

ADAPT Phase 1 Architecture Specification (DRAFT)

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Purpose of this Document

This document specifies the architecture of the ADAPT system intended for first power-on in May, 2016 and first evaluation in September 2016. This specification includes:

- description of our first test case scheduled for mid-May 2016
- overall architecture and interconnectivity discussion
- type-based description of all modules in the system
- schema of the blackboard database shared by all modules
- semantics and syntax of all stored data used to configure modules in the system
- mapping from schema of TA-1 provided input data to blackboard schema

First Test Case

(To be verified by David Burke with TA5 team) Our first evaluation target will be the social media APT setting as described by TA4. A key aspect of that setting is a command and control APT phase that persists on the described Pandex server. One activity described for that C2 phase is the use of nginx to connect to a port, listen for a while, and then disconnect. Our first test case will emulate this activity using a simple script. Using at least SPADE (SRI TA1) data, but hopefully at least one other data source, we will test our ability to detect and classify this activity.

The platform setup we will use for first test is to integrate our VM-based ADAPT platform with the "TC-in-a-box" platform provided by TA3. All modules in our system will interact with data in the Blackboard (Bb) for this test case. Modules may subscribe to notification feeds provided by other modules that indicate when new data has arrived in Bb.

Relationship to TC Common Data Model

The ADAPT architecture operates on data derived from inputs from TA1 performers and expressed in the TC Common Data Model (CDM). Our data, stored in our Blackboard database, maps directly to the CDM as shown in the Blackboard schema section of this specification. At present, this document is current with CDM v0.7.

Architecture of ADAPT

Overview of Abstraction layers in ADAPT

System activity data used and created by an ADAPT instance is graph-structured and hierarchical. Data imported from TA-1 sensors comprises the *base layer* of our database. This layer models

- units of execution in the system at various abstractions from individual events to processes
- artifacts such as files, network flows, and memory buffers
- agents such as humans (primarily for attribution purposes)
- hosts on which units of execution run and artifacts reside
- relationships among these entity classes

Because the volume of base layer data will be large, ADAPT abstracts this data to allow reasoning at lower bandwidth. We use a multi-layer hierarchical abstraction as well as a single-layer proximity abstraction.

Our hierarchical abstraction begins with the pattern layer. Pattern instances are intuitive collections of base layer data. For example, an instance of the pattern *PROCESS Reads FILE* might be comprised of a unit of execution (the process), an artifact (the file), and an event (the read), along with the relationship instances that connect these entity instances. Each pattern instance is represented in our data model as a pattern node, along with edges connecting that node to each of the base layer entity instances that comprise its pattern. By inference, edges connecting those base layer entities are included in the pattern as well.

The next layer of abstraction is the activity layer. Activities are the leaf entities in our APT grammar, and also represent intuitive computations. Activities are comprised of patterns. For example, an instance of the activity *Copy File to Directory* might be comprised of several pattern instances: {*PROCESS Opens FILE*, *PROCESS Reads FILE*, *PROCESS Opens File for Write*, *PROCESS Writes File*, and *PROCESS Closes File*}. Each activity instance is represented in our data model as an activity node along with edges connecting that node to each of the pattern instances that comprise that activity. By inference, edges connecting those pattern instances are included in the activity as well.

The next layer of abstraction is the APT Phase layer. Phases are the node entities in our APT grammar, and represent instances of APT phases as described there. Phases are comprised of activities. Each phase instance is represented in our data model as a phase node along with edges connecting that node to each of the activity instances that comprise the phase. As above, edges connecting those components are included implicitly.

The next layer of abstraction is the APT layer. APTs are the root of our APT grammar, and represent instances of entire APTs. Each APT instance is comprised of phase instances. APTs are represented by an APT node along with edges from that node to the Phases that comprise the APT instance.

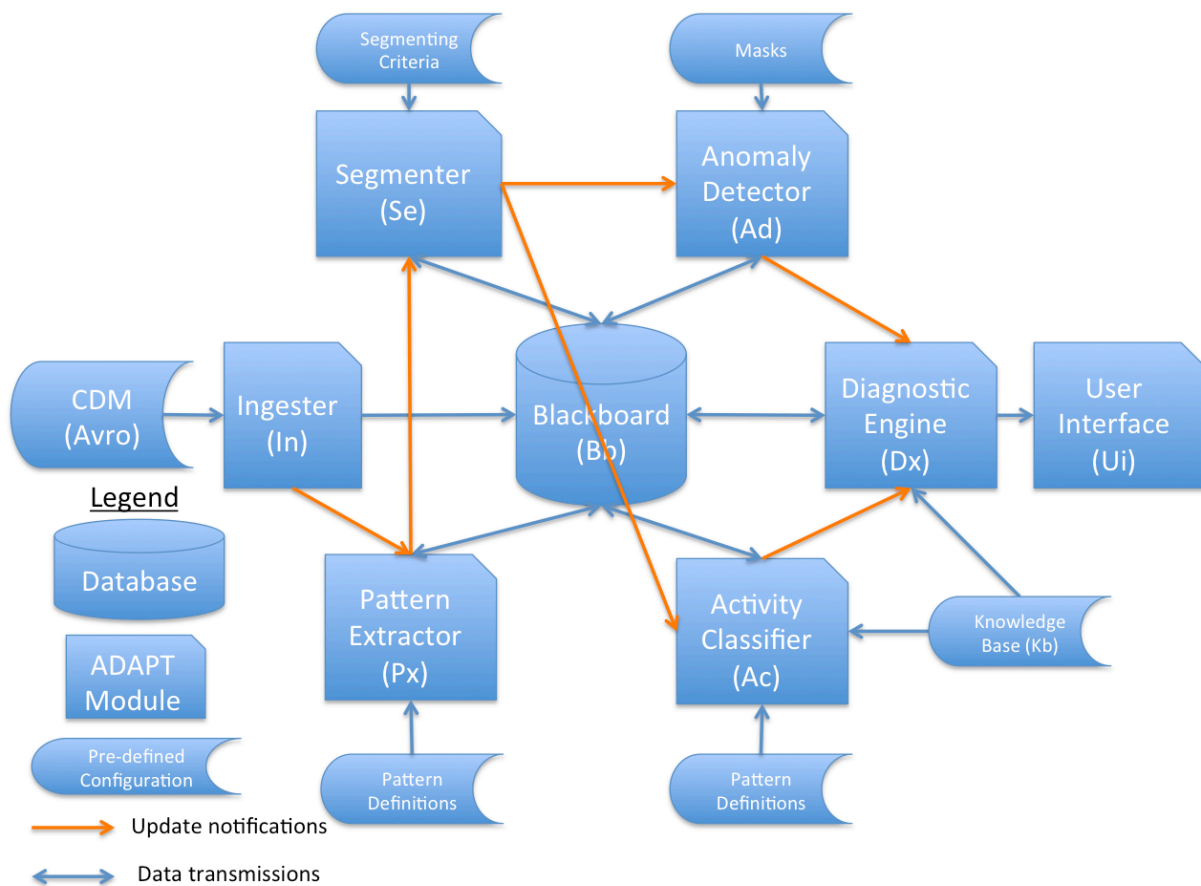
Overview of Segmentation in ADAPT

Orthogonal to the hierarchical structure above is the notion of segmentation. An ADAPT graph can be segmented into smaller graphs for ease of reasoning and computation. Thus for example base layer data can be segmented, but so can data that includes patterns, activities, and phases.

Segmentation involves grouping all such data by common characteristics. Such characteristics are typically values of properties attached to some or all nodes. For example, an ADAPT graph might be segmented by 2-hour time windows, resulting in a number of sub-graphs corresponding to 2-hour windows. As another example, an ADAPT graph might be segmented by process ID, resulting in a distinct sub-graph related to each unique process ID reported in the data. Segmentation can be accomplished using combinations of characteristics as well. For example, an ADAPT graph might be segmented into a unique subgraph for each process ID in each 2-hour window. Segments are represented by a Segment node along with edges from that node to all nodes that belong to the segment.

ADAPT Architecture

The architecture of ADAPT is shown below.



Data flow at a high level works like this:

- The Ingestor (In) takes as input data in the TA3-defined CDM Avro schema, pulling it from a Kafka queue topic provided by TA3. In produces as output base layer data in the blackboard (Bb) that conforms to the Bb schema described later
- The Pattern Extractor (Px) uses a pre-defined set of patterns. Px takes as input data from Bb,

one segment at a time (the entire graph is the default segment), and produces as output new data in Bb at the pattern layer of abstraction.

- The Segmenter (Se) uses a pre-defined set of segmentation criteria. It takes as input data from Bb (including base layer data and pattern instances) and produces as output new data in Bb at the Segment layer of abstraction described later.
- The anomaly detector (Ad) uses a pre-defined set of masks that define the features to be analyzed for anomalies. Ad takes as input data from Bb, one segment at a time, and produces as output anomaly score annotations for each segment surveyed
- The activity classifier (Ac) uses a pre-defined set of activities that are exactly the leaves in our APT grammar tree. Ac takes as input data from Bb at the pattern layer of abstraction, and produces as output new data in Bb at the activity layer of abstraction
- The Diagnostic Engine (Dx) uses the pre-defined APT grammar from Kb. Dx takes as input data from Bb at the activity layer of abstraction, along with anomaly scores attached to segments, and produces as output new data in Bb at the diagnosis layer of abstraction. Dx also communicates discovered APT candidates to the Ui for display to the user.

For our Phase 1 ADAPT System (Alpha-1), we consider only non-iterative analysis by ADAPT modules. That is, each module operates on Bb data only once. Later on, we may employ iterative processing both to accommodate streaming input data and to allow for more powerful analytics.

Describing ADAPT Modules

The following sections describe each ADAPT module. Each section should cover the following, but need be no longer than a page: * A detailed type signature for the module's inputs and outputs, suitable for other modules to interact with the module * A description of any private stored data, such as templates or knowledge, that the module will use * A description at your choice of detail of how you do the processing you do * Any limitations you see to your planned implementation that might affect our first testing * How many concurrent instances of your module will be running at a time, and how they distinguish data on which they operate * What dependencies you have on other modules

The Ingestor (In) - Tom

In:: [CDM-Element] > [[base-node], [base-edge]]

That is, the In takes in a set of CDM statements and produces a graph of nodes and edges in the Bb.

The Pattern Extractor (Px) - Erin/Trevor

Px:: [[ADAPT-node],[ADAPT-edge]]> [Pattern-definition] > [<Pattern-node,[Pattern-to-base-edge]>]

That is, Px takes in the graph in the Bb and a list of pattern definitions, and produces as output pattern nodes in the Bb and associated edges connecting those nodes to their respective base layer component nodes

The Segmenter (Se) - Adria

Se:: [[ADAPT-node],[ADAPT-edge]] > [Segment-criterion] > [<Segment-node,[Segment-to-base-

edge]>]

That is, the Se takes in a graph of nodes and edges in the Bb and a list of segmentation criteria, and produces in the Bb a set of segment nodes and the edges that connect each to the other nodes in the graph that are its members.

The Anomaly Detector (Ad) - Alan

Ad:: [[ADAPT-node],[ADAPT-edge]] > [Mask] > Segment-identifier > [<Segment-node-id,Anomaly-score>]

That is, Ad takes in the graph in the Bb, a list of masks, and a segment identifier, and produces as output a list of anomaly score annotations attached to segment nodes in the graph.

The Activity Classifier (Ac) - Hoda

Ac:: [[ADAPT-node],[ADAPT-edge]] > Segment-identifier > [<Activity-node,[Activity-to-pattern-edge]>]

That is, Ac takes in the graph in the Bb and a segment identifier, and produces as output a list of activity nodes in the Bb and the edges that connect them to their component pattern nodes.

The Diagnostic Engine (Dx) - Rui

Dx:: [[ADAPT-node],[ADAPT-edge]] > [<Phase-node,[Phase-to-activity-edge]>] Dx:: [[ADAPT-node],[ADAPT-edge]] > [<APT-node,[APT-to-phase-edge]>]

That is, Dx takes in the graph in the Bb and produces as output a list of phase nodes in the Bb and the edges that connect them to their component activities, and a list of APT nodes and the edges that connect them to their component phases.

The Blackboard (Bb) - Erin

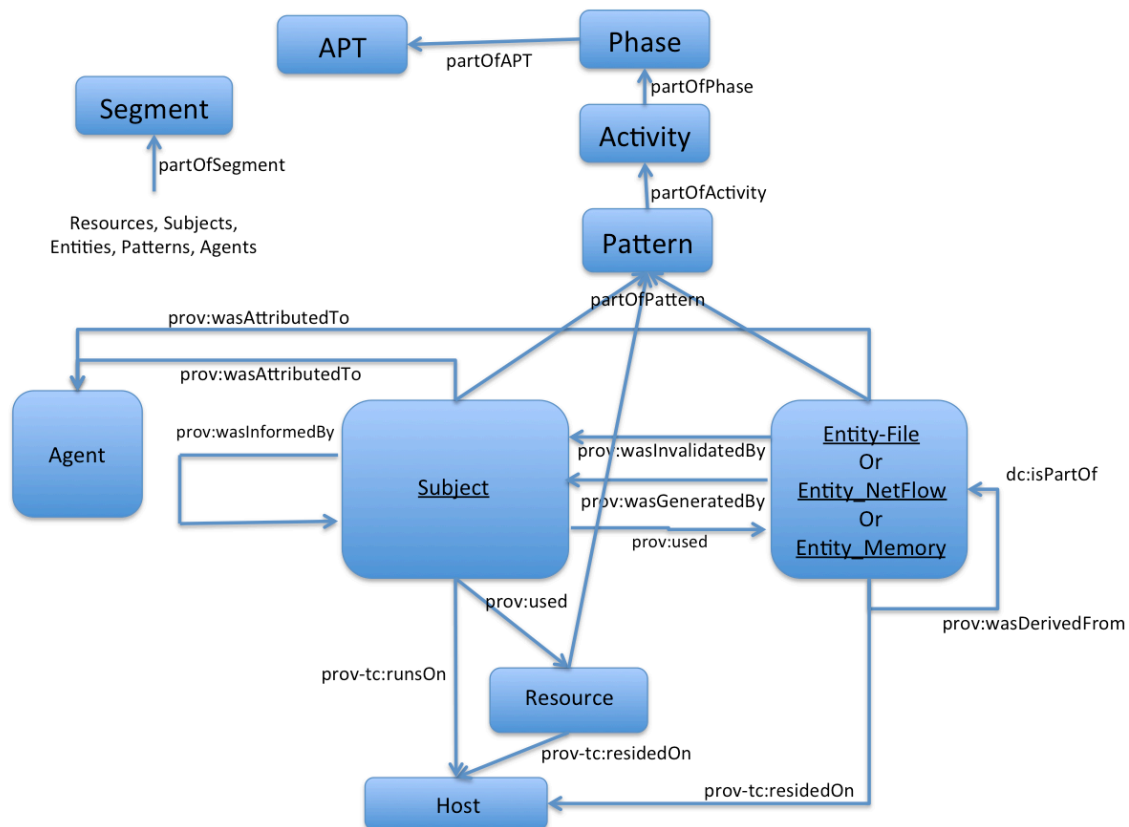
The Bb has no type signature that I can think of

The Knowledge Base (Kb) - David

The Kb has no type signature that I can think of.

Blackboard Schema for ADAPT

In this section, we describe the conceptual model we use internally to Bb is shown below, along with the mapping from the TC Common Data Model to our internal model.



Each instance of an entity or relationship class may have certain required as well as other optional attributes that describe that instance. Details of entities, relationships, and attributes in the model are defined in the Entities and Relationships sections below.

Data Types for ADAPT Schema

The following are type definitions for types used in the schema description.

prov-tc:source is used in many places, and maps to CDM enum type InstrumentationSource:

```

enum InstrumentationSource {
    SOURCE_LINUX_AUDIT_TRACE,
    SOURCE_LINUX_PROC_TRACE,
    SOURCE_FREEBSD_OPENBSM_TRACE,
    SOURCE_ANDROID_JAVA_CLEARSCOPE,
    SOURCE_ANDROID_NATIVE_CLEARSCOPE,
    SOURCE_LINUX_AUDIT_CADETS,
    SOURCE_WINDOWS_DIFT_FAROS
}

```

prov-tc:agentType is used in Agents, and maps to CDM enum type *PrincipalType*:

```

enum PrincipalType {
    PRINCIPAL_LOCAL,           // a principal local on the host
    PRINCIPAL_REMOTE          // a remote principal
}

```

prov-tc:eventType is used in Subjects, and maps to CDM enum type *EventType*:

```

enum EventType {
    EVENT_ACCEPT,
    EVENT_BIND,
    EVENT_CHANGE_PRINCIPAL,
    EVENT_CHECK_FILE_ATTRIBUTES,
    EVENT_CLOSE,
    EVENT_CONNECT,
    EVENT_CREATE_OBJECT,
    EVENT_CREATE_THREAD,
    EVENT_EXECUTE,
    EVENT_FORK,
    EVENT_LINK,
    EVENT_UNLINK,
    EVENT_MMAP,
    EVENT_MODIFY_FILE_ATTRIBUTES,
    EVENT_MPROTECT,
    EVENT_OPEN,
    EVENT_READ,
    EVENT_WRITE,
    EVENT_SIGNAL,
    EVENT_TRUNCATE,
    EVENT_WAIT,
    EVENT_BLIND
}

```

prov-tc:sourceType is used in Resources, and maps to CDM enum SourceType:

```
enum SourceType {  
    // base sensors  
    SOURCE_ACCELEROMETER,  
    SOURCE_TEMPERATURE,  
    SOURCE_GYROSCOPE,  
    SOURCE_MAGNETIC_FIELD,  
    SOURCE_HEAR_RATE,  
    SOURCE_LIGHT,  
    SOURCE_PROXIMITY,  
    SOURCE_PRESSURE,  
    SOURCE_RELATIVE_HUMIDITY,  
    // composite sensors  
    SOURCE_LINEAR_ACCELERATION,  
    SOURCE_MOTION,  
    SOURCE_STEP_DETECTOR,  
    SOURCE_STEP_COUNTER,  
    SOURCE_TILT_DETECTOR,  
    SOURCE_ROTATION_VECTOR,  
    SOURCE_GRAVITY,  
    SOURCE_GEOMAGNETIC_ROTATION_VECTOR,  
    // camera and GPS, temporary  
    SOURCE_CAMERA,  
    SOURCE_GPS  
}
```

prov-tc:trustworthiness is used in many places, and maps to CDM enum type IntegrityTag:

```
enum IntegrityTag {  
    INTEGRITY_UNTRUSTED,  
    INTEGRITY_BENIGN,  
    INTEGRITY_INVULNERABLE  
}
```

prov-tc:privacyLevel is used in many places, and maps to CDM enum type ConfidentialityTag

```
enum ConfidentialityTag {  
    CONFIDENTIALITY_SECRET,  
    CONFIDENTIALITY_SENSITIVE,  
    CONFIDENTIALITY_PRIVATE,  
    CONFIDENTIALITY_PUBLIC  
}
```


prov-tc:subjectType is used in Subjects, and maps to CDM type *SubjectType*, but adds two additional enum values:

```
enum SubjectType {  
    SUBJECT_PROCESS,  
    SUBJECT_THREAD,  
    SUBJECT_UNIT,  
    SUBJECT_BLOCK,  
    SUBJECT_EVENT  
}
```

prov-tc:genOperation is used in *wasGeneratedBy* relationships:

```
enum genOperation {  
    WRITE,  
    SEND,  
    CONNECT,  
    TRUNCATE,  
    CHMOD,  
    TOUCH,  
    CREATE  
}
```

prov-tc:delOperation is used in *wasInvalidatedBy* relationships:

```
enum delOperation {  
    DELETE,  
    UNLINK  
}
```

prov-tc:useOperation is used in *uses* relationships:

```

enum useOperation {
    OPEN,
    BIND,
    CONNECT,
    ACCEPT,
    READ,
    MMAP,
    MPROTECT,
    CLOSE,
    LINK,
    MODATTRIBUTES,
    EXECUTE,
    USEASINPUT
}

```

prov-tc:strength is used in wasDerivedFrom relationships:

```

enum Strength {
    WEAK,
    MEDIUM,
    STRONG
}

```

prov-tc:derivation is used in wasDerivedFrom relationships:

```

enum Derivation {
    COPY,
    ENCODE,
    COMPILE,
    ENCRYPT,
    OTHER
}

```

prov-tc:argValue is used in Subjects:

```

record Value {
    /** The size of the value in bytes */
    int size;

    /** The actual bytes of the value (Optional) */
    valueBytes = byte[size[]];
}

```

Other primitive types used in our model:

- *prov-tc:properties* : map;
- *prov-tc:uid* : int;
- *prov-tc:url* : string;
- *prov-tc:file-version* : int;
- *prov-tc:size* : int;
- *prov-tc:permissions* : short;
- *prov-tc:time* : ZuluTime;
- *prov:startedAtTime* : ZuluTime;
- *prov:endedAtTime* : ZuluTime;
- *prov-tc:srcAddress* : string;
- *prov-tc:srcPort* : int;
- *prov-tc:dstAddress* : string;
- *prov-tc:dstPort* : int;
- *prov-tc:pageNumber* : int;
- *prov-tc:address* : int;
- *prov-tc:pid* : int;
- *prov-tc:ppid* : int;
- *prov-tc:unitid* : int;
- *prov-tc:commandLine* : string;
- *prov-tc:importLibs* : list;
- *prov-tc:exportLibs* : list;
- *prov-tc:env* : map;
- *prov-tc:plnfo* : string;
- *prov-tc:location* : int;
- *prov-tc:ppt* : string;
- *prov-tc:args* : list<prov-tc:argValue>;
- *prov-tc:gid* : list;

Data Model Classes

ADAPT defines the following classes. In each case, we specify all currently recognized attributes. No alternates to the attributes shown are allowed. That is, the shown attributes are the only option available to represent the semantics they represent.

Entities (Objects in CDM)

An entity may be created, referenced, used, or destroyed, but does not take action on its own. Entity sub-types recognized at present in the TC domain include files, network packets, and memory locations. More may be added later. Shown below are the attributes of the entity class.

Entity-File (File Object in CDM)

Required:

- name of TA1 sensor source of the information provided (*prov-tc:source*) // maps to CDM FileObject.source
- a unique identifier for the file entity instance (*prov-tc:uid*) // maps to CDM FileObject.uid
- the URL used in the target system for the file (*prov-tc:url*) // maps to CDM FileObject.url
- the version number of the file (*prov-tc:file-version*) // maps to CDM FileObject.version

Optional:

- size in bytes of the file (*prov-tc:size*) // maps to CDM FileObject.size
- access permissions (*prov-tc:permissions*) // maps to CDM FileObject.permission
- creation time (*prov-tc:time*) // maps to CDM FileObject.lastTimestampMicros
- trustworthiness of the file (*prov-tc:trustworthiness*) // maps to CDM FileObject.integrity
- sensitivity of the file (*prov-tc:privacyLevel*) // maps to CDM FileObject.confidentiality
- other properties (*prov-tc:properties*) // maps to CDM FileObject.properties

Entity-NetFlow (NetFlow Object in CDM)

Required:

- name of TA1 sensor source of the information provided (*prov-tc:source*) // maps to CDM NetFlowObject.source
- a unique identifier for the network flow (*prov-tc:uid*) // maps to CDM NetFlowObject.uid
- the source IP address of the network flow (*prov-tc:srcAddress*) // maps to CDM NetFlowObject.srcAddress
- the source port of the network flow (*prov-tc:srcPort*) // maps to CDM NetFlowObject.srcPort
- the destination IP address of the network flow (*prov-tc:dstAddress*) // maps to CDM NetFlowObject.dstAddress
- the destination port of the network flow (*prov-tc:dstPort*) // maps to CDM NetFlowObject.dstPort

Optional:

- port modified time (*prov-tc:time*) // maps to CDM NetFlowObject.lastTimestampMicros
- access permissions (*prov-tc:permissions*) // maps to CDM NetFlowObject.permission
- trustworthiness of the flow (*prov-tc:trustworthiness*) // maps to CDM NetFlowObject.integrity
- sensitivity of the flow (*prov-tc:privacyLevel*) // maps to CDM NetFlowObject.confidentiality
- other properties (*prov-tc:properties*) // maps to CDM NetFlowObject.properties

Entity-Memory (Memory Object in CDM)

Required:

- name of TA1 sensor source of the information provided (*prov-tc:source*) // maps to CDM MemoryObject.source
- a unique identifier for the memory area (*prov-tc:uid*) // maps to CDM MemoryObject.uid
- the virtual page number of the area (*prov-tc:pageNumber*) // maps to CDM

MemoryObject.pageNumber

- the referenced virtual address (*prov-tc:address*) // maps to CDM MemoryObject.memoryAddress

Optional:

- access permissions (*prov-tc:permissions*) // maps to CDM MemoryObject.permission
- modification time (*prov-tc:time*) // maps to CDM MemoryObject.lastTimestampMicros
- trustworthiness of the memory (*prov-tc:trustworthiness*) // maps to CDM MemoryObject.integrity
- sensitivity of the memory (*prov-tc:privacyLevel*) // maps to CDM MemoryObject.confidentiality
- other properties (*prov-tc:properties*) // maps to CDM MemoryObject.properties

Resource (SourceObject in CDM)

A resource is a physical device that can generally be read, but not written, such as a GPS sensor or camera.

Required:

- a unique identifier for the resource (*prov-tc:uid*) // maps to CDM SourceObject.uid
- the type of the resource (*prov-tc:sourceType*) // maps to CDM SourceObject.type

Optional:

- port modified time (*prov-tc:time*) // maps to CDM SourceObject.lastTimestampMicros
- access permissions (*prov-tc:permissions*) // maps to CDM SourceObject.permission
- trustworthiness (*prov-tc:trustworthiness*) // maps to CDM SourceObject.integrity
- sensitivity (*prov-tc:privacyLevel*) // maps to CDM SourceObject.confidentiality
- other properties (*prov-tc:properties*) // maps to CDM ResourceObject.properties

Subject (Subject in CDM)

A subject represents activity by a thread of running computation. It may be started by another subject, and may take action on its own to start other subjects or to affect entities. We would normally call this class "activity" per W3CPROV, but activity is used elsewhere in our schema, so we adopt the CDM name instead. Subjects in our model include Events in CDM as well as Subjects in CDM

Required attributes include:

- a unique identifier for the subject (*prov-tc:uid*) // maps to CDM Subject.uid, Event.uid
- a type for the subject (*prov-tc:subjectType*) // maps to CDM Subject.type
- an event description if the type above is Event (*prov-tc:eventType*) // maps to CDM Event.type
- name of TA1 sensor source of the information provided (*prov-tc:source*) // maps to CDM Subject.source, Event.sourece
- a start time or event occurrence time (*prov:startedAtTime*) // maps to CDM

Subject.startTimestampMicros, Event.startTimeMicros

- a sequence number for events all generated by the same subject one level up in a hierarchy (*prov-tc:sequence*) // maps to CDM Event.sequence

Optional attributes include:

- a process ID (*prov-tc:pid*) // maps to CDM Subject.pid
- a process ID of its parent (*prov-tc:ppid*) // maps to CDM Subject.ppid
- a unique identifier of a unit (outer handler loop instance) (*prov-tc:unitid*) // maps to CDM Subject.unitId
- an end time (*prov:endedAtTime*) // maps to CDM Subject.endTimestampMicros
- the command line currently executing (*prov-tc:commandLine*) // maps to CDM Subject.cmdLine
- a list of imported libraries used by the Subject (*prov-tc:importLibs*) // maps to CDM Subject.importedLibraries
- a list of exported libraries offered by the Subject (*prov-tc:exportLibs*) // maps to CDM Subject.exportedLibraries
- a string of additional process information (*prov-tc:plInfo*) // maps to CDM Subject.plInfo
- additional properties of the Subject (*prov-tc:properties*) // maps to CDM Subject.properties, Event.properties
- a location in an associated Object used in an Event (*prov-tc:location*) // maps to CDM Event.location
- the size of the data affecting an Event (*prov-tc:size*) // maps to CDM Event.size
- the program point where an Event was initiated (*prov-tc:ppt*) // maps to CDM Event.programPoint
- a list of environment variables or arguments (*prov-tc:env*) // not in CDM
- a list of event parameter values (*prov-tc:args*) // maps to CDM Event.parameters

Host (Host in CDM)

A system that may host activities and entities. For now, we ignore the obvious question about hierarchies of hosts, for example, VMs running on hardware.

Required attributes include:

- a unique identifier for the host (*prov-tc:uid*). Unsigned 32b integer

Optional attributes include:

- an IP address for the host (*prov-tc:ipAddress*). Unsigned 32b integer
- name of TA1 sensor source of the information provided (*prov-tc:source*). 32B String

Agent (Principal in CDM)

An agent represents an actor that is not a Subject on a monitored machine. An agent may be human, may be a machine in the target network that has no monitoring, or may be a machine outside the

monitored network. Agents have no required attributes.

Required attributes:

- a unique identifier for the agent (*prov-tc:uid*) // maps to CDM Principal.uid

Optional attributes:

- a user ID (*prov-tc:uid*) // maps to CDM Principal.userId
- a list of group identifiers (*prov-tc:gid*) // maps to CDM Principal.groupIds
- the type of agent (*prov-tc:agentType*) // maps to CDM Principal.type
- name of TA1 sensor source of the information provided (*prov-tc:source*) // maps to CDM Principal.InstrumentationSource
- additional properties of the Subject (*prov-tc:properties*) // maps to CDM Principal.properties

Pattern (not in CDM)

A pattern is a structure comprised of base layer elements such as Subject or Entity, and might also include Agents.

Required attributes:

- A pattern template identifier that the pattern instance matches (*prov-tc:patternID*). Unsigned 16b integer.

Activity (not in CDM)

An activity is a structure comprised of pattern instances. Activities strictly correspond to leaves in our APT grammar. Required attributes:

- An activity template identifier (that is, the name of a grammar leaf) that the activity instance matches (*prov-tc:activityID*). Unsigned 16b integer.

Phase (not in CDM)

A phase is a structure comprised of activity instances. Phases strictly correspond to internal nodes in our APT grammar. Required attributes:

- A Phase identifier (that is, the ID of an APT Phase that this Phase instance stands for) (*prov-tc:phaseID*). 16b integer

APT (not in CDM)

An APT is a structure comprised of Phase instances. Optional attributes:

- A descriptive string for the APT candidate. 64B string

Segment (not in CDM)

A Segment is a subgraph of the overall provenance graph. A segment may incorporate base layer structures, pattern instances, activity instances, or phase instances. Required attributes:

- The segmentation criteria used. String
- A list of counts for each pattern type known to the system that are included in this segment. [unsigned 32b integer]
- An anomaly score. [Float]

Relationships

Some relationships in the ADAPT model map to elements of the CDM enum type EdgeType. All such mappings are called out below. Other relationships are not present in CDM, because we add them as results of our analysis.

prov:wasGeneratedBy (Models EDGE_EVENT_AFFECTS_MEMORY, *FILE*, NETFLOW to show creations)

A wasGeneratedBy relationship indicates that an entity (the object of the relationship) was created by a Subject (the subject of the relationship, which must be of type Event).

Required attribute:

- the operation performed on the artifact (*prov-tc:genOperation*).

prov:wasInvalidatedBy (Models EDGE_EVENT_AFFECTS_MEMORY, *FILE*, NETFLOW to show deletions)

A wasInvalidatedBy relationship indicates that an artifact (the object of the relationship) was deleted by a Subject (the subject of the relationship, which must be of type Event).

Optional attribute:

- the operation performed (*prov-tc:delOperation*)

prov:used (Models EDGE_EVENT_AFFECTS_MEMORY, *FILE*,

NETFLOW for all other uses)

A used relationship indicates that an Event Subject either affected or was affected by an Entity, but did not create or delete the entity.

Optional attribute:

- the operation performed (*prov-tc:useOperation*)

A Note About Provenance Tags

Provenance tags in CDM indicate entity dependencies on other entities or on subjects. A tag may define a subject or entity either as an original source or as a derivative from other original sources. As of CDM v0.7, tags are structured in this manner:

The tag expression syntax is:

```
tagExpr := tagOp(tagExpr, tagExpr, ..) | tagId | tagInfo | integrityTag |
confidentialityTag

tagOp    := sequence | union | encode | strong | medium | weak

tagInfo  := string // contains information about the tag source or other
```

Thus a tagExpr is a tree-structured representation of dependencies of the Object or Subject to which it is attached. Each node in the tree can be any one of the following

- a tagId
- an informational string
- a TagOpCode combining children tags
- an IntegrityTag
- a confidentiality tag

This expression syntax seems to have some redundancies at present to attributes of other CDM elements. In addition, the structure is poorly specified. So, our use of this information will evolve as the specification evolves.

We choose not to represent provenance tags in the ADAPT model, because these dependencies are modeled equally well by edges (relationships) in our provenance graph. Our ingester will interpret the tag expressions and create the necessary edges using the wasDerivedFrom relationship discussed below.

prov:wasDerivedFrom (not in CDM, informed by CDM tagging system)

This relationship indicates that one entity has as part of its provenance another entity or subject.

Optional attributes:

- the strength of dependency of the terminal element of the relationship instance on the origin element (*prov-tc:strength*).
- the kind of derivation used to create the terminal element from the origin element (*prov-tc:derivation*)

dc:isPartOf (maps to CDM EDGE_isPartOf)

An entity can be part of another entity. We use dc:isPartOf for this construction. This relationship has no attributes.

prov:wasInformedBy

This relationship type maps several edge types in CDM:

- EDGE_EVENT_HASPARENT_EVENT
- EDGE_SUBJECT_HASPARENT_SUBJECT
- EDGE_EVENT_ISGENERATEDBY_SUBJECT
- EDGE_EVENT_AFFECTS_SUBJECT
- EDGE_SUBJECT_AFFECTS_EVENT

Optional attributes:

- an attribute that names the source of the information provided (*prov-tc:source*)

prov-tc:runsOn (CDM Edge Type EDGE_SUBJECT_RUNSON)

This relationship connects Subjects with the hosts they run on.

prov-tc:residesOn (CDM Edge Type EDGE_OBJECT_RESIDESON)

This relationship connects entities with the hosts they run on. It has no attributes.

prov:wasAttributedTo (includes CDM Edge Type EDGE_SUBJECT_HASLOCALPRINCIPAL)

This relationship connects entities or Subjects to the agents responsible for them. It has no attributes.

prov-tc:partOfPattern (not in CDM)

This relationship connects a pattern instance to a component base layer element. No attributes.

prov-tc:partOfActivity (not in CDM)

This relationship connects an activity instance to a component pattern instance. No attributes.

prov-tc:partOfPhase (not in CDM)

This relationship connects a phase instance to a component activity instance. No attributes.

prov-tc:partOfAPT (not in CDM)

This relationship connects an APT instance to a component phase instance. No attributes.

prov-tc:partOfSegment (not in CDM)

This relationship connects a Segment instance to a component element of the segment. No attributes.