HIHAT GRAPHS

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OUTLINE

- Graph requirements
- Why HiHAT
- Types
- APIs
- How it works
- Requested feedback

- Goal: get early feedback vs. communicate final plan of record

REQUIREMENTS

- Staging
- Hierarchy
- Dynamism
- Generality
- Trait limitations
- Operations
- Retargetability, pluggability
- Interoperability

STAGING

- A key benefit of graphs is reuse
  - Create a graph, specialize it, reuse it
  - Amortize the costs of graph creation and resource binding, per-node handling
- Three key stages: nouns in blue, verbs in green
  - Template: execution and memory resources may not be bound, structure evolving
    - Still target agnostic while in template form, so doesn't use pluggable implementations
  - Instance: structure is fixed, parameters may still change
    - Execution and platform-internal resources bound when instantiated (template → instance)
  - Invocation: structure and parameters are fixed
    - Parameters passed in and data bound when invoked (instance → invocation)
- Binding
  - *Specified* in stage: exec resources @ template, data resources @ instance
  - *Occurs* and is acted upon by the verbs that transition between stages

HIERARCHY

- Three granularities
  - Overall graph – may span multiple targets or even multiple nodes
  - Instantiable subgraph – must be handlable by a single graph-handling runtime
  - Individual nodes – may be handled by any plugged-in implementation
- Distinction between instantiable and overall graphs begets hierarchy
  - Graph of subgraphs, where nodes may have associated subgraphs
- Hierarchical support goes along with support for transformation
  - Can group a set of nodes into a subgraph
  - Can replace a set of nodes with another set of nodes, e.g. decomposition, aggregation

DYNAMISM

- When nodes get dynamically added
  - 1. Prior to instantiation – part of transformation, e.g. partitioning, decomposition
    - No special handling
  - After instantiation – new work created while on execution resources
    - 2a. Continuation within the same resource constraints
    - 2b. Follow-on instantiation with new resource assignments
- 3. Nodes may also be dynamically selected
  - 3a: Within: Graph may include a superset of nodes covering multiple control flow paths
    - This may incur extra resources to cover the union (vs. sum) of all paths
  - 3b: Across: Select which of several next graphs to execute

GENERALITY

- Not tied to any given target implementation, e.g. CUDA may not be there
- Imposing no runtime-specific restrictions, e.g. file IO is ok
- User-defined implementations may be provided for any functionality
- Supports all operations, including async allocation
- Supports interactions among multiple graphs

TRAIT LIMITATIONS

- Implementation-specific support is captured in a set of architectural traits
  - Limitations on task content, e.g. file IO
  - Capabilities for memory management, e.g. ability to clear memory, thread specific
  - Limitations on structure, e.g. only one incoming dependence unless SyncAll or SyncAny
- Registered implementations declare their support for traits
  - Think of a bit vector
- Requestors declare their expected support
  - Can either trust the user to check for supported traits, or confirm support in debug mode

OPERATIONS

- Graph nodes are generic, but they have a kind and descriptor
  - Kind and descriptor in a single struct to promote consistency
  - Pointers to descriptors are type checked within a union
- Supported action kinds
  - Memory: alloc, free, memset (for convenience)
  - Invocation – available menu of primitives plus user-defined functions
  - Copy
  - Synchronization – any or all (nop that only managed dependencies)
  - Initial focus is only on low-level (common layer) primitives

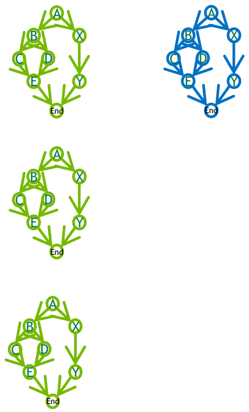
RETARGETABILITY, PLUGGABILITY

- Retargetability
  - Multiple kinds of execution resources, e.g. CPU, GPU, FPGA
  - Multiple kinds of memory resources
  - Multiple underlying runtimes, e.g. CUDA, no CUDA
- Pluggability
  - Dispatch to registered implementations that are pluggable by an admin or user
  - Implementations are selected based on target and a selector
  - Selector is applicable where the functionality may be equivalent but performance may not, e.g. different kinds of allocators, different policies

INTEROPERABILITY: MULTIPLE TARGETS

- Interface seamlessly and efficiently across multiple targets
- Synchronization: Sync objects may be used natively or via programmatic interfaces
  - They may be fully described so another agent can know how to trigger or poll them
  - Or they may be tagged and used natively by implementations that know how to use them
  - Producers and consumers can interact directly vs. through an intermediary
- Memory: Metadata in DataView object manages (among other things)
  - Which memory resources data objects can migrate to or be replicated on
  - Which execution resources can have read access, write access
  - How the stored data should currently be interpreted
- Graphs: instantiable subgraphs for each of many targets, interfacing with each other

INTEROPERABILITY: GRAPHS



- Work may be partitioned across multiple graphs
  - Graphs on the same target, e.g. sequence of subgraphs
  - Different targets on the same node, e.g. for multiple runtimes on hetero resources
  - Different nodes, with a listener thread that handles remote requests on each one
- Spanning graphs
  - Dependence edges may span graphs
  - Operations may span graphs on different targets, e.g. marshal/demarshal for a copy
- HiHAT support for cross-graph interaction
  - Interface nodes added for cross-graph dependencies and as proxies for remote actions
  - Only interface nodes interact with the runtime’s remoting capabilities

INTEROPERABILITY NODE CASES

- Incoming or outgoing dependence arcs
  - Incoming: passive, unless active polling for trigger of sync object is needed
  - Outgoing: passive for dependencies, unless active triggering of sync object is needed; may be active otherwise for a remote action on another target – see below
- Cross-target or same target
  - Only need to manage scope if same target
  - If different targets, some remoting is involved: create command, marshal parameters, put in command queue, signal target side

WHY HiHAT GRAPHS

- Retargetability
  - Multiple targets
  - Nodes (actions) are inherently retarget-ready
  - Nodes can be rebound while in template stage
- Generality
  - Node or graph granularity, graphs are serializable
  - Interfaces between graphs
  - Nodes are affinitizable to execution and memory resources
  - Graph transformation
  - Trait-based implementation restrictions

TYPES

- GraphNodeKindEnum – Alloc, Free, MemSet, Copy, Invoke, SyncAll/Any, …
- Graphs – template, instance, invocation
- Nodes – template and instance; generic wrt kind
- Descriptors – struct with kind and per-kind parameters

GRAPH STAGES

- Creation
  - Template – explicitly constructed by clients
  - Instance – created by GraphInstantiate
  - Invocation – created by GraphInvoke
  - Each of these has a handle for HiHAT; CUDA Graphs doesn’t support invocation handles
- Nodes
  - Template – needed for explicit construction
  - Instance – needed for customization of parameters
  - Invocation – apparently not needed for CUDA Graphs, but these are HiHAT actions
- Sets of nodes are only used internally
- Arrays of template or instance nodes may be obtained from queries

APIS

- Factory: GraphTemplate – Create, Destroy, Clone, Node {Add, Destroy, Move}, Edge {Add, Remove}
- Verbs: GraphInstantiate, GraphInvoke
- GraphInstanceDestroy
- Graph getters: Graph{Template, Instance} – Get[Num]RootNodes, GetCorrespondingNode
- Node getters: Graph{Template,Instance}Get – Node[Num]Dependents, Node{Exec}Descr
- GraphAggregate, GraphAddInterfaceNodes

GRAPH CONSTRUCTION

- Client owns the graph objects and is responsible for destruction
  - Explicit (*hheGraphTemplateCreate*) or implicit (*hheGraphInstantiatiate*, *hheGraphInvoke*) creation yields handle
  - *hheGraph<stage>Destroy* API for all three stages
- Specialization
  - *hheGraphTemplateClone* a graph if the original graph is to be retained
  - Modify a graph if the original graph is no longer needed
- Nodes
  - *hheGraphTemplateNodeAdd* to a graph that's under construction
  - *hheGraphTemplateNodeDestroy* and add to a cloned graph that's being modified

EDGES

- Edges are not an explicit object
  - Can add an edge as a pair of nodes vs. creating an edge object first
  - Is there a usage model for associating properties with edges vs. endpoints?
- Adding and removing edges
  - *hheGraphTemplate{Add, Remove}Edge* – not for instance since structure fixed
  - Arguments are source and target nodes
  - Edge creation is not done upon node creation – nodes may not exist yet
  - Edges are not explicitly associated with a graph – edges may span graphs

GRAPH GETTER FUNCTIONS

- Nodes are accessible for template and instance graphs, not invocation graphs
- Nodes are associated with a graph or subgraph
  - Organized hierarchically, so # nodes is specific to a level in the hierarchy
- Nodes in a graph are accessible based on dependence-based traversal
  - Get array of up to N roots: *hheGraph[Template/Instance]Get[Num]RootNodes*
  - Get array of up to N dependents: *hheGraph [Template/Instance]Get[Num]Dependents*

NODE GETTER/SETTER FUNCTIONS

- Node-specific information is captured in two structures
  - Node description, *hheGraphNodeDescr*
    - Kind of node
    - Descriptor includes execution and memory resources – mutable during template stage
    - Descriptor includes parameters – mutable during instance stage
    - These are unique per node
  - Execution description, *hheGraphNodeExecDescr*
    - Execution policies and configuration
    - These may be common to many or all nodes

- *hheGraphTemplateGetNodeDescr* returns a pointer to the *hheGraphNodeDescr*
- *hheGraphTemplateSetNodeDescr* passing in a pointer to the *hheGraphNodeDescr*
- *hheGraphTemplateGetNodeExecDescr* returns a pointer to *hheGraphNodeExecDescr*
- *hheGraphTemplateSetNodeExecDescr* passing in pointer to *hheGraphNodeExecDescr*

AGGREGATE, MOVE

- Nominal starting point: 1 flat root graph (by convention only) with all template nodes
- Next step: *aggregate* subsets of nodes into subgraphs
  - Criteria: execution resources (node descriptor) or a generic tag (ExecCfg)
  - What other criteria are interesting? Connected component(s)?
  - Matching: criteria is a subset of actual, exact match, or actual is a subset of criteria?
- Optional step: shuffle nodes among subgraphs with GraphNodeMove
  - Example: partition 30 nodes into 10+10+10, then shuffle to be 10+9+11
- Edges are unchanged upon Aggregate or NodeMove

ADDING INTERFACE NODES

- Goals
  - Make interfaces among subgraphs explicit
  - Instead of specializing all node types for interfacing, just specialize interface node
- Timing, control
  - Incremental maintenance could be wasteful – wait until needed and ready/stable
- Criteria
  - Necessary: Edge endpoints are in different subgraphs (siblings, ancestors, whatever)
  - Sufficient: May not need special handling unless in different targets

HOW IT WORKS

- Target-agnostic template nodes
- Mapping HiHAT Graphs to CUDA Graphs
- Async memory management

TARGET-AGNOSTIC TEMPLATE NODES

- Template nodes are works in progress
  - Execution and memory resources may be rebound
    - → Don’t call target-specific implementation while in template form: avoid redos
  - Created nodes will eventually be bound to at least one execution target
- Nodes vary in how target agnostic they are
  - If the functionality is supported on all targets, they are completely agnostic
  - The functionality may be supported on only a subset of targets, e.g. calloc (clear)
  - Parameters may be target specific, e.g. policies, shmem sizes
  - Preregistered function handles are target specific: scheduler knows, vs. string lookup

MAPPING HIHAT GRAPHS TO CUDA GRAPHS

- First pass
  - Creation of graph, nodes, edges at template stage is mapped to directly CUDA Graphs
  - Restrictions: all and only CUDA Graphs, one (sub)graph at a time
- Second pass
  - Creation of graph, nodes, edges at template stage is handled by only HiHAT
  - Upon instantiation of a (sub)graph, template graph, nodes, edges created for CUDA Graph, then GraphInstantiate is called
  - Eased restrictions: multiple graphs, different kinds of graphs
- Advantage: less initial work, tests directness of mapping

ASYNC MEMORY MANAGEMENT

- A target need not support full HiHAT-compatible memory management natively
  - Reference implementations could be created per target and plugged in
- Full freedom to manage alloc/free on a target or from the (CPU) host, to use sub-allocators, to access virtual addresses anywhere appropriate, on host or target
  - It's recommended that allocs via HiHAT be paired with frees via HiHAT
- "Interpolation light" using the current implementation
  - Want to be able to dynamically allocate, provide an address of returned address, use it in a node in the same graph
  - References to allocated address can be dereferenced in a global (non-parameter) variable inside another task which is control dependent on the completion of the async alloc.
  - Standard functions like memcpy could have additional versions with parameters that are addresses of parameters vs. real parameters.
- Dealing with allocation failures
  - Success or failure of an action can be encoded in the ActionHndl's completion status

REQUESTED FEEDBACK

- Generic nodes with kind descriptors
- Use of HiHAT types
- Need for explicit edge type
- Dependencies added separately from node creation?
- Multiple input dependences on any node or just SyncAll/SyncAny?
- Node access via dependence-based traversal; also as an unordered set?
- Nodes in graphs are managed hierarchically

GENERIC NODES AND KIND DESCRIPTORS

```
typedef struct {
    hhAPIEnum node_type;
    Bool remote;
    union {
        hheGraphNodeAllocDescr Alloc;
        hheGraphNodeFreeDescr Free;
        hheGraphNodeMemsetDescr Memset;
        hheGraphNodeCopyDescr Copy;
        hheGraphNodeInvokeDescr Invoke;
        hheGraphNodeSyncAllDescr SyncAll;
        hheGraphNodeSyncAnyDescr SyncAny;
        hheGraphNodeSubgraphDescr Subgraph;
        hheGraphNodeSyncAllRemoteInDescr SyncAllRemoteIn;
        hheGraphNodeSyncAllRemoteOutDescr SyncAllRemoteOut;
    } descr;
} hheGraphNodeDescr;

typedef struct {
    hheGraphTemplate subgraph;
} hheGraphNodeSubgraphDescr;
```

```
typedef struct {
    hhMemHndlSet mem_resrc_set;
    hhResrcHndlSet exec_resrc_set;
    hhDataView *out_mem_hndl;
    void **out_addr;
    size_t num_bytes;
    hhMemTrait mem_trait;
} hheGraphNodeAllocDescr;

typedef struct {
    hhMemHndlSet mem_resrc_set;
    hhResrcHndlSet exec_resrc_set;
    hhDataView dst;
    size_t dst_offset;
    hhDataView src;
    size_t src_offset;
    size_t num_bytes;
} hheGraphNodeCopyDescr;
```

ADDING A NODE

```
hhRet hheGraphTemplateNodeAdd (
   hheGraphNodeDescr        *descr;       ///< Descriptor for kind of node (NULL if nop)
   hheGraphNodeExecDescr  *exec;        ///< Descriptor struct with ExecPol, ExecCfg (NULL if not async)
   hheGraphTemplate           graph;      ///< Graph to add this node to (must not be NULL)
   hheGraphTemplateNode    *out_node  ///< Handle to created node (NULL if no handle needed)
 );

typedef struct {
   hhExecPol exec_pol;
   hhExecCfg exec_cfg;
 } hheGraphNodeExecDescr;
```

ADDING A NODE – UNDERLYING TYPES

```
typedef struct {
    void *chooser;                      ///< value or pointer to blob that selects among registered implementations
    size_t num_parameters;              ///< number of parameters for exec policy
    size_t parms[NUM_EXEC_POL_PARMS];   ///< parameters for exec policy
} hhExecPolImpl;

struct hhExecCfgImpl {
    hhExecOrderEnum exec_order;    ///< FIFO, per_dep
    hhAsyncModeEnum async_mode;    ///< Async, block, defer
    int prof_action;               ///< One or more profiling actions
    int prof_option;               ///< One or more items for profiling information to record
    int prof_state;                ///< One or more ActionStates to profile
    hhExecScopeImpl exec_scope;    ///< Execution scope
    hhTagSetImpl tags;             ///< Tags (does not implicitly include the one in exec_scope)
};
```