Business Artifacts with Guard-Stage-Milestone Lifecycles: Managing Artifact Interactions with Conditions and Events

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ABSTRACT

A promising approach to managing business operations is based on *business artifacts* (a.k.a. *business entities* (*with lifecycles*)). These are key conceptual entities that are central to guiding the operations of a business, and whose content changes as they move through those operations. An artifact type includes both an *information model* that captures, in either materialized or virtual form, all of the business-relevant data about entities of that type, and a *lifecycle model*, that specifies the possible ways an entity of that type might progress through the business by responding to events and invoking services, including human activities. While most previous work on business artifacts has focused on the use of lifecycle models based on variants of finite state machines, two recent papers have introduced and studied the *Guard-Stage-Milestone* (*GSM*) meta-model for artifact lifecycles. GSM lifecycles are substantially more declarative than the finite state machine variants, and support hierarchy and parallelism within a single artifact instance. This paper presents the formal operational semantics of GSM, with an emphasis on how interaction between artifact instances is supported. Such interactions are supported both through testing of conditions against the artifact instances, and through events stemming from changes in artifact instances. Building on a previous result for the single artifact instance case, a key result here shows the equivalence of three different formulations of the GSM semantics for artifact instance interaction. One formulation is based on incremental application of ECA-like rules, one is based on two mathematical properties, and one is based on the use of first-order logic formulas.

Keywords: Business Artifact, Business Entity with Lifecycle, Business Operations Management, Business Process Management, Case Management, Data-centric Workflow, Declarative Workflow, Event-Condition-Action Systems.

1. INTRODUCTION

There is increasing interest in frameworks for specifying and deploying business operations and processes that combine both data and process as first-class citizens. One such approach is called Business Artifacts (or "Business Entities (with Lifecycles)"); this has been studied by a team at IBM Resarch for several years [17, 4, 16], and forms one of the underpinnings for the EU-funded Artifact-Centric Services Interoperation (ACSI) project [2]. Business artifacts are key conceptual entities that are central to the operation of part of a business and that change as they move through the business's operations. An artifact type includes both an *information model* that uses attribute/value pairs to capture, in either materialized or virtual form, all of the business-relevant data about entities of that type, and a *lifecycle model*, that specifies the possible ways that an entity of this type might progress through the business, and the ways that it will respond to events and invoke external services, including human activities. The IBM team has recently [11, 6]. introduced a declarative approach to specifying the lifecycles of business entities, using the Business Artifacts with Guard-Stage-Milestone Lifecycles meta-model[1] (abbreviated as "GSM") The current paper describes

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[§]Work by this author performed while an employee of IBM India.

[1]Following the tradition of UML and related frameworks, we use here the terms 'meta-model' and 'model' for concepts

research on the formal specification and properties of an operational semantics for GSM, with an emphasis on (a) how GSM supports declarative specification of interaction between business artifacts, (b) how ECA-like rules are used to provide one of the three equivalent formulations of the GSM operational semantics, and (c) how results of [6] are generalized to the context of multiple artifact types and instances.

As described in [11], the core motivation of the research leading to GSM has been to create a meta-model for specifying business operations and processes that:

1. Will help business-level stakeholders gain insight and understanding into their business operations;
2. Is centered around intuitively natural constructs that correspond closely to how business-level stakeholders think about their business;
3. Can provide a high-level, abstract view of the operations, and gracefully incorporate enough detail to be executable;
4. Can support a spectrum of styles for specifying business operations and processes, from the highly "prescriptive" (as found in, e.g., BPMN) to the highly "descriptive" (as found in Adaptive Case Management systems); and
5. Provides a natural, modular structuring for specifying the overall behavior and constraints of a model of business operations in terms of ECA-like rules
6. Can serve as the target into which intuitive, informal, and imprecise specifications of the business operations (e.g., in terms of "business scenarios") can be mapped.

There are four key elements in the GSM meta-model: (a) *Information Model* for business entities, as in all variations of the artifact paradigm; (b) *Milestones*, which correspond to business-relevant operational objectives, and are achieved (and possibly invalidated) based on triggering events and/or conditions over the information models of active artifact instances; (c) *Stages*, which correspond to clusters of activity intended to achieve milestones; and (d) *Guards*, which control when stages are activated, and as with milestones based on triggering events and/or conditions.

This document is focused primarily on the *operational semantics* used by the GSM meta-model. This semantics is based on a variation of the Event-Condition-Action (ECA) rules paradigm, and is centered around *GSM Business steps* (or *B-steps*), which focus on what happens to a snapshot (i.e., description of all relevant aspects of a GSM system at a given moment of time) when a single incoming event is incorporated into it. In particular, the focus is on what stages are opened and closed, and what milestones are achieved (or invalidated) as a result of this incoming event. Intuitively, a B-step corresponds to the smallest unit of business-relevant change that can occur to a GSM system.

The semantics for B-steps has three equivalent formulations, each with their own value. These are:

Incremental: This corresponds roughly to the incremental application of the ECA-like rules, provides an intuitive way to describe the operational semantics of a GSM model, and provides a natural, direct approach for implementing GSM.

that the database and workflow research literature refer to as 'model' and 'schema', respectively.

Fixpoint: This provides a concise "top-down" description of the effect of a single incoming event on an artifact snapshot. This is useful for developing alternative implementations for GSM, and optimizations of them; something especially important if highly scalable, distributed implementations are to be created.

Closed-form: This provides a characterization of snapshots and the effects of incoming events using what is essentially a first-order logic formula (extended here to work with nested sets). This permits the application of previously developed verification techniques to the GSM context. (The previous work, [3, 8, 5], assumed that services were performed in sequence, whereas in GSM services and other aspects may be running in parallel.)

This document describes and motivates these three formulations of the semantics, and sketches the proof of their equivalence. Reference [6] provides a more rigorous presentation of these results, using an abstract version of GSM that permits a focus on the essential aspects of the meta-model. The current paper expands on those results in the following specific ways.

1. Generalize from a single artifact type and single artifact instance to a context of multiple artifact types and instances, including the possibility of new artifact instance creation in B-steps. (Also, collection types in artifact information models are permitted.)
2. Explain how two or more artifact instances can interact through two novel mechanisms: the use of (a) conditions in one instance that check data or status of other instances, and (b) triggering of rules in one instance based on status-change events occurring in other instances. (This in addition to the conventional approach of one instance sending a message to other instances and letting one instance call for the creation of another one.)

Although not a focus of the current document, we note that in the GSM framework, it is generally assumed that *ad hoc* queries can be made against the family of currently active artifact instances. These queries might be made by actors outside of a GSM system, and by artifact instances within the GSM system. In some cases, the queries might be subject to access controls. The ability to directly query the data held by artifact instances corresponds to the philosophical position that artifact instances correspond to business-relevant entities that are moving through the business operations, that the data they hold is business-relevant, and as a result, it should be made available to appropriate actors, and to appropriate artifact instances within the GSM system.

As mentioned in Section 6, there is a strong connection between GSM and the area of Case Management [20, 7, 21].

Due to space limitations, the exposition here is brief with a focus on the intuitions, main concepts, and main results. Full details are available in [12].

Organizationally, Section 2 gives an overview of the GSM meta-model through an example, including a discussion of how GSM supports declarative specification of interactions between business entities. Section 3 introduces some of the formalism used to specify GSM models. Section 4 introduces two main "pillars" that underly the formal approach taken by GSM. Section 5 presents the three formulations of the GSM operational semantics and their equivalence. Section 6 describes related work, and Section 7 offers brief conclusions.

2. MOTIVATING EXAMPLE

This section provides an informal introduction to GSM by describing how it can be used to model a Requisition and Procurement Orders (RPO) scenario.[2]. (The reader may also refer to [11], which illustrates the GSM meta-model using a different scenario, and provides more deeply the intuitive motivations for the GSM constructs.) Sections 3 and 4 provide a more formal introduction to GSM.

2.1. The Scenario

Briefly, in RPO a *Requisition Order* (or "Customer Order") is sent by a Customer to a Manufacturer. The Requisition Order has one or more *Line Items*, which are individually researched by the Manufacturer to determine which Supplier to buy it from. The Line Items are bundled into *Procurement Orders* which are sent to different Suppliers.

A Supplier can reject a Procurement Order at any time before completion and shipment to the Manufacturer. In this case, the Line Items of that order must be researched again, and bundled into new Procurement Orders.

We focus here on the management of the orders, from Customer to Manufacturer and from Manufacturer to Suppliers. (We do not consider assembly of the parts received from the Suppliers.) It is natural to model this scope of the Manufacturer's oerpations using three artifact types, as follows.

Requisition Order (RO): Each RO instance will manage the overall operation of a single Requisition Order from initial receipt by the Manufacturer to delivery of the good(s) requested.

Line Item (LI): Each LI instance manages a single line item of a single requisition order. The main focus is to support the research for identifying which Supplier(s) to use, and to track the progress of the line item as it moves through research to being in a procurement order to arriving at the manufacturer.

Procurement Order (PO): Each PO instance manages a single procurement order, from when it is initially sent to a supplier to the receipt of the goods or rejection by the supplier.

Due to space limitations, we do not consider error-handling in the scenario presented here. We note that typical error-handling will have business significance, and it can in general be modeled within the GSM framework.

2.2. Surrounding Framework for GSM Systems

In the general setting, a *Artifact Service Center* (*ASC*) is used to maintain a family of related artifact types and their associated instances. The ASC acts as a container and supports conventional SOA interfaces (using both WSDL and REST) to interact with an (*external*) *environment*. The most significant part of the environment for the discussion here is its ability to support 2-way service calls, which may be short-lived (as with most automated activities) or long-lived (as with most human-performed activities). The environment can also send 1-way messages into the ASC, and can request that the ASC create new artifact instances.

[2]The authors thank Joachim (Jim) Frank of IBM for first introducing them to a form of this problem scenario. We are using a simplified version of the scenario here.

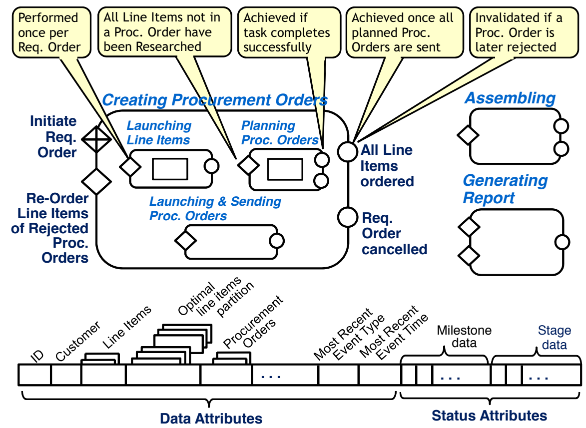

Figure 1: Sketch of (parts of) artifact type for Requisition Order

GSM, as with most BPM, case management, and workflow systems, is intended to support the *management* of business-related activities, but not support the details of executing those activities. Thus, most of the "actual work" in connection with a GSM model is typically performed by actors in the environment. In particular, values of the data attributes are in general provided by human or automated agents that perform the tasks in a GSM model.

As noted in the Introduction, there are four primary components in the GSM meta-model, summarized here (further details given below).

Information model: Integrated view of all business-relevant information about an artifact instance as it moves through the business operations.

Milestone: Business-relevant operational objective (at different levels of granularity) that can be achieved by an artifact instance. A milestone may be "achieved" (and become true when considered as a Boolean attribute) and may be "invalidated" (and become false when considered as a Boolean attribute).

Stage: Cluster of activity that might be performed for, with, and/or by an artifact instance, in order to achieve one of the milestones owned by that stage. Each milestone corresponds to one alternative way that the stage might reach completion. A stage becomes "inactive" (or "closed") when one of its milestones is achieved. Intuitively, this is because the overall motivation for executing a stage is to achieve one of its milestones.

Guard: These are used to control whether a stage becomes "active" (or "open").

Also very important in the GSM model is the following notion.

Sentry: This consists of a triggering event type and/or a condition. Sentries are used as guards, to control when stages open, and to control when milestones are acheived or invalidated. The triggering events may be incoming or internal, and both the internal events and the conditions may refer to the artifact instance under consideration, and to other artifact instances in the overall artifact system.

2.3 Drill-down into the RO Artifact Type

Figure 1 illustrates the key components of the GSM meta-model through a sketch of the Requisition Order artifact type. This artifact type is firmly based on, and centered around, the information model, shown across the bottom. Here we see *Data Attributes*, which are intended to hold all business-relevant data about a given RO instance as it moves through the business. Speaking loosely, these attributes are generally filled up from left to right, although they may be overwritten. Finally, the *Status Attributes* are illustrated there. Most importantly, these hold information about the current status of all milestones (true or false) and all stages (open or closed).

The upper portion of Figure 1 illustrates parts of the *lifecycle model* of the RO artifact type. *Milestones* are shown as small circles that are associated with stages. Some of the sentries for the milestones are suggested in the call-out boxes of that figure. For example, one of the milestone achieving sentries of All Line Items ordered will become true if all Line Items associated with the RO instance are currently members of existing, non-rejected Procurement Orders. In this case the milestone is said to be *achieved* at that moment, and also the milestone, considered as a boolean attribute, is assigned the value *true*. Milestones may also be *invalidated* or "compromised", and become false. As an example of invalidation, All Line Items ordered is invalidated if a Procurement Order is rejected, in which case the Line Items in that Procurement Order will have to be researched again and one or more new Procurement Orders will have to be generated.

The rounded-corner rectangles correspond to *stages*. (By construction, at most one milestone of a stage can be true at a time. Intuitively, each milestone of a stage corresponds to a distinct objective which might be achieved by the stage.) As illustrated by the stage Creating Procurement Orders, stages may be nested. Also illustrated are two *atomic* stages, namely Launching Line Items and Planing Proc. Orders. Both of these contain *tasks*, that involve activities that are modeled outside of the GSM model. There are three categories of task: to (a) invoke 2-way service call against the "environment", (b) send 1-way message to the environment (or to another artifact instance), and (c) send a 1-way message to the ASC that has the effect of calling for the creation of a new instance. Figure 2 illustrates in more detail how artifact systems interact with the environment using tasks that invoke services that provide a return answer; see Subsection 3.4.

The diamond nodes are *guards*. If a guard for a currently closed stage S becomes true, and if there is a parent of S it is already open, then S becomes open. The guards shown in Figure 1 are labeled with names as a convience; in the formal model these names are not accessible to the sentries.

Two broad categories of events may be used in sentries. *Incoming events* correspond to events that come *into* one or more artifact instances. There are three categories of incoming events that are generated by the environment, namely, (a) the return calls from 2-way service calls that were invoked by some artifact instance; (b) 1-way messages from the environment, and (c) requests from the environment that a new artifact instance be created. When an artifact instance generates a message intended for another artifact instance (or to create an artifact instance), the ASC acts as an intermediary. Such events, went passed by the ASC to the target (or newly created) artifact instances are also considered to be "incoming". There are three categories of such events: (d) 1-way messages

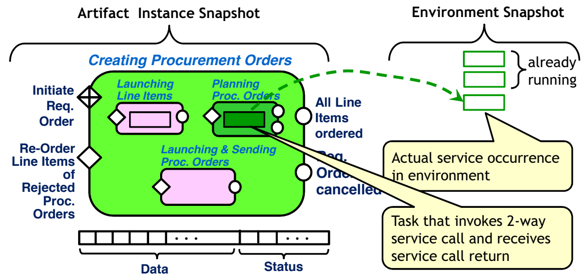

Figure 2: Invoking 2-way service calls that run in the environment

from one artifact instance to another; (e) a request by an artifact instance that a new artifact instance be created, and (f) in that case, the return message that holds the ID of the newly created artifact instance.

Internal events correspond to the changes in status of milestones (at the moment of being acheived or invalidated) and of stages (at the moment of being opened or closed).

2.4. Interaction with the environment

Figure 2 illustrates at an intuitive level how 2-way service calls are invoked by artifact instances and run in the environment. The figure shows parts of one artifact instance snapshot that is part of the way through its execution. A stage is shown in (dark) green if it is currently open, and in (light) pink if it has run at least once and is currently closed. Assume that this is the snapshot that arises after the Requisition Order has been in existence for some time, after the initial Procurement Orders have been launched, after at least one of those orders has been rejected, and just when Planning Proc. Orders opens. As illustrated in the figure, there are two 2-way service call occurrences that are already running in the environment. The act of opening the Planning Proc. Orders stage leads to the invocation of an occurrence of the 2-way service specified by the task within that stage. Note that this service may be long-running, e.g., if it is performed by a human. Eventually, it may be that the service occurrence will terminate, in which case a service call return message will be sent from the environment back to the ASC, which will in turn "route" the message to the instance that called the service occurrence. This will have the effect of closing the stage occurrence of Planning Proc. Orders. Alternatively, a different milestone might be achieved with the effect of closing the stage occurrence. This might arise, for example, if a manager determines that the overall activity should be stopped, e.g., because the customer cancelled the order. In the formal model, the service occurrence might continue to run, but the service call return would be ignored by the artifact instance that called it. In practical situations, the ASC could send a message to the agent performing the service occurrence indicating that the service occurrence should be aborted. (Also, in a practical setting, it may be that the ASC and environment support a richer style of interaction in connection with the service occurrence, so that a human performer can have an interactive engagement with selected attributes of the artifact information model; this is an area of active exploration.)

2.5 Declarative specification of artifact interactions

To conclude the discussion of the this example, we illustrate how the GSM constructs combine to permit the declarative specification of interactions between stages of a single

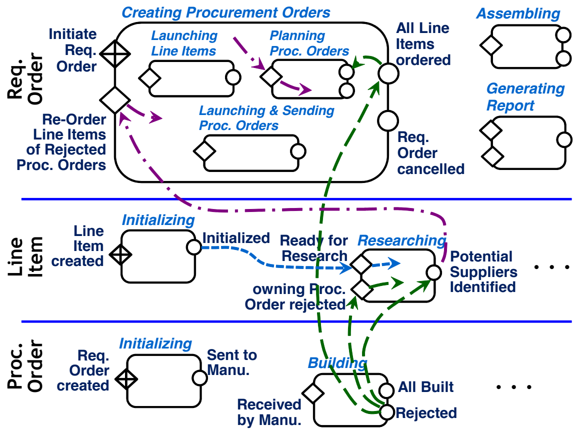

Figure 3: Interactions between artifact types

artifact instance, and between related artifact instances.

Recall that a GSM Business step (B-step) corresponds to the incorporation of a single incoming event into a GSM system, including all implied achieving/invalidating of milestones and openings/closings of stages. Using informal diagramatic conventions, the colored, dashed lines in Figure 3 illustrate three possible B-steps, which show how particular how an incoming event can trigger internal events and changes to an artifact instance.

For the first example, consider the two blue arrows (with short dashes) in the LI lifecycle. In this example, the milestone Initialized is triggered by an incoming event (e.g., that the automated process that checks certain validity conditions about the line item has completed). Also, suppose that the guard labeled Ready to Research has no condition, and has as event that the milestone Initialized has been achieved. In the notation used in the current paper, this is written as +l.Initialized (here l is the "context variable" for the type LI, and is used to refer to "self" in this case). In the B-step where milestone Initialized is achieved, the guard Ready to Research will become true and the stage Researching will be opened.

For the second example, consider the five green arrows (with long dashes) eminating from the PO milestone Rejected. These correspond to four kinds of actions that might occur in a B-step if some PO instance p achieves the milestone Rejected. In particular, the milestone All Line Items ordered for the RO instance that "owns" p, if it is currently true, will be invalidated. This corresponds to the intuition that there are now some LI instances that must be ordered from some other Supplier. Also, the milestone for successful completion of Planning Proc. Orders is invalidated whenever All Line Items ordered is invalidated. Turning to the impact on LI, for each LI instance l that is "owned" by p, the guard owning Proc. Order rejected of the Researching stage is triggered, and this stage is re-opened. And finally, in order to maintain a GSM invariant (see Subsection 3), the milestone Potential Suppliers identified for l, if true, is invalidated.

For the third example, consider the four purple arrows (with long-short dashes), starting with the one that connects the Potential Suppliers identified milestone of LI with the guard Re-Order Line Items of Rejected Proc. Orders of Creating Procurement Orders in RO. That guard has no explicit triggering event, and its condition states, basically, "for each PO instance p that achieved Rejected, each LI instance "owned" by p has achieved Potential Suppliers identified". Speaking intuitively, if this condition becomes true, then each of the LI instances from a rejected PO has been researched, and so a new round of PO planning can be initiated. In particular, as suggested by the arrow from the guard to the interior of Creating Procurement Orders, if the guard becomes true then this stage will open. Furthermore, in this example the guard of substage Planning Proc. Orders will become true once its parent stage is open, and so the substage will also open.

In practice, if the RO has many associated PO's, and PO's are being rejected every few days, then the second guard of Creating Procurement Orders might not become true for a long time. In this situation, a third guard might be added to this stage, that enables a manager to explicitly request that the stage be re-opened in order to process the LI instances that have already been researched.

When using a guard with no explicit triggering condition, it is important to ensure that the guard does not become true inappropriately. As a simple example, suppose that g is the guard of Launching Line Items in Figure 1, and the m is the milestone. In principle, the stage should open when the parent stage Creating Procurement Orders opens, and so g could be simply *true*. However, the intention is that the stage Launching Line Items should occur just once, and not repeatedly. This can be achieved here by using not p.m as the guard g. This device, of including the negations of milestones of a stage as conjuncts into a guard, is a useful pattern when using guards without triggering conditions.

2.5. Adding Flowchart Arrows to Lifecycle Models

We briefly mention that conditional flowchart arrows can be added as a formal part of an artifact lifecycle model The specification of the most common kind of flowchart arrow arises when there is a guard g of form "**On** $+x.m$ **if** φ" where m is a milestone. This is essentially equivalent to having a flow arrow from the milestone m to guard g, where the arrow is annotated with the condition φ, meaning that the arrow should be traversed when the miletone is achieved but only if φ is true at that time. If desired, additional kinds of arrow can be incorporated, corresponding to different combinations of how one kind of status change (i.e., achieving or invalidating a milestone, or opening or closing a stage) can lead to another status change.

3. GSM MODELS

This section and the next provide an overview of the formalism needed to state the equivalence theorem. As such, there will be some redundancy with the informal introduction to GSM presented in Section 2. This section focuses on the information and lifecycle components of artifact types and GSM models. (Full definitions are provided in [12].

3.1. Domain types and extended FOL

The artifact meta-model presented here supports the use of arbitrary scalar types, including Boolean, integer, etc. Two specialized types are **IncEVENT**, which ranges over the possible (names of) types of incoming events, and **TIMESTAMP**, which ranges over the "logical" timestamps corresponding to the times that B-steps are executed. Also, for each artifact type R we assume a set $\mathbf{ID}_R$ of ID's for instances of type R.

The domains of all of these types are extended with the null value $\perp$. Also, relations over the scalar types, i.e., types with structure finite set of tuple of scalar types (based on name-value pairs), are supported. Finally, the family of all *permitted* types for artifact attributes is denoted $\textbf{TYPES}_{\text{permitted}}$.

(In the practical GSM meta-model, arbitrarily deep nesting of the relation construct is permitted.)

In the formal GSM meta-model, we use an extension of First-Order Logic (FOL) that supports (i) multiple sorts; (ii) objects with structure record of scalars and collection of record of scalars; (iii) the "dot" notation to form path expressions (both into record types and to follow links based on artifact IDs), and a binary predicate $\in$ to test membership in a collection; and (iv) quanitification over both collection types in artifact instances and over the full domain of currently active instances of an artifact type. Given that the artifact pre-snapshots are uniquely identified by their IDs, it is well-known that expressions in this extended FOL can be transformed into equivalent expressions in classical FOL.

3.2. Artifact types and GSM models

This subsection introduces the notion of artifact type, which provide the structure for instances of business artifacts, and the notion of GSM model, which provides the structure for families of related business artifact types and their instances.

Definition: An *artifact type* has the form $(R, x, \mathit{Att}, \mathit{Typ}, \mathit{Stg}, \mathit{Mst}, \mathit{Lcyc})$ where the following hold:

- R is the *name* of the artifact type.
- x is a variable that ranges over the (IDs of) instances of R. This is called the *context variable* of R and is used in the logical formulas in *Lcyc*.
- *Att* is the set of attributes of this type. *Att* is partitioned into the set $\mathit{Att}_{\mathit{data}}$ of *data attributes* and $\mathit{Att}_{\mathit{status}}$ of *status attributes* (see below).
- *Typ* is the *type function* for the data attributes, i.e., $\mathit{Typ}: \mathit{Att} \rightarrow \textbf{TYPES}_{\text{permitted}}$.
- *Stg* is the set of *stage names*, or simply, *stages*.
- *Mst* is the set of *milestone names*, or simply, *milestones*.
- *Lcyc* is the *lifecycle model* of this artifact type (defined below).

The set *Att*, and in particular $\mathit{Att}_{\mathit{data}}$, must include an attribute *ID*, which holds the identifier of the artifact instance.

Additional restrictions are made so that events and their time of occurrence can be tested by sentries. In particular, $\mathit{Att}_{\mathit{data}}$ should include *mostRecEventType*, which holds the type of the most recent incoming event that affected this artifact instance; and *mostRecEventTime*, which holds the logical timestamp of the processing of that most recent incoming event. For each milestone $m \in M$, there are two attributes in $\mathit{Att}_{\mathit{status}}$, namely: A *milestone status value* attribute, denoted as m, of type Boolean, and a *milestone toggle time attribute*, denoted as $m^{\mathit{mostRecentUpdate}}$, which holds the most recent time that the status value changed. Analogously, for each stage $S \in \mathit{Lcyc}$, there are two attributes in $\mathit{Att}_{\mathit{status}}$, namely: a *stage status value* attribute, denoted as active_S, of type Boolean, and a *stage toggle time attribute*, denoted as $\mathit{active}_S^{\mathit{mostRecentUpdate}}$.

An artifact type $(R, x, \mathit{Att}, \mathit{Typ}, \mathit{Stg}, \mathit{Mst}, \mathit{Lcyc})$ is often referred to using simply its name R. We use $\textbf{ID}_R$ to denote the type of IDs of artifact instances of R.

The structure of artifact type lifecycle models is defined next.

Definition: Let $(R, x, \mathit{Att}, \mathit{Typ}, \mathit{Stg}, \mathit{Mst}, \mathit{Lcyc})$ be an artifact type. The lifecycle model *Lcyc* of R has structure (*Substages*, *Task*, *Owns*, *Guards*, *Ach*, *Inv*) and satisfies the following properties.

- *Substages* is a function from *Stg* to finite subsets of *Stg*, where the relation $\{(S, S') \mid S' \in \mathit{Substages}(S)\}$ creates a forest. The roots of this forest are called *top-level stages*, and the leaves are called *atomic stages*. A non-leaf node is called a *composite stage*.
- *Task* is a function from the atomic stages in *Stg* to *tasks*,
- *Owns* is a function from *Stg* to finite, non-empty subsets of M, such that $\mathit{Owns}(S) \cap \mathit{Owns}(S') = \emptyset$ for $S \neq S'$. A stage S *owns* a milestone m if $m \in \mathit{Owns}(S)$.
- *Guards* is a function from *Stg* to finite, non-empty sets of *sentries* (defined below). Each element of $\mathit{Guards}(S)$ for $S \in \mathit{Stg}$ is called a *guard* for S.
- *Ach* is a function from M to finite, non-empty sets of sentries. For milestone m, each element of $\mathit{Ach}(m)$ is called an *achieving sentry* of m.
- *Inv* is a function from M to finite sets of sentries. For milestone m, each element of $\mathit{Inv}(m)$ is called an *invalidating sentry* of m.

If $S \in \mathit{Substages}(S')$, then S is a *child* of S' and S' is the *parent* of S. The notions of *descendant* and *ancestor* are defined in the natural manner.

We now have:

Definition: A *GSM model* is a set Γ of artifact types with form $(R_i, x_i, \mathit{Att}_i, \mathit{Typ}_i, \mathit{Stg}_i, \mathit{Mst}_i, \mathit{Lcyc}_i)$, $i \in [1..n]$, that satisfies the following:

- **Distinct type names:** The artifact type names R_i are pairwise distinct.
- **No dangling type references:** If an artifact type $\textbf{ID}_B$ is used in the artifact type R_i for some $i \in [1..n]$, then $R = R_j$ for some (possibly distinct) $j \in [1..n]$.

(As a convenience, we also assume that all of the context variables are distinct.)

Let GSM model Γ be as above. As will be seen, the sentries of guards and milestones in one GSM type R_i of Γ may refer to the values of attributes in Att_j for type R_j for any $j \in [1..n]$, not just for $j = i$.

3.3. (Pre-)Snapshots and Instances

The notions of "snapshot" and "instance" for both artifact types and GSM models are now introduced. Structural aspects of these notions are captured using the auxiliary notion of "pre-snapshot". While our focus is on snapshots and instances, we shall use pre-snapshots to describe the incremental construction of a new GSM snapshot resulting from the impact of an incoming event on an existing GSM snapshot.

Let Γ be a GSM model, and $(R, x, \mathit{Att}, \mathit{Typ}, \mathit{Stg}, \mathit{Mst}, \mathit{Lcyc})$ be an artifact type in Γ. In this context, an artifact instance *pre-snapshot* of type R is an assignment σ from *Att* to values, such that for each $A \in \mathit{Att}$, $\sigma(A)$ has type $\mathit{Typ}(A)$. (Note that $\sigma(A)$ may be $\perp$ except for when $A = \mathit{ID}$.)

Let σ be an artifact instance pre-snapshot and let $\rho = \sigma(\mathit{ID})$. If understood from the context, we sometimes use ρ to refer to the pre-snapshot σ. In this case, if A is an attribute of R, then $\rho.A$ is used to refer to the value of $\sigma(A)$. If attribute A has type $\mathbf{ID}_{R'}$ for some artifact type R' with attribute B, then $\rho.A.B$ refers to the B-value of the (pre-)instance identified by $\rho.A$. More generally, *path expressions* can be constructed that correspond to arbitrarily long chains of this kind of reference.

The relationship of stages and milestones is fundamental to the GSM meta-model. Core aspects of this relationship are captured in the following three *GSM Invariants*, which apply to artifact instance pre-snapshots. Let σ be an instance pre-snapshot of artifact type R with ID ρ. The GSM Invariants are specified as follows.

GSM-1: Milestones false for active stage. If stage S owns milestone m, and if $\rho.\mathit{active}_S = \mathit{true}$, then $\rho.m = \mathit{false}$.

GSM-2: No activity in closed stage. If stage S has substage S', and $\rho.\mathit{active}_S = \mathit{false}$, then $\rho.\mathit{active}_{S'} = \mathit{false}$.

GSM-3: Disjoint milestones. If stage S owns distinct milestones m and m', and $\rho.m = \mathit{true}$, then $\rho.m' = \mathit{false}$.

The third invariant stems from the intuition that milestones serve as alternative ways that a stage may be closed. This invariant is typically enforced in practice by syntactic properties of the milestone achieving sentries. The first two are enforced as part of the operational semantics below.

An artifact instance *snapshot* of type R is an instance pre-snapshot σ of type R that satisfies the three GSM Invariants.

An *artifact instance* of R is a sequence $\sigma_1, \ldots, \sigma_n$ of snapshots of type R such that $\sigma_1(\mathit{ID}) = \sigma_2(\mathit{ID}) = \cdots = \sigma_n(\mathit{ID})$. Intuitively, an instance of R will correspond to a single conceptual entity of type R that evolves as it moves through some business operations.

We now turn to GSM (pre-)snapshots and instances. A *pre-snapshot* of Γ is an assignment Σ that maps each type R of Γ to a set $\Sigma(B)$ of pre-snapshots of type R, and that satisfies the following structural properties:

- **Distinct ID's:** If σ and σ' are distinct artifact pre-instance snapshots occurring in the image of Σ, then $\sigma(\mathit{ID}) \neq \sigma'(\mathit{ID})$.
- **No dangling references:** If an ID ρ of type $\mathbf{ID}_R$ occurs in the value of a non-ID attribute of some pre-snapshot in $\Sigma(R')$ for some R' in Γ, then there is a pre-snapshot σ in $\Sigma(R)$ such that $\sigma(\mathit{ID}) = \rho$.

Finally, a *snapshot* of Γ is a pre-snapshot Σ of Γ such that each artifact instance pre-snapshot in the image of Σ is an instance snapshot.

Let Γ be a GSM model and Σ a pre-snapshot of Γ. We now extend the function Σ to ID's and path expressions in the natural manner, so that an expression such as $\Sigma(x. < \mathit{path} > .A[x/\rho])$ will evaluate to the value of attribute A for the artifact instance identified by the path $\rho.<\mathit{path}>$ when followed in (pre-)snapshot Σ.

3.4. Events and Tasks

As mentioned informally in Subsection 2.3, there are three kinds of *incoming* events (1-way message, 2-way service call return, and artifact instance creation request), and three kinds of *generated* events (1-way message, 2-way service call, and service call return for artifact instance creation request). These events are represented in the formalism as *messages* that have types, payload signatures, and a unique artifact type as target, For a *ground* event, the main part of the payload is a sequence $(A_1{:}c_1, \ldots, A_n{:}c_n)$ where, for each $i \in [1..n]$, A_i is a data attribute of the target type and c_i is a value of appropriate type. Depending on the message type there may also be payload attributes to help with correlation of service call returns. Specifically, for 2-way service calls and returns, attributes for the calling artifact instance and calling time stamp are included. For artifact instance creation requests the payload carries initialization values for the new instance, and the service call return carries the ID of the newly created instance (and, if the request was made by an artifact instance, the ID of the calling instance). In practice, the message payloads may also include fault information.

Speaking informally, incoming events are received by the sentries associated with guards and milestones. Generated events are created by tasks contained in atomic stages. In particular, there are task types for generating 1-way messages (when invoked they wait for a "handshake" from the ASC indicating success or failure) and 2-way service calls (when invoked they wait for the ASC to provide the service call return from the called service or a time-out message).

3.5. The Immediate Effect of an Incoming Event

Let Σ be a snapshot, e a ground incoming event, and t a logical timestamp greater than all logical timestamps occurring in Σ. The ASC determines the set of artifact instances in Σ that are *directly affected* by e, using an event-specific queries against the family of active artifact instances. Briefly, for 2-way service call returns the correlation information in the message payload is used to identify the relevant artifact instance. 1-way messages might impact multiple artifact instances.

The *immediate effect* of e on Σ at time t, which is denoted as $\mathit{ImmEffect}(\Sigma, e, t)$, is the pre-snapshot that results from incorporating e into Σ, including

- Changing the values of the *mostRecEventType* and *mostRecEventTime* attributes of directly affected (or created) artifact instances, and
- Changing the values of data attributes of directly affected artifact instances (or initializing those data attribugtes in a newly created artifact instance), as indicated by the payload of e.

The immediate effect does not incorporate any changes to status attributes, nor cause any firing of guard or milestone sentries; this is addressed by the notion of B-step, presented next.

3.6. GSM Business Steps ("B-steps") and Logical Timestamps

We now describe the central notion of "GSM Business step" ("B-step"). Recall from Subsection 2.4 that an artifact model Γ is used in connection with an abstract model of the (external) environment; this is typically denoted as Ω. In application, an *Artifact Service Center* (*ASC*) is used as a container for the set of artifact instances of of the artifact types in Γ. The ASC can provide a variety of functionalities, including the relay of messages from an artifact instance out to the environment or to other artifact instances, and the relay of messages from the environment into the artifact instances.

The operational semantics for GSM are focused on the notion of B-steps, which correspond to the impact of a single incoming event occurrence e at a logical timestamp t on a snapshot Σ of a GSM model Γ. This is illustrated in Figure 4. The semantics characterizes 5-tuples of the form $(\Sigma, e, t, \Sigma', \mathit{Gen})$, where the following hold.

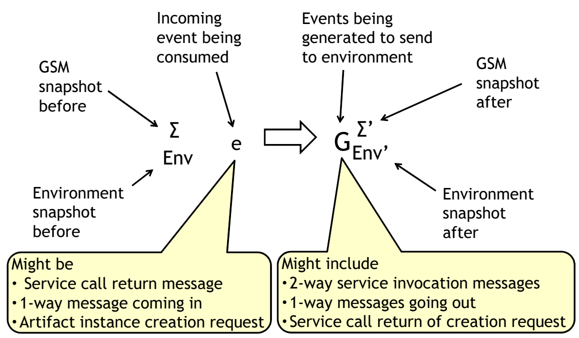

Figure 4: Illustration of a single GSM Business step (B-step)

1. Σ is the *previous* snapshot.
2. e is a ground occurrence of an incoming event type associated with Γ.
3. t is a logical timestamp which is greater than all logical timestamps occurring in Σ.
4. Σ' is the *next* snapshot.
5. *Gen* is the set of ground *generated event occurrences*, all of whose types are outgoing event types associated with Γ.

To illustrate the notion of B-step, we describe key aspects of the incremental formulation of the operational semantics. In this case, Σ' is constructed in two phases (see Figure 5). The first is to incorporate e into Σ, by computing *ImmEffect*(Σ, e, t). (If *ImmEffect*$(\Sigma, e, t) = \Sigma$ then the incoming event e is discarded and no B-step performed.) The second phase is to incorporate the effect of the guards, achieving sentries for milestones, invalidating sentries for milestones, and the first two GSM invariants. A family of ECA-like rules corresponding to these constructs is derived from Γ (see Subsection 4.2). The second phase is achieved by building a sequence $\Sigma = \Sigma_0, \Sigma_1 = \textit{ImmEffect}(\Sigma, e, t), \Sigma_2, \ldots, \Sigma_n = \Sigma'$ of pre-snapshots, where each step in the computation, called a *micro-step*, corresponds to the application of one ECA-like rule, and where no ECA-like rule can be applied to Σ_n. (There are restrictions on the ordering of rule application, as detailed in Subsection 5.1.) Here Σ' corresponds to the result of the B-step. For each micro-step one also maintains a set G_j of *generated events*, which are sent to the environment at the termination of the B-step.

Although the creation of Σ' and *Gen* from Σ and e may take a non-empty interval of clock time, in the formal model we represent this as a single moment in time, called a *logical timestamp*. One can think of t as the clock time at the moment when the system began processing event e. (There may be a queue of such events, so the start time of processing may be different than the time that the ASC receives e.)

Each message in *Gen* is the result of opening an atomic stage with a message-generating task inside. The attributes of the message payloads are drawn from the data attributes of the the artifact instance, which remain fixed once *ImmEffect*(Σ, e, t) is computed. Thus, given the set of stages opened by a B-step it is straightforward to determine the set of messages that will be generated by that B-step. For this reason, the set *Gen* is not considered in the formalism below.

3.7. Sentries

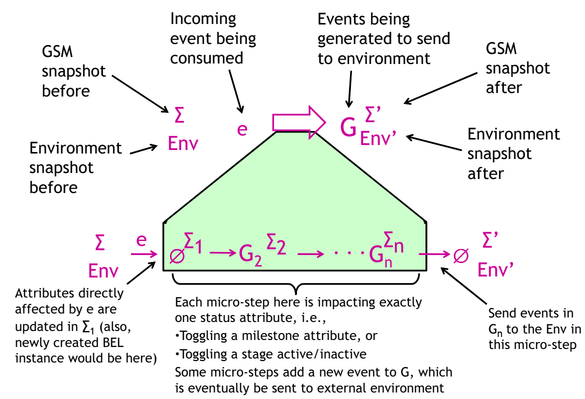

Figure 5: Incremental formulation of GSM semantics

The set **IncEVENT** of incoming event types includes all possible incoming 1-way message types, 2-way service call return types, and the artifact instance creation 2-way service calls.

Definition: An *event expression* for an artifact type R with context variable x is an expression $\xi(x)$ having one of the following forms.

- **Incoming event expression:** This includes expressions of the form $x.M$ (for 1-way message type M), $x.F^{\textit{return}}$ (for service call return from F), and $x.\textit{create}_R^{\textit{call}}$ (which is a call to create an artifact instance of type R).
- **Internal event expression** (also known as **status change event expression**): This includes
  1. $+\tau.m$ and $-\tau.m$, where τ is a well-formed path expression of form $x.<\textit{path}>$ with type $\mathbf{ID}_{B'}$ for some artifact type R' in Γ, and where m is a milestone of type R'. Intuitively, an event occurrence of type $+\tau.m$ [$-\tau.m$] arises whenever the milestone m of the instance identified by $x.<\textit{path}>$ changes value from false to true [true to false, respectively].
  2. $+\tau.\textit{active}_S$ and $-\tau.\textit{active}_S$, where τ is a well-formed path expression of form $x.<\textit{path}>$ with type $\mathbf{ID}_{B'}$ for some artifact type R' in Γ, and where S is a stage name of type R'. Intuitively, an event occurrence of type $+\tau.\textit{active}_S$ [$-\tau.\textit{active}_S$] arises whenever the stage S of the instance identified by $x.<\textit{path}>$ changes value from closed to open [open to closed, respectively].

Definition: A *sentry* for artifact type R is an expression $\chi(x)$ having one of the following forms, where x is the context variable of R: "**on** $\xi(x)$ **if** $\varphi(x)$", "**on** $\xi(x)$", or "**if** $\varphi(x)$", and where the following hold.

(a) If $\xi(x)$ appears, then it is an event expression for R.

(b) If $\varphi(x)$ appears, then $\varphi(x)$ is a well-formed formula over the artifact types occurring in Γ that has exactly one free variable.

Expression $\xi(x)$, if it occurs in the sentry, is called the *(triggering) event*. Expression $\varphi(x)$, if it occurs in the sentry, is called the *condition*.

We now consider what it means for a pre-snapshot Σ to *satisfy* a sentry χ at time t, denoted $(t, \Sigma) \models \chi$. Satisfaction of a condition by Σ is straightforward, and not considered further. If χ involves an incoming event type E, the expression $\rho.E$ for artifact instance ρ is true if $\rho.\textit{currEventType} = E$

and ρ.*currEventTime* $= t$. Similarly, if χ involves a status change event of form $\odot\rho.\tau.s$ (for polarity $\odot$, path expression τ, and status attribute s), the event expression is considered true if the value of $\rho.tau.s$ matches the polarity $\odot$ and $\rho.\tau.s^{mostRecentUpdate} = t$.

4. PAC RULES AND POLARIZED DEPENDENCY GRAPH

This section introduces two pillars of the GSM operational semantics. First is a family of ECA-like rules, called "Prerequisite-Antecedant-Consequent (PAC)" rules (Subsection 4.2). Second is the notion of "Polarized Dependency Graph (PDG)" (Subsection 4.3), which is used to provide a form of stratification for the set of PAC rules associated with a GSM model.

4.1. Two intuitive principles

This subsection introduces and motivates two more-or-less equivalent intuitive "principles" that have guided the design of the GSM semantics. The first principle is phrased in terms of the incremental formulation of the GSM semantics, and the second is phrased in terms of the fixpoint formulation.

Toggle-once Principle. In a B-step (Σ, e, t, Σ'), if Σ' is constructed from (Σ, e, t) through the incremental application of PAC rules, then each status value attribute can change at most once during that construction.

Change Dominates Principle: In a B-step (Σ, e, t, Σ'), if the antecedents of two rules calling for opposite changes to a status value attribute $\rho.s$ of an artifact instance are both applicable to Σ', then the rule that changes the value of $\Sigma(\rho.s)$ dominates over the other rule, and $\Sigma'(\rho.s) \neq \Sigma(\rho.s)$.

A primary intuitive motivation behind these principles is that a B-step is intended to be a "unit of business-relevant change". In terms of the incremental semantics, this means that if a status value attribute changes during application of PAC rules, then that change should be visible (and incorporated into Σ'), rather than being hidden in the internal processing that computes Σ'. In terms of the Change Dominates Principle, this means that if there is a reason to change a status value attribute, then the change should be "documented" in one of the snapshots that is presented to the business, i.e., should be visible in between B-steps.

4.2. Prerequisite-Antecedent-Consequent Rules

All three formulations of the semantics for GSM are based on a variation of Event-Condition-Action (ECA) rules, called *Prerequisite-Antecedent-Consequent* rules, or *PAC* rules. Each such rule has three parts. The rules can be interpreted in two ways. The first is in the context of the incremental formulation, at a point where we have built up the sequence $\Sigma = \Sigma_0$, *ImmEffect*$((, \Sigma, ,)e, t) = \Sigma_1, \ldots, \Sigma_i$. The other context is that of the fixpoint formulation, which focuses on the completed B-step (Σ, e, t, Σ'). We now give the intuition of the three components of the rules, in their grounded form, for both of these contexts.

Prerequisite: This part of the rule is considered relative to Σ in both contexts. It may be thought of as a prerequisite for determining whether the rule is relevant to (Σ, e, t).

Antecedent: This part of the rule is considered relative to Σ_i in the incremental formulation, and relative to Σ' in the fixpoint formulation. If the rule is relevant, then the antecedent can be thought of as the "if" part of a condition-action rule. As will be seen below, the antecedant will correspond to a sentry, and thus may include both a (first-order logic equivalent of a) triggering event and a condition.

Consequent: In the incremental formulation, if the rule is relevant, and if the antecedent is true in Σ_i, then the rule is considered to be *eligible*, and it may be *fired* to create Σ_{i+1} according to the consequent. In the fixpoint formulation, if the rule is relevant and Σ' satisfies the antecedent, then Σ' should also satisfy the result called for by the consequent.

For the fixpoint formulation, the reader may wonder why the antecedent is considered relative to Σ' rather than Σ. Intuitively, the focus is on creating Σ' to be the fixpoint, in the spirit of logic programming, of applying the PAC rules to *ImmEffect*(Σ, e, t). In logic programming, the fixpoint itself satisfies all of the if-then rules, considered as first-order logic formulas. Similarly, in GSM the fixpoint Σ' satisfies the AC part of each PAC rule, considered as a first-order logic formula.

Figure 6 describes two sets of *abstract* PAC rules that may be associated with a GSM model Γ. Part (a) of the figure lists the templates for the set $\Gamma_{PACsimp}$ of *simplified PAC rules* for Γ. Part (b) lists the template PAC-4; the set Γ_{PAC} of (*enhanced*) *PAC rules* for Γ is the set of rules formed from $\Gamma_{PACsimp}$ by removing rules generated from PAC-4^{simp}, and adding all rules generated by PAC-4. Brief intuitions behind both sets of rules are now described.

Consider first the simplified PAC rules (Figure 6(a)). The first three kinds of rule are called *explicit*, and they correspond, respectively, to guards, to milestone achieving sentries, and to milestone invalidating sentries. The second three kinds of rule are called *invariant preserving*, because they focus on preserving the Invariants GSM-1 and GSM-2. (Recall that Invariant GSM-3 is assumed to be maintained by properties of the milestones themselves.)

Consider PAC-1. The antecedent is basically the guard that the rule is derived from. If S is the child of S', then the conjunct $x.active_{S'}$ is added to the antecedent. The consequent corresponds to the intention of the guard to open stage S. In the incremental semantics leading to the computation of Σ' from (Σ, e, t), it is possible that both S' and S are closed in Σ, that some incremental step opens S', and that a subsequent incremental step opens S. In the final result Σ', both S and S' are open.

In general, the prerequisites are included to ensure that the Toggle-Once property is maintained.

We consider briefly PAC-4^{simp} and PAC-4, which are focused on Invariant GSM-1. PAC-4^{simp} follows the pattern and intuition of PAC-5 and PAC-6, and can be used in many situations. There are situations, however, in which it is desirable for a guard of a stage S to include as a condition that one or more of the milestones owned by S are currently not true. (This was illustrated in connection with stage Launching Line Items in Section 2.) In such cases, PAC-4^{simp} is needed so that the GSM model will still satisfy the well-formedness condition.

4.3. Stratification via Polarized Dependency Graphs

In the general case, the set of PAC rules of a GSM model Γ will involve a form of negation. As is well-known from

	Basis	Prerequisite	Antecedent	Consequent
Explicit rules				
PAC-1	Guard: if **on** $E(x)$ **if** $\varphi(x)$ is a guard of S. (Include term $x.active_{S'}$ if S' is parent of S.)	$\neg x.active_S$	**on** $E(x)$ **if** $\varphi(x) \wedge x.active_{S'}$	$+x.active_S$
PAC-2	Milestone achiever: If S has milestone m and **on** $E(x)$ **if** $\varphi(x)$ is an achieving sentry for m.	$x.active_S$	**on** $E(x)$ **if** $\varphi(x)$	$+x.m$
PAC-3	Milestone invalidator: If S has milestone m and **on** $E(x)$ **if** $\varphi(x)$ is an invalidating sentry for m.	$x.m$	**on** $E(x)$ **if** $\varphi(x)$	$-x.m$
Invariant preserving rules				
PAC-4^{simp}	Opening stage invalidating milestone: If S has milestone m.	$x.m$	**on** $+\, x.active_S$	$-x.m$
PAC-5	If S has milestone m.	$x.active_S$	**on** $+\, x.m$	$-x.active_S$
PAC-6	If S is child stage of S'.	$x.active_S$	**on** $-\, x.active_{S'}$	$-x.active_S$

(a) PAC rules for Γ, "simplified" version

	Basis	Prerequisite	Antecedent	Consequent
PAC-4	Guard invalidating milestone: If S has milestone m and has guard **on** $E(x)$ **if** $\varphi(x)$ of S, where $E(x)$ is not $-x.m$, and where $\neg x.m$ does not occur as a top-level conjunct in $\varphi(x)$. (Include term $x.active_{S'}$ if S' is parent of S.)	$x.m$	**on** $E(x)$ **if** $\varphi(x) \wedge x.active_{S'}$	$-x.m$

(b) The "enhanced" rule template for PAC-4, which helps to maintain Invariant GSM-1.

Figure 6: Prerequisite-Antecedent-Consequent (PAC) rule templates associated with a GSM model Γ

logic programming and datalog, the presence of negation in rules can lead to non-intuitive outcomes. (Examples in the GSM context are provided in [12].) In the GSM operational semantics this will be avoided using an approach reminiscent of stratification as developed in those fields [1, 9]. In particular, the approach involves (i) requiring that a certain relation defined on the rules be acyclic, and then (ii) requiring that the order of rule firing comply with that relation.

Let Γ be a GSM model. We construct the *polarized dependency graph* (*PDG*) of Γ, denoted *PDG*(Γ), as follows. The set V_Γ of nodes for *PDG*(Γ) contains the following for each artifact type R in Γ.

- For each milestone m of R, nodes $+R.m$ and $-R.m$
- For each stage S of R, nodes $+R.active_S$ and $-R.active_S$
- For each guard g of R, nodes $+R.g$

The set E_Γ of edges for *PDG*(Γ) is based largely on the rules in Γ_{PAC}. In the following, R, R' range over not necessarily distinct artifact types in Γ; s, s' range over not necessarily distinct status attributes of those types; and "$\odot, \odot'$" correspond to polarities, that is, they range over $\{+, -\}$. Also, let x, x' be the context variables for R, R', respectively.

- Suppose that (π, α, γ) is a PAC rule in Γ_{PAC} having the form of PAC-2, PAC-3, PAC-5, or PAC-6.

– If α includes as a triggering event the expression $\odot'\tau(x).s'$ and γ is $\odot x.s$, where $\tau(x)$ evaluates to ID's of type R', then include edge $(\odot' R'.s', \odot R.s)$.

– If α includes in its condition an expression $\tau(x).s'$ and γ is $\odot x.s$, where $\tau(x)$ evaluates to ID's of type R', then include edges $(+R'.s', \odot R.s)$ and $(-R'.s', \odot R.s)$.

- Suppose that (π, α, γ) is a PAC rule in Γ_{PAC} having the form of PAC-1, that is created because of guard g for stage S in type R.

– If α includes as a triggering event the expression $\odot'\tau(x).s'$, where $\tau(x)$ evaluates to ID's of type R', then include edge $(\odot' R'.s', +R.g)$.

– If α includes in its condition an expression $\tau(x).s'$, where $\tau(x)$ evaluates to ID's of type R', then include edges $(+R'.s', +R.g)$ and $(-R'.s', +R.g)$.

- Suppose that (π, α, γ) is a PAC rule in Γ_{PAC} having the form of PAC-4, that is created because of guard g and milestone m for stage S in type R.

– If α includes as a triggering event the expression $\odot'\tau(x).s'$, where $\tau(x)$ evaluates to ID's of type R', then include edge $(\odot' R'.s', -R.m)$.

– If α includes in its condition an expression $\tau(x).s'$, where $\tau(x)$ evaluates to ID's of type R', then include edges $(+R'.s', -R.m)$ and $(-R'.s', -R.m)$.

- Finally, if g is a guard for stage S in type R, then include edge $(+R.g, +R.active_S)$.

Definition: A GSM model Γ is defined to be *well-formed* if *PDG*(Γ) is acyclic.

The acyclicity of the PDG is used to guide the ordering of rule application in the incremental formulation. For example, if in the PDG there is an edge from $-R.m$ to $+R'.g$, this indicates that in the incremental formulation, all rules that might make $\rho.m$ false (for any ρ of type R) should be considered before any rule that might use $\rho'.g$ to open its stage (for any ρ' of type R'). Lemma 5.1 below states that if such an ordering is followed, then the result is guaranteed to exist and be unique.

In some cases it is helpful to use a more lenient notion of well-formed, that is based on the acyclicity of all of the *event-relativized* PDGs. For an event type E, the event-relativized PDG for Γ and E is constructed in the same manner as *PDG*(Γ), except that a rule (π, α, γ) is not considered if π is an incoming event type different from E. (Although not considered here, the results of Section 5 hold for this more lenient notion of well-formed.)

5. THREE FORMULATIONS OF THE GSM OPERATIONAL SEMANTICS

This section describes the three formulations of the GSM operational semantics, and then presents the equivalence theorem. The section closes with comments about B-steps considered in a series.

5.1. The Incremental Formulation

Assume that GSM model Γ is given, and let us focus on incorporating event e into snapshot Σ at time t. Recall from Subsection 3.6 and Figure 5 that the incremental formulation is based on the construction of a sequence $\Sigma = \Sigma_0, \Sigma_1 = \mathit{ImmEffect}(\Sigma, e, t), \Sigma_2, \ldots, \Sigma_n = \Sigma'$ (where $\Sigma_1 \neq \Sigma$).

Given Σ_j, $j \geq 1$, an ground PAC rule (π, α, γ) is *applicable* to (or *eligible* to fire with) Σ_j if $\Sigma \models \pi$ and $\Sigma_j \models \alpha$. *Applying* (or *firing*) such a rule would yield a new pre-snapshot Σ_{j+1}, that is constructed from Σ_j by "applying" the effect called for by γ (that is, toggling exactly one status attribute of one artifact instance).

In the incremental formulation, the application of the ground PAC rules must *comply* with the ordering implied by *PDG*(Γ), i.e., for each pair r, r' of ground rules with abstract actions $\odot R.s$ and $\odot' R'.s'$, respectively, if $\odot R.s < \odot' R'.s'$ then the rule r must be considered for firing before the rule r' is considered for firing.

LEMMA 5.1: *Suppose that (Σ, e, t) is a snapshot, ground event, and time greater than all times in Σ. Suppose further that $\Sigma_1 = \mathit{ImmEffect}(\Sigma, e, t)$. Then there is at least one snapshot Σ' obtained by firing the rules of Γ_{PAC} in an ordering that complies with PDG(Γ). Furthermore, if Σ' and Σ'' are constructed through applications of the rules in Γ_{PAC} using any rule firing order that complies with PDG(Γ), then $\Sigma' = \Sigma''$.*

Proof (sketch): The existence of at least one Σ follows primarily from the facts that a change called for by one rule cannot be "undone" be another rule (mainly due to the prerequisites of the rules and the definition of rule eligibility), and the fact that any sequence of rule firings will terminate (because there are only finitely many status attributes in a pre-snapshot). For uniqueness, assume that Σ' and Σ'' are different end results, and let $\odot\rho.s$ be a least ground status attribute that only one of Σ' or Σ'' changes, where ρ is of type R. Suppose without loss of generality that Σ' is the one where $\rho.s$ changes. Since Σ', Σ'' agree on all of the ground nodes that correspond to the abstract nodes preceding $\odot R.s$ in *PDG*(Γ), the rule that triggered the change to $\odot\rho.s$ in Σ' is also applicable in Σ'', and could thus be fired there, yielding a contradiction. □

Definition: A tuple (Σ, e, t, Σ') *satisfies* the incremental formulation of the GSM operational semantics if Σ' is the unique result of applying the PAC rules in appropriate order to *ImmEffect*(Σ, e, t).

5.2. The Fixpoint Formulation

The fixpoint formulation for the GSM semantics is analogous to the fixpoint characterization used in logic programming. In our context, we start with *ImmEffect*(Σ, e, t) and characterize snapshots Σ' that satisfy two key mathematical properties stemming from Γ_{PAC}.

Intuitively, the first property states that Σ' must comply with all of the demands of the PAC rules.

Definition: Given Γ and (Σ, e, t) as above, with non-trivial immediate effect, then snapshot Σ' is *compliant* with respect to Γ_{PAC} and (Σ, e, t) if

- Σ' and *ImmEffect*(Σ, e, t) agree on all data attributes, and
- for each ground PAC rule (π, α, γ) of Γ_{PAC}, if $\Sigma \models \pi$ and $\Sigma' \models \alpha$, then $\Sigma' \models \gamma$.

Intuitively, the second property states that if a status attribute toggles between Σ and Σ', then that toggling must be "justified" by some ground PAC rule.

Definition: Given Γ and (Σ, e, t) as above, with non-trivial immediate effect, then snapshot Σ' is *inertial* with respect to Γ_{PAC} and (Σ, e, t) if the following holds for each artifact instance ID ρ in $\Sigma_1 = \mathit{ImmEffect}(\Sigma, e, t)$ having type R, and each status attribute s of type R: if $\Sigma_1(\rho.s) \neq \Sigma'(\rho.s)$ then there is some ground PAC rule (π, α, γ) of Γ_{PAC} such that: (a) $\Sigma_1 \models \pi$; (b) $\Sigma' \models \alpha$; and (c) the value of $\Sigma'(\rho.s)$ corresponds to the application of γ.

Definition: A tuple (Σ, e, t, Σ') *satisfies* the fixpoint formulation if Σ' is compliant and inertial with respect to Γ and (Σ, e, t).

5.3 The Closed-Form Formulation

The closed-form formulation of the GSM semantics is based on the observation that the properties of compliance and inertial can be captured in an extended FOL formula. The construction of the overall formula is reminiscent of constructions used for logic programming with negation, and in particular, when characterizing "negation as failure" [13].

The formula will work on structures of the form (Σ, e, t, Σ'). To express the formula over this structure, following the convention from verification theory, we use atomic formulas of the form $\varphi(x_1, ..., x_n)$ to range over Σ, and of form $\varphi(x'_1, ..., x'_n)$ to range over Σ'. Also, given a formula α involving un-primed variables, we use α' to denote the formula obtained from α by priming all of the variables (and thus making all of the atomic formulas relevant to Σ'.

For a type R of Γ, status attribute s in R, and polarization $\odot$, let *Cnsq*$(\odot R.s)$ be the set of rules in Γ_{PAC} whose consequent is $\odot R.s$. Also, define $\psi_{+R.s}$ to be

$$((\neg R.s \ \wedge \ \bigvee_{(\pi,\alpha,+R.s)\in \mathit{Cnsq}(+R.s)}(\pi \ \wedge \ \alpha')) \rightarrow R.s') \ \wedge$$
$$((\neg R.s \ \wedge \ \bigwedge_{(\pi,\alpha,+R.s)\in \mathit{Cnsq}(+R.s)} \neg(\pi \ \wedge \ \alpha')) \rightarrow \neg R.s')$$

and define $\psi_{-R.s}$ to be

$$((R.s \ \wedge \ \bigvee_{(\pi,\alpha,-R.s)\in \mathit{Cnsq}(-R.s)}(\pi \ \wedge \ \alpha')) \rightarrow \neg R.s') \ \wedge$$
$$((R.s \ \wedge \ \bigwedge_{(\pi,\alpha,-R.s)\in \mathit{Cnsq}(-R.s)} \neg(\pi \ \wedge \ \alpha')) \rightarrow R.s')$$

Finally, the closed-form formula Ψ_Γ is defined as the conjunction of all of the formulas $\psi_{\odot R.s}$, along with a formula $\psi_{\mathit{incorp\text{-}event}}$ (not defined here) that states that the data attributes of Σ' match those of *ImmEffect*(Σ, e, t) (and that a new artifact instance has been created if e calls for that to happen).

Definition: A structure (Σ, e, t, Σ') *satisfies* the closed-form formulation of the GSM operational semantics if $(\Sigma, e, t, \Sigma') \models \Psi_{Gamma}$.

5.4. The Equivalence Theorem

The equivalence of the three formulations of the GSM semantics holds for all GSM models Γ such that *PDG*(Γ) is acyclic.

THEOREM 5.2: *Let Γ be a well-formed GSM model; Σ, Σ' two snapshots of Γ, e a ground incoming event, t a timestamp that is after all timestamps in Σ. Assume ImmEffect$(\Sigma, e, t) \neq \Sigma$. Then the following are equivalent.*

- (Σ, e, t, Σ') *satisfies the incremental formulation.*
- (Σ, e, t, Σ') *satisfies the fixpoint formulation.*
- (Σ, e, t, Σ') *satisfies the closed-form formulation.*

There is exactly one Σ' that satisfies these properties.

Proof (sketch): The second two formulations are equivalent because Ψ_Γ captures in extended FOL precisely the conditions of compliant and inertial. Let Σ' be constructed according to the incremental formulation. Note that the application of rules is monotonic, in the sense that in the sequence of rule firings, each rule applied makes a new change to the preceding pre-snapshot, and no change is "undone". Also, if a rule is fired, then all attributes in its antecedant cannot change after that rule firing. Finally, since no rule can be applied to Σ', we have the compliance property. For inertial, note that a status attribute is changed from Σ to Σ' only if there is a rule firing that changed it. For the opposite direction, given Σ' that is inertial and compliant, one can identify a ground rule that justifies each change between Σ and Σ'. Order these rules according to *PDG*(Γ). Based on this, create a sequence of pre-snapshots that satisfies the incremental formulation. Uniqueness follows from Lemma 5.1. □

5.5. B-steps in series

This subsection briefly considers situations in which it makes intuitive sense to consider a cluster of B-steps as a single unit. Recall that if an atomic stage contains a computational task (e.g., assigning one data attribute to equal another one), then this stage is opened in one B-step b_1 and is closed in some subsequent B-step b_2. Because the assignment is purely computational, it makes sense to have b_2 happen immediately after b_1. The same is true if B-step b_1 generates a message to the ASC intended for another artifact instance, or that calls for creation of an artifact instance, and b_2 processes that message. In practice, we define an *mega-B-step* to be a family of B-steps that starts with incorporation of an incoming event from the environment, and includes any subsequent B-steps stemming from automated actions within the BSC. Mega-B-steps are not guaranteed to terminate, nor to be unique. (We also note that in some unnatural corner cases, once a B-step has been computed there may be a rule r that is applicable. This can arise if the action of r "undoes" a change made during the preceding B-step. In such cases, it may be appropriate to include a B-step for applying such rules r into the mega-B-step.)

6. RELATED WORK

The GSM approach draws on previous work on ECA systems (e.g., [15]), but develops a variant useful for data-centric management of business operations and processes.

There is a strong relationship between the business artifact paradigm and Case Management [20, 7, 21]. Both approaches are data-centric, and support *ad hoc*, constrained styles for managing what activities should be performed and when. In both [20] and GSM, models are defined by adorning activities with a form of pre- and/or post-conditions, and the operational semantics is based on ECA rules derived from them. GSM appears to be more general than [20], and incorporates an explicit milestone construct. The approaches of [20] and GSM may be relevant to providing formal foundations for Case Management systems.

The AXML Artifact model [14] supports a declarative form of artifacts based on Active XML. The approach takes advantage of the hierarchical nature of the XML data representation used in Active XML. In contrast, GSM uses milestones and hierarchical stages that are guided by business considerations.

DecSerFlow [19] is a fully declarative business process language, in which the possible sequencings of activities are governed entirely by constraints expressed in a temporal logic. Condition-Response-Graph structures [10] support a family of intuitive constructs that are somewhat related to the GSM constructs, but with formal semantics defined using DecSerFlow. Neither system incorporates data with the prominence that GSM does. GSM does not attempt to support the level of declarativeness found in DecSerFlow, but instead relies on ECA-like rules and a fixpoint characterization.

There is a loose correspondence between the artifacts approach and proclets [18]. Both approaches focus on factoring business operations into components, each focused on a natural portion of the overall operations, and where communication between components is supported in some fashion. GSM places places more emphasis on data, and uses conditions against multiple artifact instances as a declarative form of communication between them.

7. CONCLUSIONS

This paper extends on-going work in the general area of event-driven, declarative, and data-centric business process management. Building on two previous papers that introduce the Guard-Stage-Milestone (GSM) approach for specifying business artifact lifecycles, this paper describes how GSM supports the interaction between artifact instances, both through triggering of (status change) events and through conditions that directly test the data in other artifact instances. The overall behavior of a GSM system is specified in terms of ECA-like rules, providing a declarative flavor. The ECA rules are derived from the guards and milestones of stages, providing a natural modular structure for the rules. A precise operational semantics is given for this context, and three formulations for that semantics are shown to be equivalent.

Several research directions are currently being pursued, including transactional properties, enabling stages to operate on members of a collection attribute, enabling stages to operate on multiple artifact instances at the same time, and incorporating people and roles.

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