; This wire (for terminal T0 of N4) is the value
; that has been read for A.
(defun n4-t0@ (in st)
  (g :t0 (n4@ in st)))
```

Producer-consumer with global variables (p. 3)

Next, we say how state is updated.

```
(defun st1$state-step (node in st)
  (case node
    (n1 (s :b 1 st)) ; Wr B, 1
    (n3 (s :a 1 st)) ; Wr A, 1
    (n5 (s :a 2 st)) ; Wr A, 2
    (n6 (s :b 2 st)) ; Wr B, 2
    (otherwise st)))

(defun st1$state-rec (in st trace)
  (if (consp trace)
      (st1$state-step (car trace)
                      in
                      (st1$state-rec in st (cdr trace)))
    st))

(defun st1$state (node in st trace)
  (st1$state-rec in st (cdr (member-equal node trace))))
```

Producer-consumer with global variables (p. 4)

Then, we define the actual node and wire functions in terms of the state as of the time the diagram is first entered, e.g.:

```
; Node N3 does a write, so returns nothing:
(defun n3 (in st trace)
  (n3@ in (st1$state 'n3 in st trace)))

; Node N4 returns a record with the value it reads.
(defun n4 (in st trace)
  (n4@ in (st1$state 'n4 in st trace)))

; This wire (for terminal T0 of N4) is the value
; that has been read.
(defun n4-t0 (in st trace)
  (n4-t0@ in (st1$state 'n4 in st trace)))
```

Producer-consumer with global variables (p. 5)

Example that evaluates to T:

```
(let ((trace (reverse '(n1 n2 n3 n4 n5 n6))))
  (and (st1$valid-tracep trace)
       (equal (n4 nil '((:a . 0) (:b . 0)) trace)
              '((:T0 . 1)))))
```

```
N1: Wr B, 1
N2: Rd B
N3: Wr A, 1
N4: Rd A
N5: Wr A, 2
N6: Wr B, 2
```

Producer-consumer with global variables (p. 6)

First Theorem: N4 reads 1 or 2. The following invariant could be automatically generated. Proof using functional instantiation replaces explicit induction by a base and an induction step.

```
(defun st1$state-inv1 (in st trace)
  (implies (member-equal 'n3 trace)
           (member-equal (g :a (st1$state-rec
                                 in st trace))
                         '(1 2))))
```

The key observation is that N4 is after N3:

```
 N3: Wr A, 1
 N4: Rd A
```

The invariant then yields the theorem:

```
(implies (and (st1$valid-tracep trace)
              (subsetp-equal *st1$nodes* trace))
         (member-equal (n4-t0 in st trace) '(1 2)))
```

Producer-consumer with global variables (p. 7)

Second Theorem: If N2 reads 2 for B, then N4 reads 1 for A.

```
(implies (and (st1$valid-tracep trace)
              (subsetp-equal *st1$nodes* trace)
              (equal (n2-t0 in st trace) 2))
         (equal (n4-t0 in st trace)
                1))
```

Producer-consumer with global variables (p. 8)

```
N1: Wr B, 1        N5: Wr A, 2
N2: Rd B [2]       N6: Wr B, 2
N3: Wr A, 1
N4: Rd A [1?]
```

Our reasoning goes as follows.

```
N6 << N2 {by invariant:}
   If N1 << N and not N6 << N, then value of B is 1
N4 reads 1 for A {by invariant:}
   If N5 << N3 << N, the value of A at N is 1
```

The user is expected to create the two invariants, but our .lisp file suggests that the system could then prove them automatically.

Producer-consumer with global variables (p. 9)

The above example is file `state-1.lisp`. We have created two elaborations:

- `state-2.lisp`
  Re-working of `state-1.lisp`, reading directly from inputs instead of using constants.
- `state-3.lisp`
  Re-working of `state-2.lisp`, but using proper wires for inputs and thus using mutual-recursion for wire, node, and state functions.

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Producer-consumer with a feedback loop (p. 1)

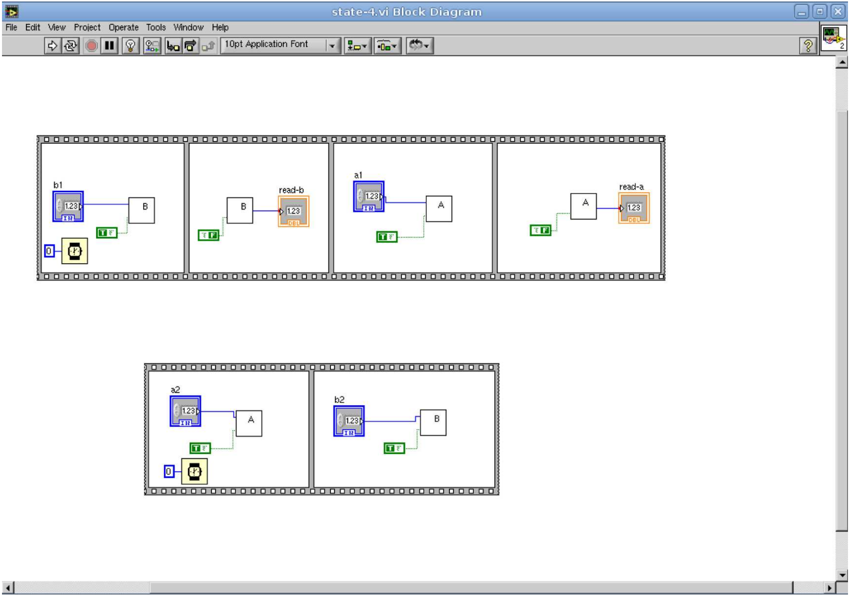
The key element for this version of the problem is a latch VI, which is *non-reentrant* : only one instance is being evaluated at a time.

File `state-4.lisp` includes this “wonderful” graphic:

```
;             -----
; -- wrp -- |     |
; -- din -- | ITE | -- out --
;      st -- |     |      V
;     / ^     -----       |
;    0  |                 |
;       ----------------
```

The main VI instantiates two different (but isomorphic) such latches, A and B, each three times (two writes and one read, each):

Producer-consumer with a feedback loop (p. 2)



Producer-consumer with a feedback loop (p. 3)

This example is similar to the earlier one, though more complex. We see a first attempt to handle hierarchical state elements.

```
(defun st1$state-step (node in new-st st trace)
  (declare (xargs :measure (st1$measure node trace :state-step)))
  (if (and (st1$valid-tracep trace)
           (member-equal node trace))
      (case node
        (n1 (s :latch-b ; WR B, b1
               (latch-b{post-state} (s* :wrp (n1-wrp-t0 in st trace)
                                        :din (in-b1 in st trace))
                                    (g :latch-b new-st))
               new-st))
        (n2 (s :latch-b ; Rd B
               (latch-b{post-state} (s* :wrp (n2-wrp-t0 in st trace)
                                        :din 0)
                                    (g :latch-b new-st))
               new-st))
        ....
        (otherwise new-st))
    new-st))
```

Producer-consumer with a feedback loop (p. 4)

The proofs of the two theorems are similar to the earlier ones. But there are no “@” functions – state as of entry to a node doesn’t tell you the state at input wires. (Initially I got this wrong!)

However, we first need to prove invariants about the bits of state indicating whether the feedback element has ever been entered, e.g. for Latch A:

```
(implies
 (st1$valid-tracep trace)
 (let ((n3p (member-equal 'n3 trace))
       (n5p (member-equal 'n5 trace)))
   (equal (g :st{first}
              (g :latch-a
                 (st1$state-rec in st trace)))
          (if (or n3p n5p)
              nil
            (g :st{first} (g :latch-a st))))))
```

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Atomic read-modify-write using sub-VIs (p. 1)

Sub-VI Inc, `state-5.lisp` (to be fixed like `state-4.lisp`):

```
;             ----
;      en -- |    |
;     st0 -- | 1+ | -- out --
;      /^    |    |     V
;     / |     ----      |
;    0  |               |
;        ----------------
```

Main VI from `state-5.lisp`: two writes, then a read.

```
; N1: Inc[En=T]     N2: Inc[En=T]
; ----------------------------------
;        N3: Inc[En=NIL]
```

Theorem proved:

```
(implies (and (vi0$valid-tracep trace)
              (g :st0{first} (g :inc st))
              (subsetp-equal *vi0$nodes* trace))
         (equal (n3-out in st trace) 2))
```

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Hierarchy (work in progress)

We do not yet handle loops with state. Work in progress:

- A rather detailed 6-page plan that could deal nicely with loops and other hierarchy
- Main idea: notion of *node* is extended to *hierarchical node*: in essence, a path of enclosing node instances down towards a leaf node.
- A *trace* is then a list of hierarchical nodes. A *valid trace* must respect loop indices, in particular.

Conclusion (p. 1)

There's a good start on handling state:

- Trace model, with helpful (and proved) supporting rules
- Examples have been worked
- Hierarchy has been considered

The next step is to implement the hierarchical approach to work the motivating example from Jacob Kornerup:

> *There are two loops with 100 iterations each, one incrementing and the other decrementing a global integer at each iteration. The increment/decrement operations are atomic. Prove that the final value of the global equals its initial value.*

Conclusion (p. 2)

Guiding principles to balance are the following.

- Work simple examples to develop methodologies.
- But keep in mind future automation and scalability.
- And use a suitable translation:
  - Stick to the earlier, simpler approach if there is no state.
  - Sub-VIs using feedback loop don't need interpreter, since state isn't updated until sub-VI is exited.