Using ACL2 in the Design of Efficient, Verifiable Data Structures for High-Assurance Systems

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Motivation

- Cyber resilience is an increasingly important requirement for Rockwell Collins customers, both government and commercial
- As DARPA HACMS Air Vehicle team lead, we researched methods/tools to create “clean-slate” cyber-resilient systems
- Our air vehicles resisted all attacks by the HACMS red team
- On the new DARPA CASE program, challenges include:
- Making cyber resilience a first-class systems engineering property, on par with the various existing “ilities”
- Applying cyber-resilient engineering methods and tools to systems including significant legacy elements

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Motivation (cont'd.)

- Additionally, new autonomy functions such as route planning, inference, pattern recognition, etc. present a significant V&V challenge, due to the lack of a human operator, as well as complex new data structures and algorithms
- Proof techniques for these data structures exist, but are oriented to unbounded, functional data types
  - Functional data structure implementations are not often efficient in space or time, so developers generally take a more imperative approach
- We need to find proof techniques that embrace the "natural" functional proof style, yet apply to more efficient data structure implementations
  - Including GPU-based and hardware-based data structures

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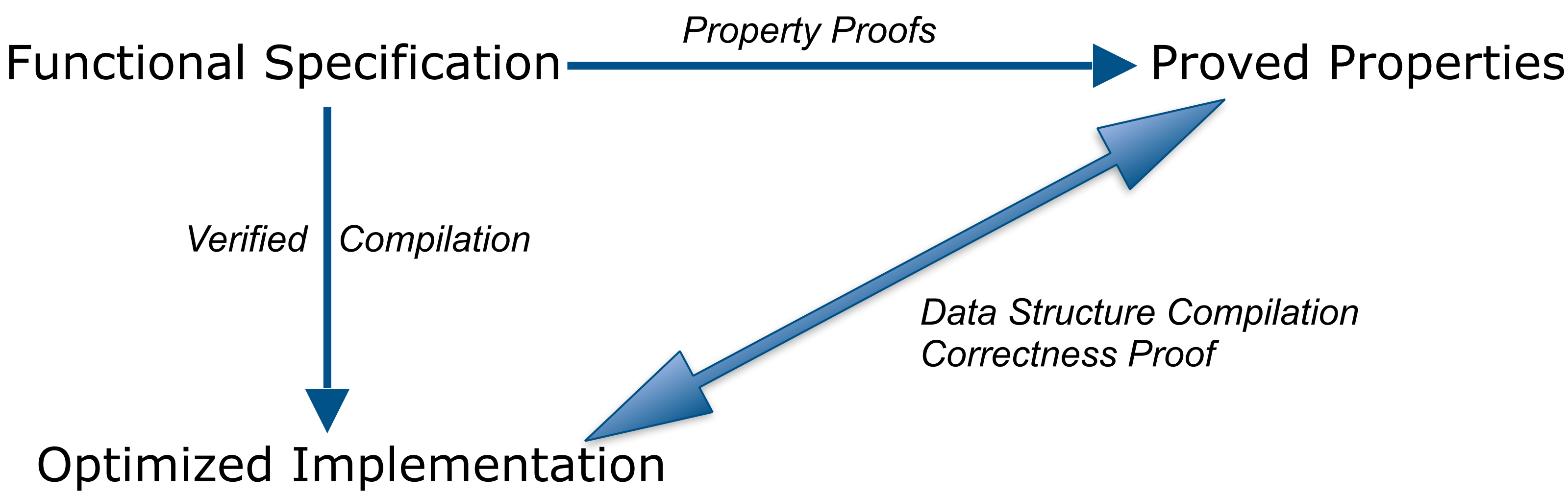
Verified Data Structure Compilation and Property Proofs

- Once we develop the Data Structure Compilation Correctness Proof, properties proved of the functional data structure specification will also hold for the optimized implementation



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DASL: A Domain-Aware System Language

- We have developed a "Domain-Aware" System Language, DASL, that embodies our vision:
  - DASL is a system-level language, appropriate for expressing algorithms and data structures that can be compiled to traditional programming languages, GPU languages, as well as Hardware Description Languages (HDLs)
  - HOL4 gives semantics to DASL evaluation, and we use proved source-to-source transformations in HOL4 to compile DASL code
  - DASL is a "mashup" of concepts from Ada, ML, and the C family of languages, and has a similar feel to modern languages such as Swift and Rust

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DASL Data Structure Compilation to Linear Form

- DASL provides ML-like functional data structure specifications
  - Data structure specification includes a maximum size
- DASL compiles Data Structure Specifications into a linearized form requiring no heap allocation or deallocation, in keeping with high-assurance development tenets
  - (e.g. DO-178C Level A)
- The DASL toolchain produces proofs that data structure operations on the compiled form are equivalent to the same operations on the high-level functional form
  - Proves that in-place updates are equivalent to functional (copying) updates, given that no "old" copies of the data structure are allowed
- User-defined properties are introduced using `spec` statements

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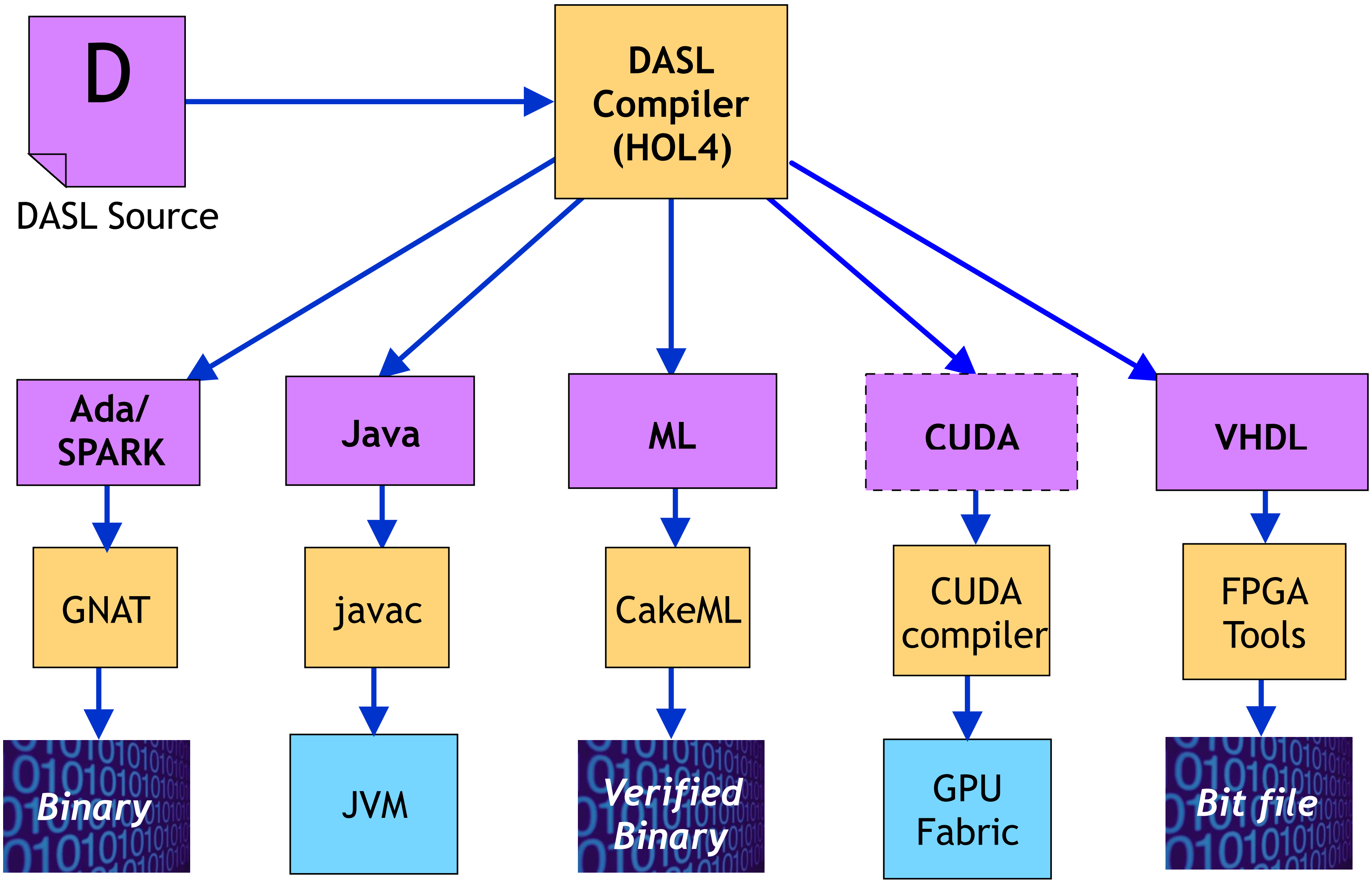
DASL Code Generation Options



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Related Work: Theorem Provers and Verified/ Verifying Compilers

- A number of verified/verifying compilers have emerged recently
  - e.g., CompCert C compiler, CakeML
- Concurrently, theorem provers have increasingly supported the translation of logic functions to code, e.g.:
  - OCaml code from Coq
  - Verified binary code from HOL4 functions via CakeML tools
  - Assembly code from Gallina (Coq)
    - Œuf, CertiCoq
  - Isabelle/HOL
    - ML, OCaml, Haskell, Scala
    - Interface to CakeML
  - C code from PVS (PVS2C)
  - ACL2 is both a logic *and* a programming language (Applicative subset of Common Lisp)

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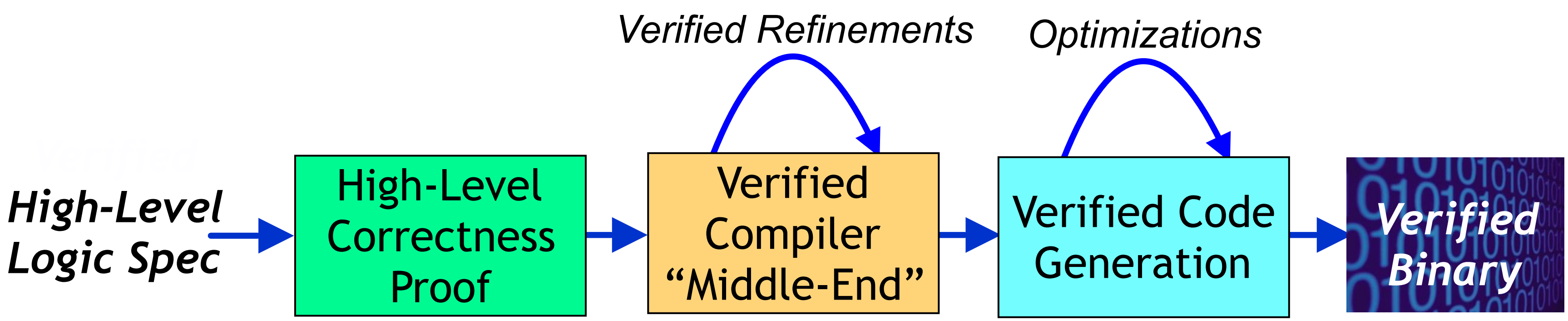
Related Work: Theorem Provers and Verified/ Verifying Compilers (cont'd.)

- Verified/Verifying compilers for conventional programming languages are a boon for establishing compiler correctness, but do nothing to prove correctness of the source code
- We are particularly interested in tools that provide a verified connection between high-level specifications of algorithms and data structures expressed in a logic (where algorithm correctness proofs can be readily performed) and (hopefully efficient) low-level implementations (the bits in the box)



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The **`sized`** Declarator and Compilation to Array-Based Form

- The DASL **`sized`** declarator informs the toolchain that an otherwise unbounded datatype declaration has limited size:

```
sized pq: PQType (MAX_VERTICES);
```

- sized datatypes can be compiled to an array-based form with destructive updates, similar to the way that ACL2 single-threaded objects (stobjs) are compiled

- Array-based form greatly simplifies code generation for GPUs and hardware

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Example DASL datatype: Binary Search Tree (BST)

- Binary Search Tree from Sedgewick and Wayne's *Algorithms* (4th edition) translated into DASL:

```
package BSTree =

const MAX_VERTICES : uint = 500000;

datatype BSTree
  = Leaf
  | Node :
     (key   : uint,   -- Key (sorted) = 0 => "null key"
      val   : uint,   -- Associated data = 0 => "null val"
      size  : uint,   -- Nodes in this subtree
      left  : BSTree,
      right : BSTree);

sized BSTRoot: BSTree(MAX_VERTICES);
```


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Binary Search Tree (BST) (cont'd)

- BST has operators for isEmpty(), sizeOf(), getVal(), insert(), delete(), deleteMin(), deleteMax(), etc.

- Example BST Operator in DASL: deleteMin()

```
function deleteMin(bst: inout BSTree) {
  match bst {
    'Leaf =>
      skip;
    'Node n =>
     { match n.left {
         'Leaf =>
            bst := n.right;
         'Node nl =>
            deleteMin(n.left);
       }
       n.size := 1 + sizeOf(n.left) + sizeOf(n.right);
     }
  }
}
```


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DASL Graph Datatypes

- Another unique DASL feature is a specialized graph datatype declarator, and its associated sized declarator:

```
graphtype DKGraph (nodeLabel = vertexLabelTy,
                   edgeLabel = edgeLabelTy);

sized dkg: DKGraph (MAX_VERTICES, MAX_EDGES_PER_VERTEX);
```

- The DASL toolchain compiles this declaration to an array-based form, and generates several associated functions for manipulating the array-based form:

```
getOutEdges(), setOutEdges(), addEdge(), labelVertex(),
 labelEdge(),…
```


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Example graphtype: Depth-First Search

- graphtype declaration

```
type vertexLabelTy = uint;
type edgeLabelTy = uint;

graphtype graph (nodeLabel = vertexLabelTy,
                 edgeLabel = edgeLabelTy);

const MAX_NODES : uint = 50000;
const MAX_EDGES : uint = 4;
type vertex = uint;

sized theGraph : graph (MAX_NODES, MAX_EDGES);
```


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Depth-first search in DASL

```
function DFS_span (vtarget: in vertex, G: in graph,
                   spanning_tree: inout BST,
                   fringe: inout vertex_pair_list) {
  var v, vpred: vertex;
  in
    match fringe {
      -- Out of vertex pairs to process
      'Empty => skip;
      'Node n => {
        -- Found target vertex
        if exists(vtarget, spanning_tree) then
          skip;
        else {
          (v, vpred) := n.elt;
          rest(fringe);
          -- if v already found, on to the next fringe element
          if exists(v, spanning_tree) then
            DFS_span(vtarget, G, spanning_tree, vertex_pair_list);
          else {
            mark(v, vpred, spanning_tree);
            explore(MAX_EDGES, v, G, spanning_tree, vertex_pair_list);
            DFS_span(vtarget, G, spanning_tree, vertex_pair_list);
          }}}}}
```


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Array-Based Graph Representation

- Based on a data structure layout approach created for efficient GPU execution (Harish and Narayanan, HiPC 2007); used to code Dijkstra’s All-Pairs Shortest Path algorithm (APSP)
- Amenable to efficient CUDA, OpenCL implementation, as well as hardware implmentation (VHDL)
- Implementated APSP using ACL2 single-threaded object (ACL2 Workshop 2013)
  - Execution of Dijkstra’s shortest path algorithm on compiled graph using stobjs was linear in number of vertices up to at least 1 million vertices at 10 edges per vertex
- DASL compiler analyzes **`datatype`**, **`graphtype`**, and **`sized`** declarations, creates appropriate array-based layout, and instantiates runtime functions

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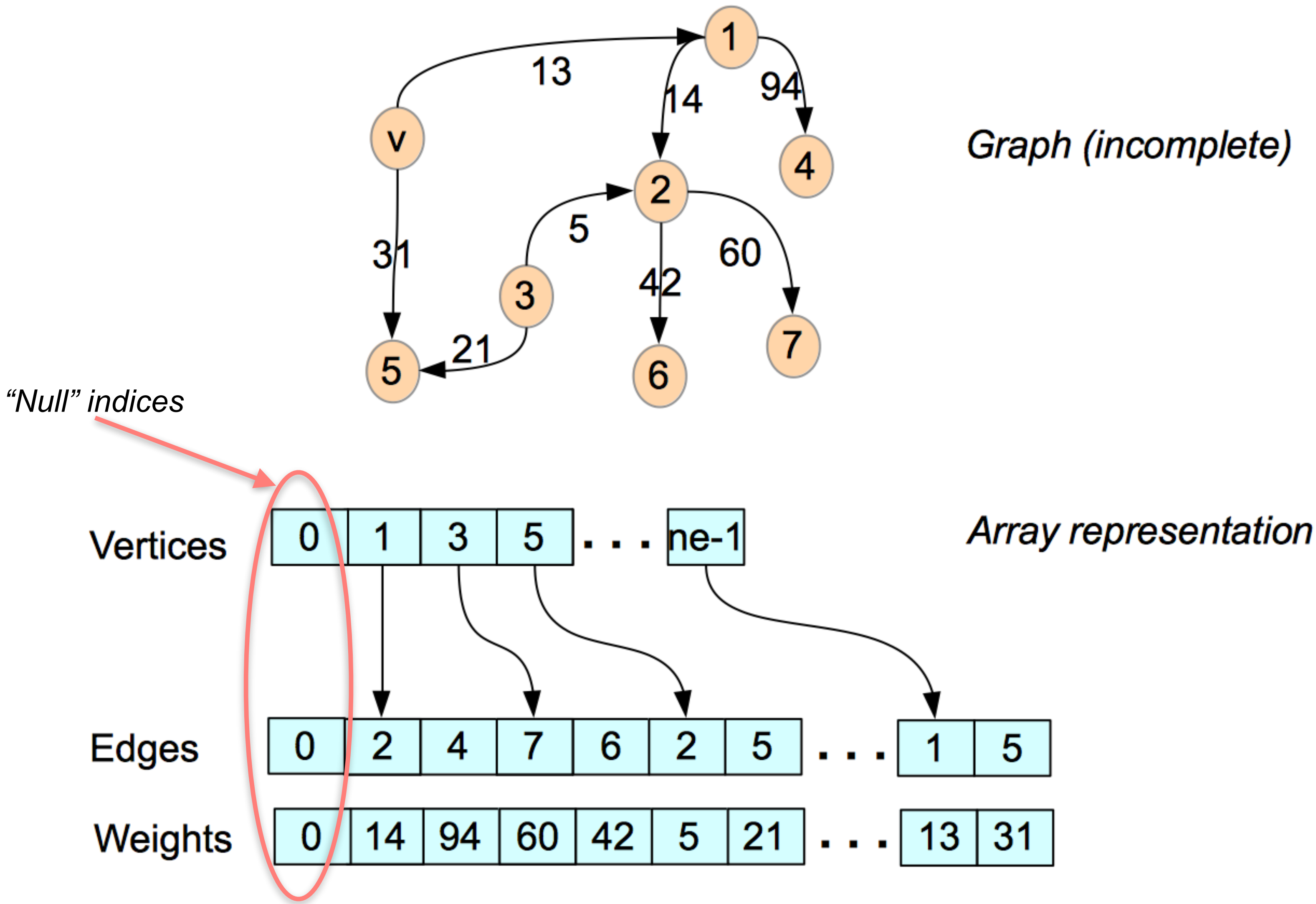
Graph Compilation Example, Two Edges per Vertex



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Prototyping DASL Data Structure Design in ACL2

Even though we are implementing DASL in HOL4, we chose to prototype the DASL data structure design in ACL2. Why?

- ACL2 is the most capable system we know of for the creation, proof, and execution of formal specifications
  - Using ACL2, we have been able to easily scale our data structure prototypes to millions of vertices and edges
- ACL2 provides sophisticated proof libraries (books) for reasoning about aggregate data structures
- Single-threaded objects (stobjs) provide functional data structure definitions with destructive "under-the-hood" implementations.
- Guards combine a type-like discipline with the power of proof

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Prototyping DASL Data Structure Design in ACL2 (cont'd)

- ACL2 is a mostly-automated theorem prover, and is quite adept at automated inductive proofs
- Tail recursion in ACL2 combines recursive functional style with efficient compilation to loops
- ACL2's simple packaging facility provides separate namespaces for datatypes/graphtypes
- All functions admitted to ACL2 must first be proven to terminate
  - This encourages the ACL2 developer to explicitly consider termination issues when writing functions

- We have thus constructed a Rudimentary ACL2 Semantic Laboratory for DASL:

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RASL DASL

- Source of original prototype of DASL array-based memory layout and DASL datatype runtime API
    - No garbage generation/collection overhead
- Utilizes ACL2 single-threaded objects for all data structures
    - RASL DASL functions are applicative, yet implement array updates destructively “under-the-hood”
    - Each data structure defined in its own package
- All target functions are written in tail-recursive style, so that recursion can be compiled to looping
- Embrace the restriction that all ACL2 functions must be proved to terminate
- All functions have guards for “super-defensive” programming

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Binary Search Tree Declaration in RASL DASL

```
(in-package "BST")

(defconst *MAX_VTX* 65535)
(defconst *MAX_VTX1* (1+ *MAX_VTX*)) ;; 2**16
(defconst *MAX_EDGES_PER_VTX* 2)
(defconst *MAX_EDGE* (* *MAX_VTX* *MAX_EDGES_PER_VTX*))
(defconst *MAX_EDGE1* (1+ (* *MAX_VTX* *MAX_EDGES_PER_VTX*)))
(defconst *MAX_EDGE_MINUS* (1+ (- *MAX_EDGE* *MAX_EDGES_PER_VTX*)))

(defstobj Obj
;; padding -- keeps ACL2 from turning (nth *VTXHD* Obj) into (car Obj)
  (pad :type t :initially 0)
  (vtxHd :type (integer 0 65535) :initially 0)
  (vtxTl :type (integer 0 65535) :initially 0)
  (vtxCount :type (integer 0 65535) :initially 0)
;; (V) This contains a pointer to the edge list for each vertex
  (vtxArr :type (array (integer 0 131069) (*MAX_VTX1*)) :initially 0)
;; (K) Keys for each vertex
  (keyArr :type (array (integer 0 *) (*MAX_VTX1*)) :initially 0)
;; (D) Data Value array
  (valArr :type (array (integer 0 *) (*MAX_VTX1*)) :initially 0)
;; (E) This contains pointers to the vertices that each edge is attached to
  (edgeArr :type (array (integer 0 65535) (*MAX_EDGE1*)) :initially 0)
 :inline t)
```


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Sample BST Function in RASL DASL

```
((defun getVal (count key vtx Obj)
  (declare (xargs :stobjs Obj
                  :guard (and (natp count) (natp key) (natp vtx))))
  (cond
   ((not (mbt (Objp Obj))) 0)    ;; Only positive values stored. 0 = 'null'.
   ((not (mbt (natp count))) 0)
   ((not (mbt (natp key))) 0)
   ((not (mbt (natp vtx))) 0)
   ((zp count) 0)
   ((zp key) 0)                  ;; Only positive keys stored. 0 = 'null'.
   ((zp vtx) 0)
   ((> vtx *MAX_VTX*) 0)
   ((mbe :logic (zp (vtxCount Obj))
         :exec (int= (vtxCount Obj) 0)) 0) ;; no vertices
   ((zp (keyArri vtx Obj)) 0)
   ((< key (keyArri vtx Obj))
    (getVal (1- count) key (edgeArri (left (vtxArri vtx Obj)) Obj) Obj))
   ((> key (keyArri vtx Obj))
    (getVal (1- count) key (edgeArri (right (vtxArri vtx Obj)) Obj) Obj))
   ;; (= key (keyArri vtx Obj))
   (t (valArri vtx Obj))))

(defmacro getV (key Obj)
  `(getVal (vtxCount ,Obj) ,key (vtxHd ,Obj) ,Obj))
```


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Depth-First Search in RASL DASL

fringe: doubly-linked list of (vtx, vtx_prev) pairs

mark/spanning tree (Binary Search Tree)

```
(defun dfs_span (count vtarget gObj BST::Obj DLPR::Obj)
  (declare (xargs :stobjs (gObj BST::Obj DLPR::Obj)
                  :guard (and (natp count) (natp vtarget))))
  (cond
   ((not <recapitulation of :guard conditions>) (mv BST::Obj DLPR::Obj))
   ((zp count) (mv BST::Obj DLPR::Obj))
   ((> vtarget *MAX_VTX*) (mv BST::Obj DLPR::Obj))
   ((BST::existp vtarget BST::Obj) (mv BST::Obj DLPR::Obj)) ;; Found target vtx
   ((zp (DLPR::ln DLPR::Obj)) (mv BST::Obj DLPR::Obj))
   (t (mv-let (v vpred) (DLPR::nthelem 0 DLPR::Obj)
        (cond
         ((not (posp v)) (mv BST::Obj DLPR::Obj))
         ((> v *MAX_VTX*) (mv BST::Obj DLPR::Obj))
         ((not (posp vpred)) (mv BST::Obj DLPR::Obj))
         ((> vpred *MAX_VTX*) (mv BST::Obj DLPR::Obj))
         ((BST::existp v BST::Obj)
          (seq2 BST::Obj DLPR::Obj
                (BST::nop BST::Obj)
                (DLPR::rst DLPR::Obj)
                (dfs_span (1- count) vtarget gObj BST::Obj DLPR::Obj)))
         (t (seq2 BST::Obj DLPR::Obj
                  (mark v vpred BST::Obj)
                  (seq DLPR::Obj
                       (DLPR::rst DLPR::Obj)
                       (explore *MAX_EDGES_PER_VTX* v gObj BST::Obj DLPR::Obj))
                  (dfs_span (1- count) vtarget gObj BST::Obj DLPR::Obj)))))))))
```


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Functional Correctness Proofs in RASL DASL

- Since we have a formalization of the DASL data structure form in ACL2, we should perform functional correctness proofs
- Doubly-linked list correctness proofs are relatively simple
- For Binary Search Trees, we have a nice correctness property, namely that inorder traversal of the BST yields a sorted list:

```
(defthm bstp-ordered-posp-of-inorder-traversal
  (implies
   (bstp Obj)
   (ordered-posp (inorder Obj))))
```

where **bstp** is a BST well-formedness property that says, mainly, that all non-zero keys of the "left" children of any given non-zero vertex **vtx** of the BST are less than (**keyArri vtx Obj**), and that the keys of the "right" children of **vtx** are greater than **(keyArri vtx Obj)**

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Functional Correctness Proofs (cont'd.)

- Thus, for any Binary Search Tree mutator function **`mut`**, we need to prove:

```
(defthm mut-preserves—ordered-posp-of-inorder-traversal
  (implies
   (bstp Obj)
   (ordered-posp (inorder (mut <args> Obj)))
```

which, in turn, requires that **`bstp`** is upheld by **`mut`**. Not surprisingly, this isn't easy using a stobj-based infrastructure, what with arrays, tail-recursive functions, and whatnot

- The hard part is establishing that the "keys of left subtree all less than" and the "keys of right subtree all greater than" functions continue to hold after **`mut`**

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Functional Correctness Proofs (cont'd.)

- To perform the proofs of the **`all-lt-p`** and **`all-gt-p`** functions (not shown for space), we need to define some lower-level well-formedness invariants on the underlying stobj representation of the BST, and show that they hold after **`mut`**.
- Many possible invariants — how do we know which to define?
  - Use "The Method": Try some high-level proofs, and see what low-level properties pop up in the failed subgoals
- Using "The Method" led to three well-formedness predicates for the BST stobj:
  - The non-zero vertex array element for vertex index **`vtx`** is

```
(1+ (* (1- vtx) *MAX_EDGES_PER_VTX*))
```

  - All non-zero edge array elements are unique, i.e. no two edges "point to" the same vertex
  - All non-zero edges "point to" a non-zero entry in the vertex array; no "dangling edges"

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Functional Correctness Proofs (cont'd.)

- The latter two invariant functions are computationally expensive; however, they are only called by functions that are used in proofs, and are not called by any runtime BST function
- Using these discovered wellf-formedness predicates, we have been able to prove that the **`all-lt-p`** and **`all-gt-p`** functions continue to hold after the **`insert`** mutator
  - The "long pole in the tent" to proving the top-level BST functonal correctness properties
- Currently working to make these proofs more efficient by disabling more functions and unnecessary theorems
  - **`all-lt-p`** proof takes approximately 30 minutes of proof time on an ancient 2012 MacBook Pro

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Status and Next Steps

- *Completed*:
  - HOL4 DASL toolchain supports datatypes and graphtypes
  - Basic Data structure prototyping using RASL DASL complete
    - Several data structures developed, e.g. stacks, lists, binary search trees, priority queues, directed graphs
    - Several applications implemented, including breadth/ depth-first search, lexer/parser, and inference engine
- *Next Steps*:
  - Complete binary search tree functional correctness proofs
    - “Hard part” done
  - Improve book certification times
  - Complete DASL proof infrastructure in HOL4
  - Demonstrate end-to-end DASL datatype proof using CakeML
  - Demonstrate DASL compilation to VHDL/FPGA

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