Formal Verification of LabVIEW Diagrams

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Outline

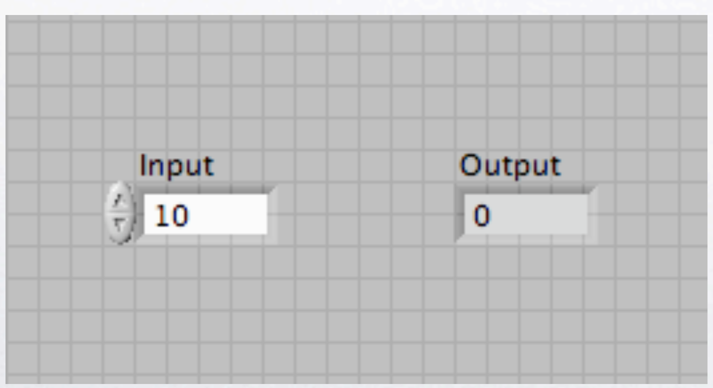
- Project History
- LabVIEW Overview
- Overview of approach
- Walk through example verification
- Conclusion

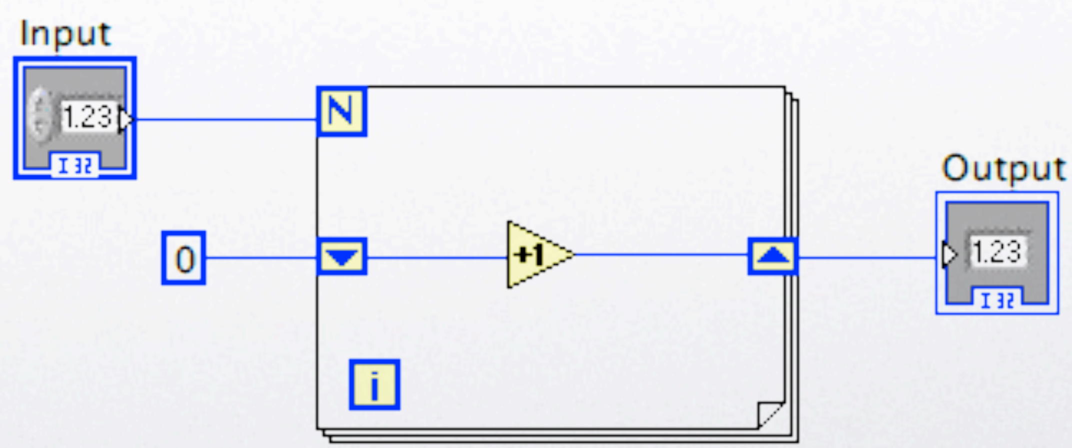
Project History

- 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 as an intern in 2005
- Summer 2007: Alternate approach models LabVIEW programs, including loop structures, directly as ACL2 functions. At the end of the summer Grant left for Edinburgh and transferred his work to Mark Reitblatt
- Current: Approach has been fully automated, expanded and used to verify a dozen examples

LabVIEW (in brief)

- Graphical dataflow language (G) with control structures
- Shift register memory elements
- Separate Front (user interface) and Back (implementation) panels



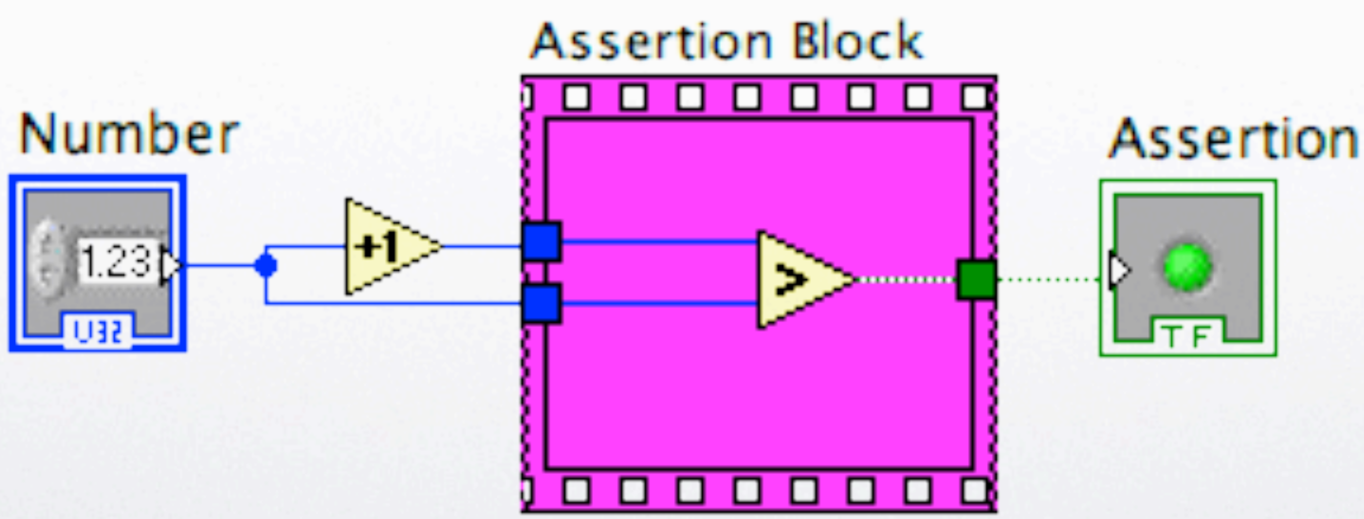


Why LabVIEW?

- Mostly functional
- Memory safe
- Simple control structures

Our Approach

- Add “assertion” blocks to LabVIEW/G



Our Approach (cont.)

- Translate LabVIEW/G diagrams into ACL2 functions (shallow embedding)
- Each node takes a record (IN) as input
- Returns a record binding its outputs to terminal names
- Wires extract values from records

Naming

- LabVIEW/G doesn't allow naming of (most) nodes
- Human readability is essential to understanding proofs
- Auto-naming of nodes based on type

Naming (cont.)

- Fn nodes are named as fntype-number
  - ADD-1
- Constant nodes are named by value
  - CONSTANT[0]-2
  - Third instance of the constant '0'

Naming (cont.)

- Wires are named a little differently
- Each wire retrieves one terminal from one node
- Wire named after its source

CONSTANT[0]-2<_T_0>

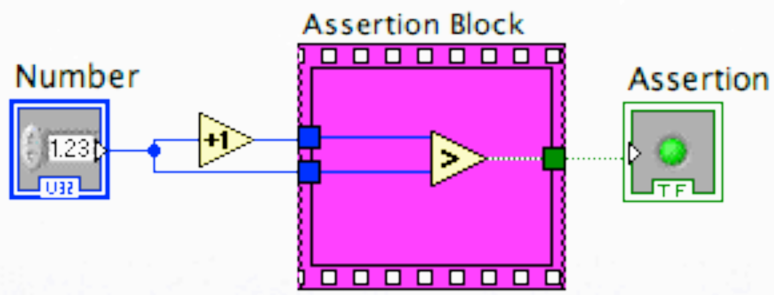
Translation


```
(DEFUN-N CONSTANT[0]-0 (IN)
          (S* :|_T_0| 0))

(DEFUN-W CONSTANT[0]-0<_T_0> (IN)
          (G :|_T_0| (CONSTANT[0]-0 IN)))

(DEFUN-N INCREMENT-0 (IN)
          (S* :X+1 (1+ (CONSTANT[0]-0<_T_0>
                              IN))))
```

- (G :key rec) returns the value associated with :key in rec
- (S* :key1 val1 :key2 val2 ...) creates new record binding :keyi to vali

Our Approach (cont.)

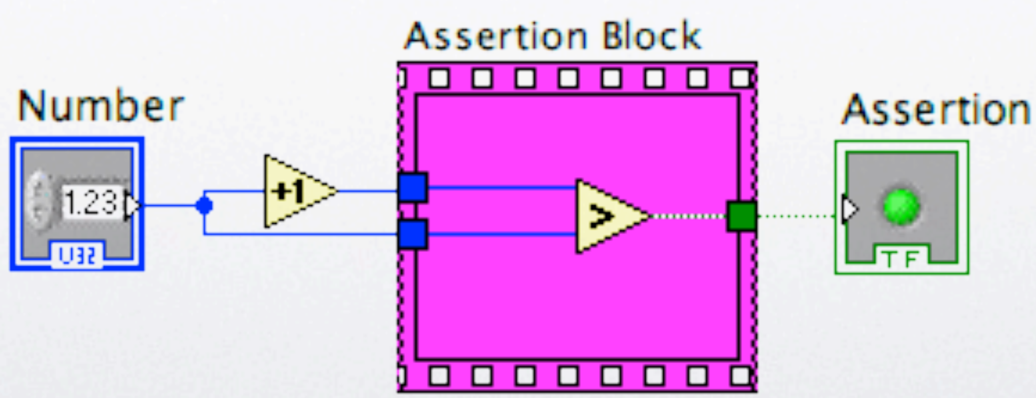
- Translate assertions into proof obligations




```
(DEFTHM ASSERTION-BLOCK-HOLDS
        (IMPLIES (AND (NATP (G :NUMBER IN)))
                 (G :ASN (ASSERTION-BLOCK IN))))
```

Limitations

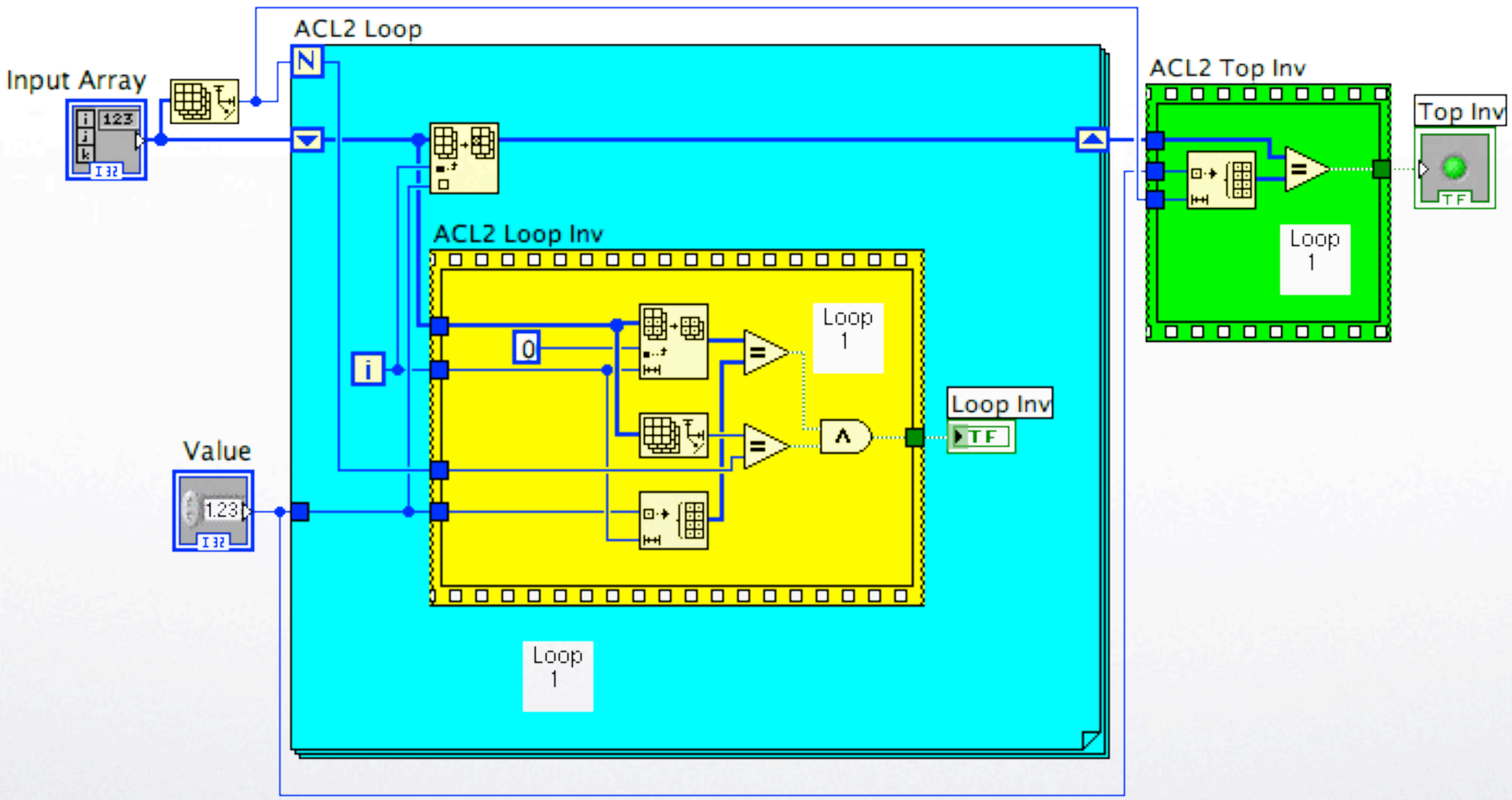
- Currently only for-loops are automated
- We use unbounded arithmetic, so this is a theorem for us, but not for LabVIEW/G



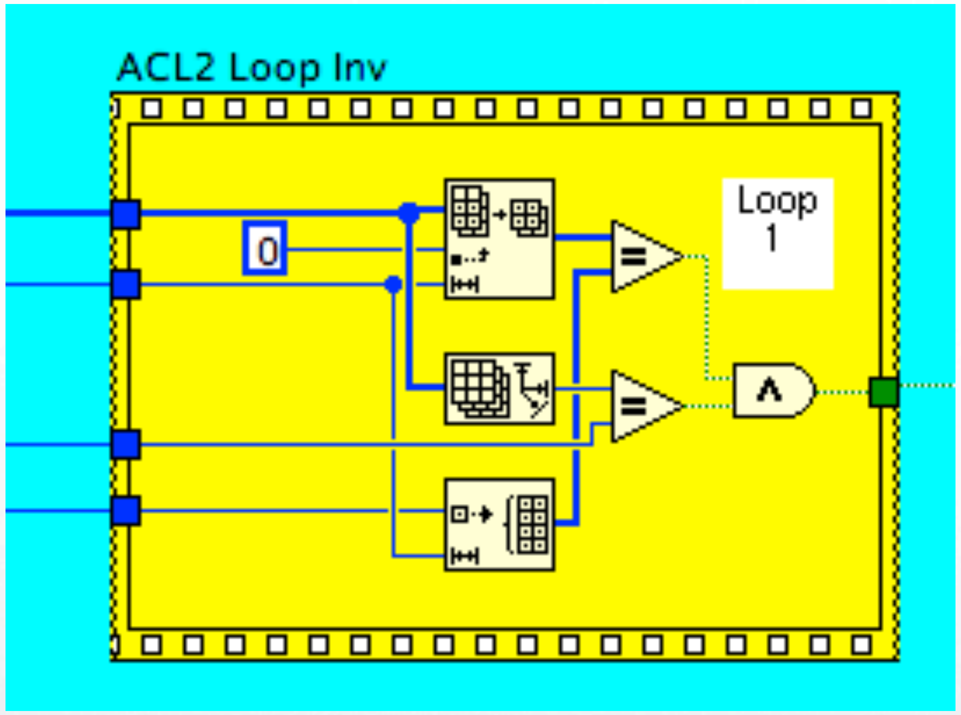
Loop Assertions

- Assertions about loops (in general) require inductive proofs
- We split loop assertions into "top" assertions and loop invariants

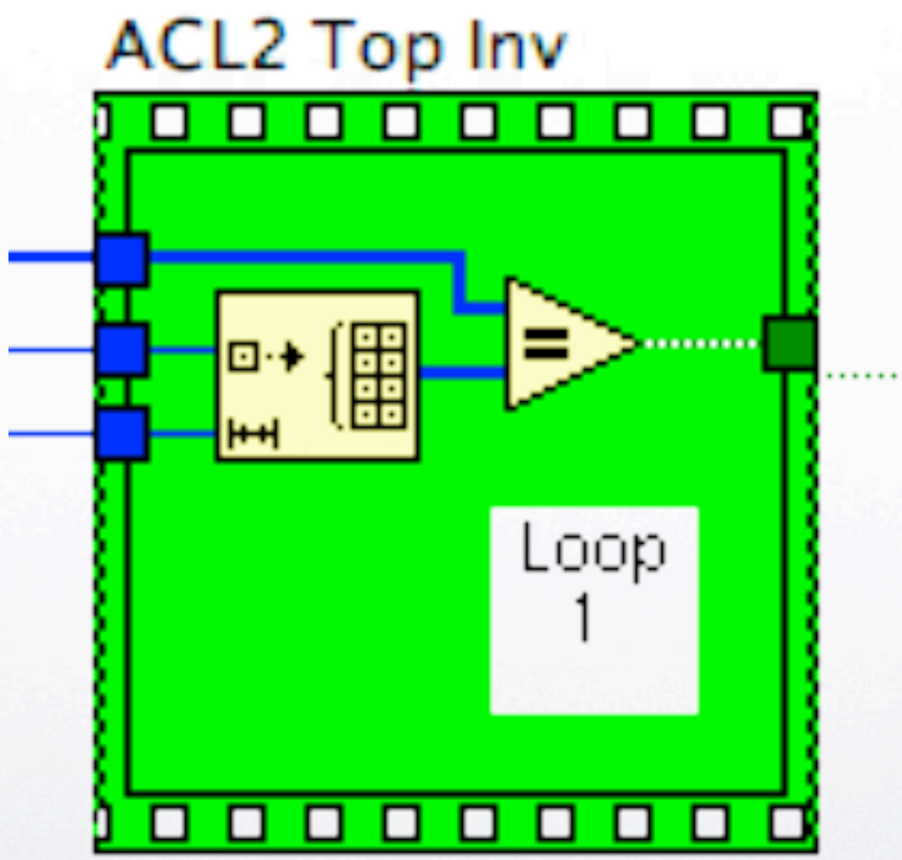
Loop Assertions (cont.)



Loop Invariant



Loop Assertion



Proving Loop Assertions

- Hold the user's hand to prove invariants
- Autogenerate highly structured proof scaffolding
- Strictly guide proof process through theory control

LabVIEW Loops

- We separate for-loop structures into 4 ACL2 functions
- $step function
  - Executes loop body and binds outputs to next iteration inputs

```
(DEFUN FOR-LOOP$STEP (IN)
  (S :|_T_4| (G :|_T_1| (|_N_5| IN)) IN))
```

LabVIEW Loops (cont.)

- $loop function
  - Compares loop counter to loop bound
  - Updates loop counter and calls $step fn

```
(DEFUN FOR-LOOP$LOOP (N IN)
(DECLARE (XARGS :MEASURE (NFIX (- N (G :LC IN)))))
(COND ((OR (>= (G :LC IN) N)
           (NOT (NATP N))
           (NOT (NATP (G :LC IN))))
       IN)
      (T (FOR-LOOP$LOOP N (S :LC (1+ (G :LC IN))
           (FOR-LOOP$STEP IN))))))
```

LabVIEW Loops (cont.)

- $init function
  - Binds loop variables to initial values

```
(DEFUN FOR-LOOP$LOOP$INIT (IN)
       (S* :LC 0
           :|_T_2| (CONSTANT[10]-1<_T_0> IN)
           :|_T_4| (CONSTANT[0]-0<_T_0> IN)))
```

LabVIEW Loops (cont.)

- Top function
  - Binds loop bound and calls $loop fn with results of $init fn

```
(DEFUN-N FOR-LOOP (IN)
  (FOR-LOOP-SRN$LOOP (CONSTANT[10]-1<_T_0> IN)
      (FOR-LOOP-SRN$LOOP$INIT IN)))
```

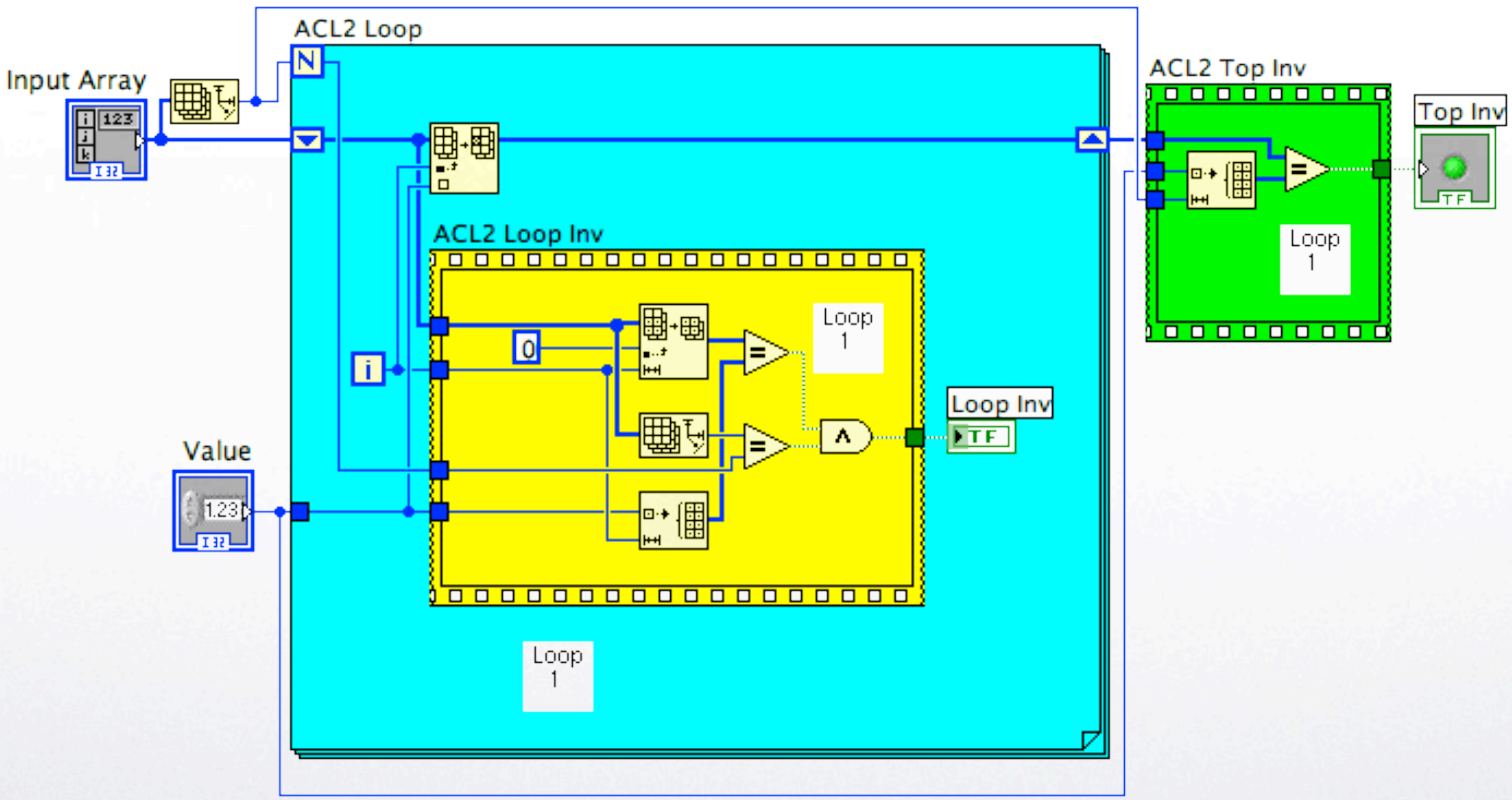
LabVIEW Structures

- LabVIEW loops are split into inner and outer structures
  - Inner structures are called “Self-reference Nodes” (SRN)
  - SRN nodes contain the body of the loop
  - Outer nodes map external values to internal names

Generic Theory

- We use a generic theory to avoid induction in the invariant proof
  - Use encapsulate to define a generic $step, $loop and $prop (invariant)
  - Prove that if $prop holds on entry to $loop and is preserved by $step then it holds when $loop is run

Example Diagram



Extend Loop Invariant

```
(DEFUN |LOOP-INV-SRN$PROP| (N IN)
  (DECLARE (IGNORABLE N))
  (AND (|LOOP-INV-SRN$HYPS| IN)
       (EQUAL N (G :|_T_3| IN))
       (G :ASN (ACL2-LOOP-INV IN))))
```

- LOOP-INV-SRN$HYPS is a type predicate that recognizes the types on the inputs to LOOP-INV-SRN
- ACL2-LOOP-INV is the name of the loop invariant

Loop Inv. is Preserved

```
(DEFTHMDL |LOOP-INV-SRN$PROP{FOR-LOOP-SRN$STEP}|
  (IMPLIES (AND (NATP (G :LC IN))
                (< (G :LC IN) N)
                (|LOOP-INV-SRN$PROP| N IN))
           (|LOOP-INV-SRN$PROP| N
            (S :LC (1+ (G :LC IN))
               (|FOR-LOOP-SRN$STEP| IN))))))
```

- Note that this lemma is disabled

Use Generic Theory

```
(DEFTHML |LOOP-INV-SRN$PROP{FOR-LOOP-SRN}|
  (IMPLIES (AND (NATP N)
                (NATP (G :LC IN))
                (|LOOP-INV-SRN$PROP| N IN))
           (|LOOP-INV-SRN$PROP| N (| FOR-LOOP-SRN$LOOP| N IN)))
  :HINTS
  (("Goal" :BY (:FUNCTIONAL-INSTANCE
                LOOP-GENERIC-THM
                (STEP-GENERIC |FOR-LOOP-SRN$STEP|)
                (PROP-GENERIC |LOOP-INV-SRN$PROP|)
                (LOOP-GENERIC |FOR-LOOP-SRN$LOOP|))
           :IN-THEORY
           (UNION-THEORIES '(|LOOP-INV-SRN$PROP{FOR-LOOP-SRN$STEP}|)
                           (THEORY 'MINIMAL-THEORY))
           :EXPAND ((|FOR-LOOP-SRN$LOOP| N IN))))
  :RULE-CLASSES NIL)
```

Inv Holds on Input, with type hyps

```
(DEFTHML ACL2-LOOP-INV$INV{INIT}
  (IMPLIES (ACL2-LOOP-INV$INV{PRE} IN)
           (|LOOP-INV-SRN$PROP| (INPUT1<_T_0> IN)
            (|LOOP-INV-SRN$PROP$INIT| IN)))
  :RULE-CLASSES NIL)
```

Loop Inv. Holds w/o type hyps

```
(DEFTHML ACL2-LOOP-INV$INV
  (IMPLIES (ZERO-ARRAY$INPUT-HYPS IN)
           (ACL2-LOOP-INV$INV+ IN))
  :HINTS
  (("Goal"
    :IN-THEORY
    (UNION-THEORIES '(ACL2-LOOP-INV$INV{PRE})
                    (THEORY 'MINIMAL-THEORY))
    :USE (ACL2-LOOP-INV$INV$CONDITIONAL
          ACL2-LOOP-INV$INV{PRE}{HOLDS})))
  :RULE-CLASSES NIL)
```

Loop counter = Loop bound

```
(DEFTHML LC$FOR-LOOP-SRN
  (IMPLIES (AND (NATP N)
                (NATP (G :LC IN))
                (<= (G :LC IN) N))
           (EQUAL (G :LC (|FOR-LOOP-SRN$LOOP| N IN)) N))
  :HINTS (("Goal" :BY (:FUNCTIONAL-INSTANCE
                       LOOP-GENERIC-LC
                       (STEP-GENERIC |FOR-LOOP-SRN$STEP|)
                       (PROP-GENERIC |LOOP-INV-SRN$PROP|)
                       (LOOP-GENERIC |FOR-LOOP-SRN$LOOP|))
           :IN-THEORY (THEORY 'MINIMAL-THEORY)
           :EXPAND ((|FOR-LOOP-SRN$LOOP| N IN)))))
```

Top Inv. Holds

```
(DEFTHM ACL2-TOP-INV$INV
  (IMPLIES (GAUSS$INPUT-HYPS IN)
           (G :ASN (ACL2-TOP-INV IN)))
  :HINTS (("Goal" :IN-THEORY (DISABLE |FOR-LOOP-SRN$LOOP|)
           :USE (ACL2-LOOP-INV$INV
                 LEMMA-2-ACL2-LOOP))))
```

- Uses several (simple) lemmas not shown here

Lemma Library

- Lemmas about LabVIEW primitives essential to automatic proofs
- Primitive definitions are disabled by default to (weakly) remove dependence upon defintions
- Currently ~80 theorems

Future Work

- Compositional Verification
  - Initial Approach done by hand
  - Use encapsulate to export diagram properties
- Use bounded arithmetic
- Use encapsulate for primitive definitions
- Diagrams containing state

Conclusion

- Prototype system for verifying LabVIEW diagrams
- About a dozen (fully automatic) examples completed
- Feasibility of approach has been proven (for state-free diagrams)