K. Hornsby and M. Egenhofer (2000) Identity-Based Change: A Foundation For Spatio-Temporal Knowledge Representation. International Journal of Geographical Information Science 14(3): 207-224.

Identity-Based Change: A Foundation for Spatio-Temporal Knowledge Representation

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Acknowledgments

This work was partially supported by the National Science Foundation under NSF grant number SBR–8810917 and by a Massive Digital Data Systems contract sponsored by the Advanced Research and Development Committee of the Community Management Staff. Max Egenhofer's research is further supported through NSF grants IRI-9613646, SBR-9700465, BDI-9723873, and IIS-9970123; grants from the National Imagery and Mapping Agency under grant number NMA202-97-1-1023; the Air Force Research Laboratory under grant number F30602-95-1-0042; the National Institute of Environmental Health Sciences under grant number 1 R 01 ES09816-01, and Bangor Hydro-Electric Co.

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Abstract

As efforts grow to develop spatio-temporal database systems and temporal geographic information systems that are capable of conveying how geographic phenomena change, it is important to distinguish the elements that are fundamental to scenarios of change. This paper presents a model based on the explicit description of change with respect to states of existence and non-existence for identifiable objects. Such changes are of concern when, for instance, modeling and reasoning about nations that are subsumed through conflict only to return once more at a later time, or about water bodies that fluctuate due to seasonal or climatic change. The basis for tracing these changes is the concept of object identity. Identity, distinct from an object's properties, values, or structure, is that unique characteristic that distinguishes one object from another. Based on a small set of primitives relating to the identity states of objects, we model the semantics associated with change and through a systematic derivation, a complete set of identity-based change operations evolves from the primitives. These operations are basic to the types of change commonly experienced by geographic phenomena and modeled by researchers studying spatio-temporal change. This approach highlights the minimum elements necessary for reasoning about change, namely, object identity, an ordering of identity states, and co-occurrence of identity states.

1. Introduction

The spatial data models currently used as the foundation for geographic information systems (GISs) fall short of conveying the rich and complex ways in which phenomena change over space and time. One of the major limitations of today's systems, for example, is that they capture only a *snapshot* of reality, reliant as they are on databases that contain only current data. Yet, the world around us does not always change according to neat increments—neither do people conceptualize change as discrete snapshots. Growing awareness of the importance of GIS to a broader group of users means that the demands on these systems to represent scenarios found in the everyday world increase. This changing view of the role of information systems includes improving the methods for querying and conveying how phenomena change.

Traditionally, changes to geographic phenomena have been derived from a temporal reference frame. Temporal aspects of GIS have been investigated from the perspective of cartography (Langran 1992; Renolen 1996), data models (Frank 1994; Peuquet 1994; Worboys 1994), and spatial databases (Armstrong 1988; Al-Taha and Barrera 1990) although to date, no single model for including time in a GIS has been adopted. Time has proved difficult to formalize, especially as more than one type of conceptualization of time is needed for GISs (Frank 1998).

A more explicit focus on change has considered the semantics associated with change, such as those typically encountered as part of many basic spatio-temporal processes including the appearance and disappearance of entities and production or transmission of entities (Claramunt and Thériault 1995; Claramunt and Thériault 1996). These studies, however, have omitted certain kinds of change and so far no systematic treatment of change has been undertaken.

This paper presents an approach to spatio-temporal knowledge representation based on the explicit description of possible changes to geographic phenomena modeled at a high level of abstraction as identifiable objects. Starting with a set of basic types of change with respect to the existence and non-existence of objects with identity, a methodology is presented that systematically builds on these fundamental concepts and derives further types of change that are possible. The set

of change operations that results can be found in most scenarios of geographic change. This change-based model provides a better understanding of the set of possible alterations to which an object can be subject as it evolves over space and time and enables the extension of spatial data models and the development of GIS query languages that incorporate such semantics of change.

The foundation of the model is a set of primitives and the operations that can be performed on them. These primitives are *identity states of objects* and *transitions*. The term *object* refers to the representation of real world phenomenon in an information system (Kim 1990) that may exist as a physical entity, such as a building or a river, or something conceptual, such as a state or county. Objects may be naturally delineated such as islands or lakes, or they may be *fiat*, representing the case when an object is created through human imagination or convention, such as the creation of counties or other administrative units (Smith 1995). Although, in general, it is possible for objects to contain other objects, in this investigation, discussion is restricted to single objects that do not change into parts or aggregates (Hornsby and Egenhofer 1998).

The methods presented in this paper are based upon a classification of alterations to objects through tracking changes to *object identity*. In scenarios of change, identity is a key factor in proving the existence or non-existence of an object as well as being able to track similarities or differences in objects. Object identity is a trait that distinguishes an object from all others (Khoshafian and Copeland 1986). It provides a way to represent the individuality or uniqueness of an object, independent of its attributes and values. In object-oriented programming and object-oriented databases, the concept of a unique object identity is commonplace (Khoshafian and Baker 1996). It has been recognized as a tool to help track changes to objects (Clifford and Croker 1988; Abiteboul and Kanellakis 1989; Al-Taha and Barrera 1994; Hornsby and Egenhofer 1997) and aids the idea of an object being a stable and enduring element, something on which a perspective may be held (Smith 1996). *Identity states* are associated with objects, capturing the notion that although an object's identity is enduring, the state of identity may change, for instance, from existing to non-existing. In this work, existence refers to the physical presence or occurrence of an object or, for conceptual objects, the belief in or perception of an object. The United States, for example, can

be modeled as an existing object. This object is not a physically existing object, but rather an object that has been created by human decree (Smith 1995). Objects and their associated identity states are linked through another primitive, a *transition*. Transitions model the progression of an object from one state of identity directly to another.

Changes to identity are described in the form of an iconic visual language. A visual language uses pictorial or iconic primitives to allow one to model what are normally abstract and ephemeral concepts and associates these icons with a certain logical interpretation (Chang 1990; Glinert 1990). Visual languages provide an alternative means of communication with a computer system, which is often easier and clearer than a SQL-like database query languages (Catarci *et al.* 1993). The visual language presented in this paper is referred to as the *Change Description Language.* It is based on an iconic representation of different kinds of change and is used to depict a scenario of change, i.e., the identity states of objects and the transitions between these states. The approach distinguishes and classifies different types of change, from modifications to single objects based on a set of primitives, such as creating or eliminating objects, to more complex scenarios that involve combinations of change operations, for instance, spawning a new object from an existing one. The model is developed through a systematic treatment of which combinations of operations are feasible and which are infeasible. Stepwise extensions of the model enable the representation of other semantic concepts, such as the meaning associated with different methods of creating new objects, spatial relations among objects, or properties of objects (Hornsby and Egenhofer 1997). At one level, the Change Description Language can be seen as a query language describing identity-based change in a qualitative fashion. The semantics of the changes stem directly from the primitives and their combinations.

The remainder of this paper is structured as follows: Section 2 describes different types of change. Section 3 discusses how models that incorporate change are being introduced to GISs. Section 4 introduces the basic identity operations through the definition of the Change Description Language. Section 5 extends the identity-based change operations by focusing on the possible combinations of identity states and transitions between two objects. The result is a set of identity

operations that are plausible according to certain semantic constraints. Section 6 illustrates an application of the Change Description Language to a scenario that models changes in native land ownership. Conclusions and needs for future research are presented in Section 7.

2. Types of change

Space, time, and change are an integral part of everyday life and figure largely in commonsense reasoning (Egenhofer and Mark 1995). Consider these examples that involve change: the TV weather forecaster describes the development of a storm system over the past two days, explains how it is affecting current weather patterns, and forecasts what may happen in the next twenty-four hours; or a mortgage company analyzes the change in ownership of a set of land parcels over the past eight months in order to predict opportunities or risks for the company. Epidemiologists respond to changes in disease distributions and search for clues in the evolving pattern of disease occurrence that will aid in the prevention of further spread of the illness (Cliff *et al.* 1981; Cliff *et al.* 1992), while coastal geomorphologists are interested in describing the materials and processes that affect coastal forms (Raper and Livingstone 1995). A forester sees change when viewing tree and vegetation growth in a new area or environment (Lowell *et al.* 1996), while to an image processing specialist change may refer to the alteration in land cover between dates of imaging (Lillesand and Kiefer 1987). As a contrast to these geographic views of change, database software engineers refer to change as an update of a database through the addition, deletion, or modification of data (Silberschatz *et al.* 1997).

Some of these examples describe continuous change. The flow of water, the moving plume of an oil spill, and the weather are examples of phenomena that continually evolve. Similarly, the spread of disease or wave action on a beach may be viewed as being continuous. Other changes are regarded as being discrete, as with the change in ownership of a land parcel, which happens instantaneously (Al-Taha 1992). Change can involve the creation or destruction of a phenomenon, or the joining or splitting of some entity. In general, however, change refers to the fact that an object or phenomenon is altered or transformed into something different through the result of some

action or process. In this paper, we confine our discussion to change as it applies to identifiable, discrete objects and focus, in particular, on describing changes with respect to the identity states of objects—i.e., tracking the existence of an object over time.

3. Modeling change

Various models of change have been developed by mathematicians, geographers, philosophers, and computer scientists. The French mathematician René Thom (1975; 1983) considered different types of change in his work on morphodynamic theory and offered a taxonomy for basic types of change or *archetypal morphologies* including 'to begin,' 'to end,' and 'to emit (give birth),' which corresponded in his view to commonly encountered actions and events in the world experience. Mathematical functions have been used to model the temporal rate of change of geographic phenomena (Tobler 1985) as well as for modeling continuous change in spatial regions (Galton 1997).

One common method of capturing change has been to rely on a sequence of *snapshots* or discrete displays at sequential moments in time (Langran 1992; Peuquet 1994). This approach to visualizing and describing change has been used in work such as a study on the diffusion of AIDS in Pennsylvania (Gould *et al.* 1991). The snapshot approach is a procedure used by cartographers based on animating sequences of maps (DiBiase *et al.* 1992). Various supporting techniques can also be applied, such as playing the sequence of discrete displays at different speeds like frames of a movie, changing the duration of a scene to affect the pace of an animation, or altering the order in which scenes are presented. Researchers interested in capturing the complexities of underlying processes, however, are often dissatisfied with the snapshot approach, because this method overlooks the events, each of which occurred separately, that take place between the snapshots (Chrisman 1998). Indeed, the changes that occur between snapshots are not explicitly stored—instead, they must be determined by comparing the spatial patterns of two successive states. Another commonly cited disadvantage of the snapshot approach is the storage of redundant

information (Langran 1992; Peuquet and Wentz 1994) that occurs from the representation of those locations where no change occurred.

Other approaches contribute the view that an information system should preserve known links between events and their consequences. In this case, the events behind change should be considered, with the belief that GISs should be capable of monitoring and analyzing successive states of the spatial entities (Claramunt and Thériault 1995). Renolen (1996) traces object states through a sequence of events or mutations creating a *history graph*, and capturing changes to objects over time. History graphs express certain events including splitting and merging and can be further extended to describe the duration of events. Although these studies focus explicitly on change, there is no systematic approach to determine the complete set of processes or mutations and all events are expressed with respect to a timeline.

The recognition of different types of change and the need for an improved understanding of the processes underlying geographic change have been echoed in the work by those researchers investigating improved temporal capabilities for GIS (Langran 1992; Frank 1994; Peuquet and Wentz 1994; Peuquet 1994; Worboys 1994; Egenhofer and Golledge 1998). Traditional temporal query languages for GIS focus on an ability to address such queries as:

- What is the state of a phenomenon at time t?
- What locations have been affected by the phenomenon over the time period Δt?
- What phenomena exhibited certain characteristics at time t?

Scenarios of change, however, may require additional information. It may be necessary, for example, to query about the existence of an object or to perform queries about future states of an object such as:

- Is this object in existence at time t?
- Is this object at time t_2 the same object as encountered at time t_1?
- Has this object always been existing?
- What future changes are possible to this object?

Extensions to query languages that capture these semantics are possible through the development of a language that describes identity-based changes. A possible set of operations for tracking the evolution of a temporal feature's identity has been explored by Clifford and Croker (1988) and Al-Taha and Barrera (1994). Using object identity to track changes to objects is further explored by Hornsby and Egenhofer (1997; 1998).

The present paper provides a *systematic* derivation of identity-based change operations based on the notions of existence and non-existence, distinguishing the complete set of possible operations.

4. Basic identity operations

The identity-based model of change is comprised of primitive elements that can be combined to yield meaningful change operations. The primitives are based on identity states of objects and are founded on the concept of existence. Existence is different to the notion of *appearance*, a similar concept in the visual domain (Hornsby and Egenhofer 1998). The identity states of an object represent states in the real world, rather than states of database objects; therefore, the model of change presented in this paper describes changes as they occur(red) to entities in the real world.

4.1. Primitives of identity-based change

The model uses three basic symbols to convey the primitives of the model. These primitives arise from the fact that an object can be in one of two identity states: either existing, describing the case in which an identifiable object is present, or non-existing. We further discriminate non-existence to distinguish between non-existing identity states: non-existing without history and non-existing with history: Non-existing without history describes the situation in which no object with identity is existing or has existed previously. The term *history* refers to the (previous) existence of an object with identity; and *without history* means that no previous object with that identity has existed. This case is contrasted with the third primitive, which represents a non-existing object *with history*. In this case, an object with identity previously existed, but has been eliminated and

no longer exists. The primitives are visualized through a Change Description Language (CDL) (Figure 1). To aid identification of unique identities, objects have been given a label.

The change from one state of an object to the next is captured through an arrow and is referred to as the fourth primitive, *transition* (Figure 2). A transition links two identity states of the same object. Scenarios reflecting changes to object identity are developed from the left of the transition arrow to the right, where left corresponds to *before* and right to *after*. Transitions are assumed to be direct, with no intermediate states being portrayed. Within this setting, temporal change is represented qualitatively based on the temporal order of events, an approach to temporal reasoning that has been found to be valid for many of the domains using GIS (Frank 1994).

As a transition links different identity states of the same object, the CDL requires the objects to be drawn along the same horizontal. Co-occurrence of transitions affecting *different* objects is modeled through aligning the objects vertically (Figure 3a). Any transition linking two different identities along the same horizontal would be a violation of the CDL's semantics (Figure 3b). Transitions also must connect objects that are nearest neighbors with respect to temporal ordering (Figure 3c). No quantitative measures of time are represented with the CDL. Although concurrent states can be depicted, information on the *duration* of a transition is neglected.

4.2. Identity operations based on the four primitives

A set of change operations is derived through systematic combinations of the four primitives that model the identity state of an object and a transition. Since each of the three identity states can be linked through a transition with each other, a total of $3^2=9$ combinations can be found (Figure 4). It is worth noting that in certain contexts, some of these combinations would seem to be impossible or contradictory to a domain ontology and therefore may be considered unacceptable.

The nine combinations form a basic set of identity-based change operations:

- The transition between two identity states that are non-existing without history is referred to as the operation `continue non-existence without history` (Figure 4a).

- The transition from a non-existing object without history to an existing object with identity is referred to as a `create` operation (Figure 4b). In this case, an object with its identity is created.
- The transition from a non-existing object without history to a non-existing object with history describes a `recall` operation (Figure 4c).
- The operation `destroy` represents the permanent removal of an existing object resulting in a non-existing object without history (Figure 4d).
- The operation `continue existence` reflects a transition between two states of an existing object (Figure 4e).
- A transition from an existing object to a non-existing object with history conveys the operation `eliminate` (Figure 4f).

The remaining three combinations involve transitions with objects that are non-existing with history.

- The transition from a non-existing object with history to a non-existing object without history that captures the semantics of a `forget` operation (Figure 4g).
- The transition from a non-existing object with history to an existing object conveys the semantics of a `reincarnate` (Figure 4h), describing the fact that the same identity has existed previously.
- `continue non-existence with history` (Figure 4i).

These basic operations are powerful enough to distinguish the semantics of different changes such as the elimination of one object and the creation of a new object with a different identity (Figure 5a), from the case in which an object is eliminated and subsequently recreated (Figure 5b). In the latter case, the operations are applied to the same identity, capturing the semantics of a *reincarnation.*

Given these change operations, it becomes possible to connect sequences of these operations together in order to model scenarios of change. There are, however, certain constraints on the occurrence of the basic change operations in a scenario of change. Since the `create` operation

signifies that an identity has not existed previously, we employ a constraint that: a `create` operation can occur only once for each identity (Figure 6).

5. Change operations involving two objects

More complex scenarios of change involve two objects, such that one object has an impact on the identity change of the other. In this case, three transitions co-occur: one between the two states of object A, another one between the two states of object B, and a third between the first state of object A and the second state of object B—a *cross-object transition.* The cross-object transition is an additional primitive of the model of change. It is symbolized in the CDL with a diagonal arrow that links two objects of different identity (Figure 7). The types of operations involving cross-object transitions are referred to as *dependent change operations*. This section derives systematically a set of dependent change operations and analyzes which operations are plausible.

5.1. Derivation of dependent change operations involving two objects

Four concepts underlie cross-identity transitions:

- an initiating object with identity,
- the identity state of the initiating object before a transition and after a transition,
- an object that exists before a transition may continue to exist or may be removed (eliminated or destroyed) and
- non-existing objects may be without history or with history.

These four conditions involve stepwise refinements and lead to a hierarchy of constraints describing the states of object A and B both before and after a transition (Figure 8). Since the refinements are Boolean in nature, they establish criteria that provide a complete coverage and they are mutually exclusive. This property implies that any such change operation must have one and only one true value for the state before a transition and one true value for the state after the transition. With 3*3 bases possible, a total of eighty-one combinations are possible (Figure 9). Not all of these combinations are plausible however. We impose constraints that limit the set of

possible change operations from the total set of eighty-one. This includes all case where: object A is non-existing before a transition and object B's identity state does not change over a transition.

In the first case, a number of the combinations result in a non-existing object linked through a cross-object transition to either non-existing or existing identity states of object B. These combinations involve contradictory semantics and do not seem to make cognitive sense for most geographic phenomena of which we are aware.

The second case refers to combinations where, for example, object B's identity state does not change, although, a cross-object transition takes place. Object B may be existing (Figure 10), non-existing with history, or non-existing without history, before *and* after the cross-object transition, such that no identity change has occurred.

Removal of these implausible combinations results in a final set of eighteen dependent change operations between two objects (Figure 11).

5.2 Groupings of Dependent Change Operations

The set of dependent change operations represent situations that satisfy the constraints and produce meaningful results. Some of these operations are similar to each other and can be grouped together for easier interpretation. The way that the groupings are undertaken can vary according to different rationales. We have chosen to group the results according to the state of the dependent object with respect to the cross-object transition.

5.2.1 Change Operations That Result in Dependent Object in Cross-Object Transition to be Existing After a Transition

The first group of dependent change operations includes those cases in which the dependent object is existing after a cross-object transition. The first two cases describe scenarios where object B exists and the original identity, A, continues to exist after the transition. For instance, an existing object A is linked through a cross-object transition with a reincarnated object B (Figure 12a). The second example is similar except object B is newly created as a result of the cross-object transition (Figure 12b). This combination of primitives and transitions captures the semantics of a spawn-like

operation. An example of this type of change occurs when a new city is spawned from an existing city. In this context, it is valid for a cross-object transition to link at least two existing objects of different identity, and in this way, a connection is established between predecessor and successor objects.

The four remaining change operations in this section involve cross-object transitions between two different identities that co-occur with the demise of the original identity. These operations capture metamorphose-like semantics. In the first case, object B is non-existing with history to begin with and then is reincarnated through the transition with object A. Object A is eliminated as a result of the transition (Figure 12c). The next example is similar except that object B is newly created (Figure 12d). In one case, object B is reincarnated after the transition with object A. Object A is destroyed as a result of the transition (Figure 12e). In the final example, object A is destroyed simultaneous with the creation of new identity B (Figure 12f).

5.2.2 Change Operations That Result in Dependent Object in Cross-Object Transition Becoming Non-Existing After a Transition

One group of dependent change operations involves a cross-object transition where object B no longer exists as a result of the transition. The first case, for instance, object B is eliminated while A continues to exist after the cross-object transition (Figure 13a). Similarly, existing object A is linked through a transition to object B that becomes non-existing without history (Figure 13b). The original object continues to exist. These combinations of operations reflect the semantics associated with takeovers, for example, or replacing another object and identity.

Another group of change operations involves both objects ceasing to exist. In the first case, both objects become non-existing with history after all transitions (Figure 13c). The second case is where through a cross-object transition with object A, object B is destroyed while object A is eliminated (Figure 13d). The next scenario is where object A is destroyed simultaneous with the elimination of object B (Figure 13e) and finally, both objects are destroyed as a result of the transition (Figure 13f).

5.2.3 Change Operations Where Dependent Object in Cross-Object Transition is Non-Existing Before a Transition

This group of change operations involves cases where object B is non-existing both before and after a cross-object transition with object A. In the first two cases, A continues to exist after the transition, while B is forgotten (Figure 14a) or B is recalled (Figure 14b). The next two cases are those where object A is eliminated and B is forgotten (Figure 14c) or recalled (Figure 14d). Finally, there are the cases where object A is destroyed and object B is forgotten (Figure 14e) or recalled (Figure 14f).

6. Applying the Change Description Language

The Change Description Language can be used to convey changes expressed through a natural language description of some scenario. An example is given based on changes in native land ownership relating to the Maine Indian Land Claims in the late 1970s—a case involving more than one view of land ownership.

In the late 1970s, the State of Maine was at the center of a controversy regarding native land claims. The Passamaquoddy Tribe and Penobscot Nation claimed that Maine and its predecessor state, Massachusetts acquired land in the 1790s without the requisite Congressional approval, and filed a native land claim for 12.5 million acres, the approximate size of their lost ancestral hunting grounds. This claim represented a land area approximately two-thirds the size of the State of Maine, an area that was then home to a population of 350,000 non-native people (Brodeur 1982). The claim was eventually settled as the "Maine Indian Claims Settlement Act of 1980," in which the U.S. Federal Government awarded the Indians sufficient funds towards purchase of 300,000 acres, as well as a trust fund (United States 1980).

Certain key events relating to native land ownership have been chosen for modeling and only *identity-based* changes relating to existence and non-existence are described:

- Governor Pownal of Massachusetts issues a proclamation in 1759 that the land of the Passamaquoddies has been lost through conquest to the State of Massachusetts.

- The State of Massachusetts issues 23,000 acres to the Passamaquoddies through a Treaty in 1794.
- Maine separates from Massachusetts and joins the Union in 1820.
- By the 1960s, 6000 acres of the 23,000 acres of Passamaquoddy land had been sold by the State of Maine.

In modeling these events, two unique objects with identities are established for representing Passamaquoddy- and Massachusetts-owned land, respectively (Figure 15). One possible view is that when Passamaquoddy land is lost through conquest, the object and identity are destroyed. There follows a `reincarnation` of the Passamaquoddy identity when the land treaty with Massachusetts takes effect. A third object, Maine, is created through a spawn-like operation when Maine separates from Massachusetts and is recognized officially as a State. Finally, although 6000 acres of Passamaquoddy land is sold by Maine and this event is actually the trigger that set off a chain of events that eventually led to the land claim, at the level of identities, no change is incurred.

Since no changes relating to the spatial properties of an object are being modeled, the CDL does not explicitly represent any details relating to acreage, specific land holdings, etc. Further extensions to the language are necessary in order to describe operations of splitting or joining objects. This example illustrates, however, the presence and absence of identities through time and shows how objects can be tracked even through periods of non-existence.

7. Conclusions

Describing spatio-temporal phenomena with respect to change opens new doors to understanding the underlying components of change and recognizing the semantics associated with change. This paper has examined change from the perspective of describing *identity changes* to objects that represent geographic phenomena found in the real world. Identity allows us to distinguish objects from each other. Identity also provides a mechanism with which to track changes, such as the existence or non-existence of an object over time.

Modeling change from this perspective begins with a consideration of what operations on an object's identity are possible. A set of basic identity-based change operations relating to states of existence and non-existence has been derived with sequences of these changes to objects being visualized through use of an iconic *Change Description Language*. Scenarios of change between different objects can be modeled with this language and the sequences of operations compared. In addition, the language can be used to model scenarios of change as viewed from different perspectives—for instance, two contrasting views of land ownership changes. Higher-level change operations can be derived through a process of systematically combining the possible states of object identity before and after a transition. Such scenarios result in a directed graph. Its three core elements are identity, co-occurrence, and temporal ordering of identity states. All three elements of the model are needed in order to describe change at a most basic level. If we were to eliminate the requirement for co-occurrence, this would reduce our ability to reason over multiple identities and the representation would be restricted to identity states of only one object. If we take away the constraint of ordering, we effectively reduce the model to a representation of objects at one identity state and this does not convey change. Finally, if the requirement for identities is removed, then there remains nothing to represent with the model. Therefore, all three elements are necessary for describing change.

Understanding all the possible configurations of changes to identity combined with the ability to compare current combinations of change operations with historic sequences of change is useful for predicting or forecasting future modifications to an object. This comprehensive derivation of identity operations will also make it possible to develop spatial query languages such that they reflect the constraints of the identity-based model and offers users the ability to incorporate the semantics of change as necessary in their work.

Although no explicitly spatial information has been incorporated in this model of change, it has been shown that tracking changes to an object's identity over periods of existence and non-existence, gives useful insights into the behavior of an object over time that are relevant to many cases of spatio-temporal change. The model can be extended, adding information about the

properties of an object, spatial relations among objects, and temporal histories associated with an object.

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Figure 12: Dependent change operations where a different identity exists after a cross-object transition: (a) object A continues to exist and object B is reincarnated, (b) object A continues to exist and object B is created, (c) object A is eliminated and B is reincarnated, (d) object A is eliminated and B is created, (e) object A is destroyed and B is reincarnated, and (f) object A is destroyed and B is created.

Figure 13: Change operations that involve a transition where object B no longer exists as a result of a cross-object transition with object A: (a) A continues to exist and B is eliminated, (b) A continues to exist and B is destroyed, (c) A and B are eliminated, (d) A is eliminated and B is destroyed, (e) A is destroyed and B is eliminated, and (f) A is destroyed and B is destroyed.

Figure 14: Change operations where object B is non-existing: (a) object A continues to exist while object B is forgotten, (b) object A continues to exist and object B is recalled, (c) A is eliminated and object B is forgotten, (d) object A is eliminated and object B is recalled, (e) A is destroyed and B is forgotten, and (f) A is destroyed and B is recalled.

Figure 15: Changes of Passamaquoddy (P) land ownership to Massachusetts (MA) and Maine (ME) modeled with the Change Description Language.

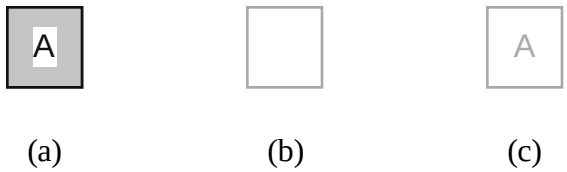


Figure 1: Basic symbols used for (a) object existence, (b) non-existing object without history, and (c) non-existing object with history.

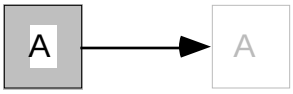
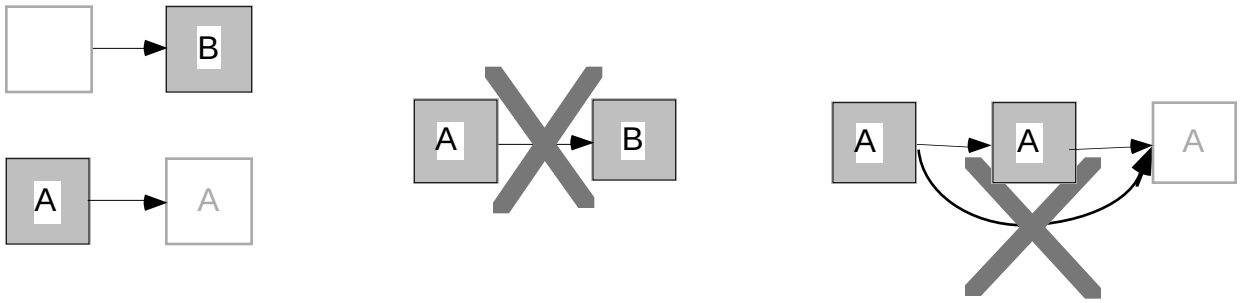


Figure 2: A transition between two identity states of an object.



(a) (b) (c)

Figure 3: Visualizing transitions: (a) valid transitions for two objects, A and B, (b) invalid transition from object A to B, and (c) invalid transition between two identity states.

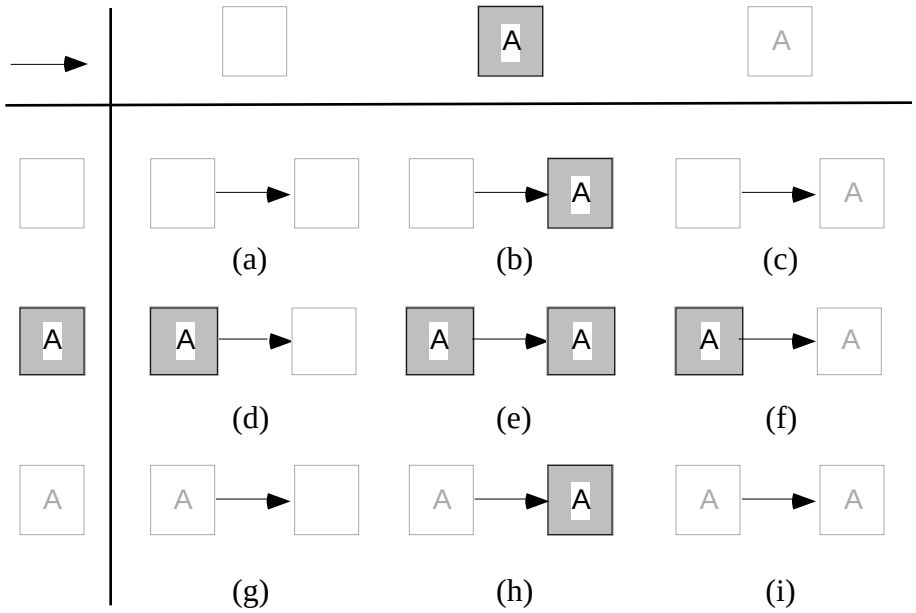


Figure 4: Combination of the primitives relating to existence, non-existence, and transition resulting in change operations: (a) `continue non-existence without history`, (b) `create`, (c) `recall`, (d) `destroy`, (e) `continue existence`, (f) `eliminate`, (g) `forget`, (h) `reincarnate`, and (i) `continue non-existence with history`.

(a) (b)

Figure 5: Two semantically distinct combinations of `eliminate` and `create`: (a) `eliminate` operation applied to object A and a `create` operation forming an object B and (b) `reincarnate` of object A.

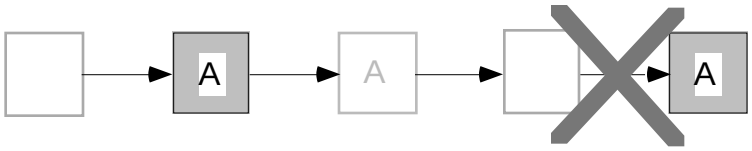


Figure 6: A `create` operation can occur only once for each object.

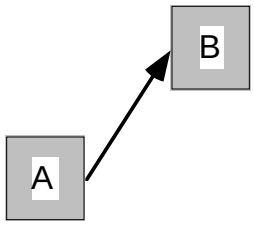


Figure 7: Change operations between two objects: a cross-object transition from object A to object B is symbolized with a diagonal arrow.

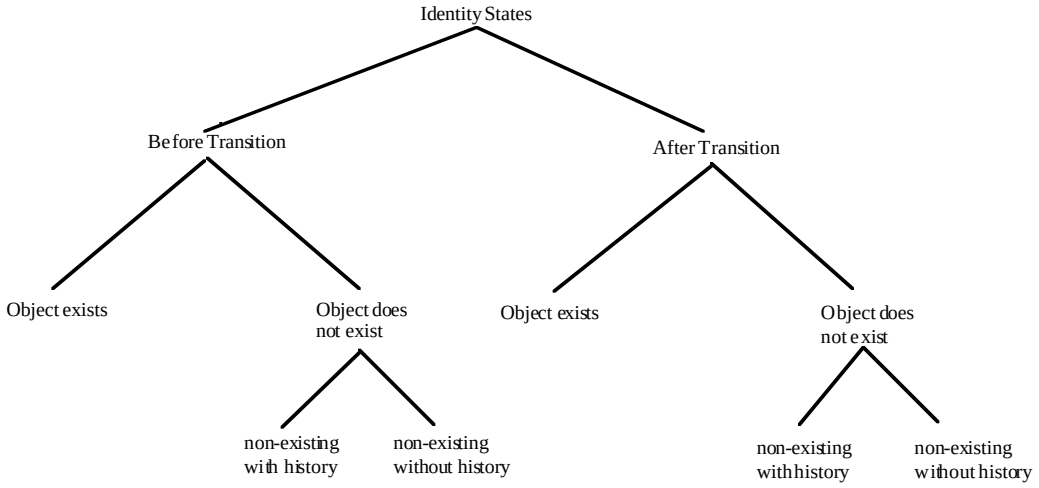


Figure 8: Possible states for one object over a transition

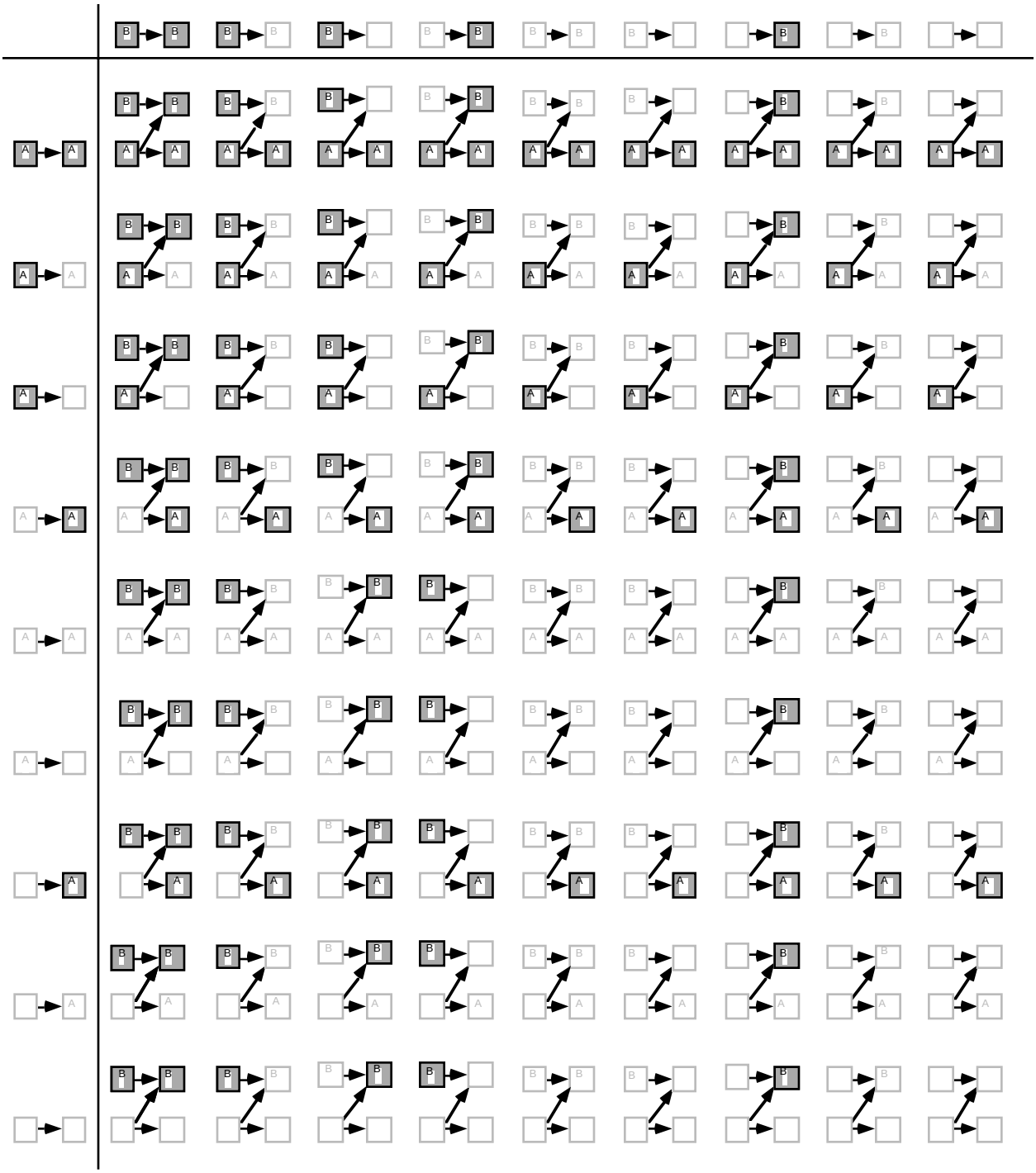


Figure 9: Change Description Language visualization of the 81 possible combinations of change operations involving two objects and a cross-object transition.

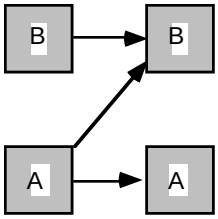


Figure 10: Invalid combination where objects A and B exist before *and* after the transition (i.e., no identity change occurred).

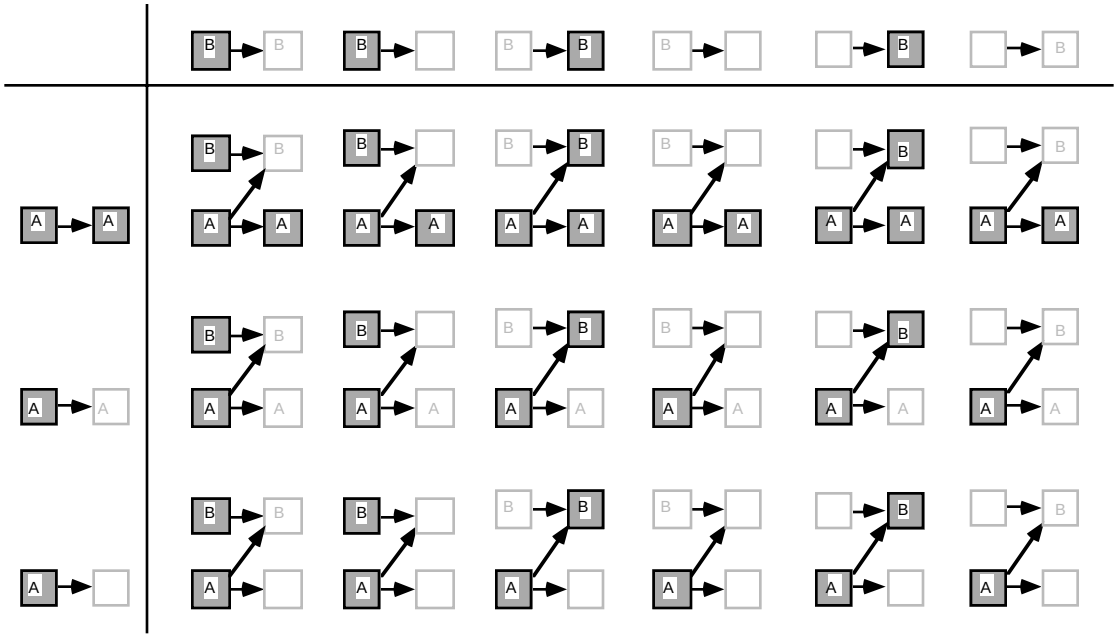
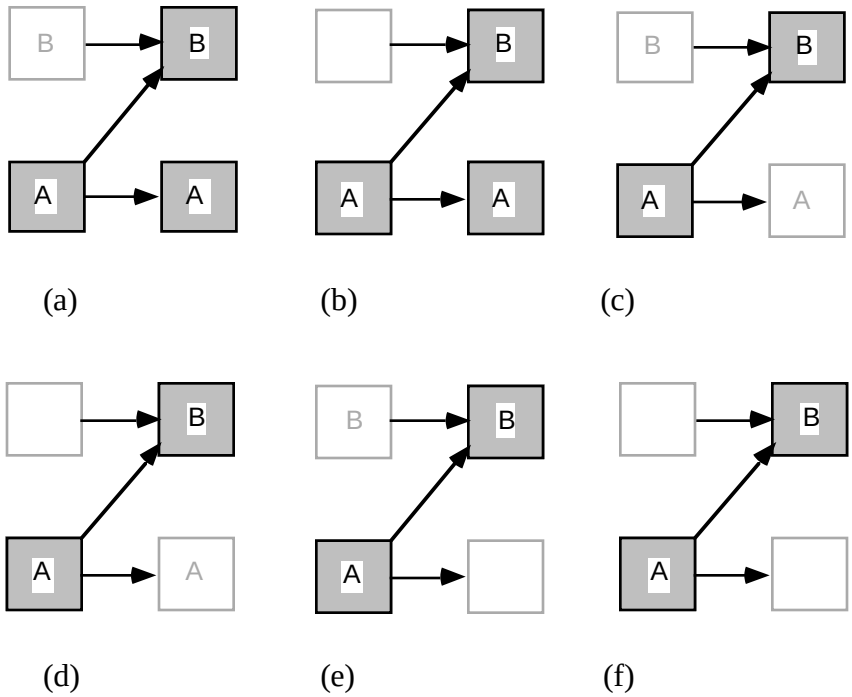


Figure 11: Constraints limit the possible combinations from 81 to 18 plausible change operations between two objects.



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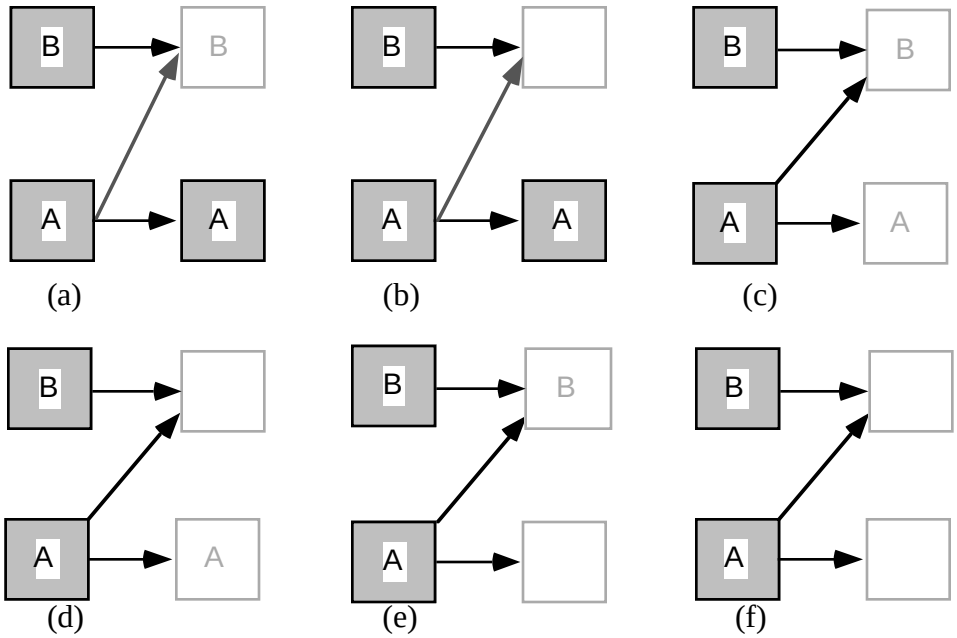

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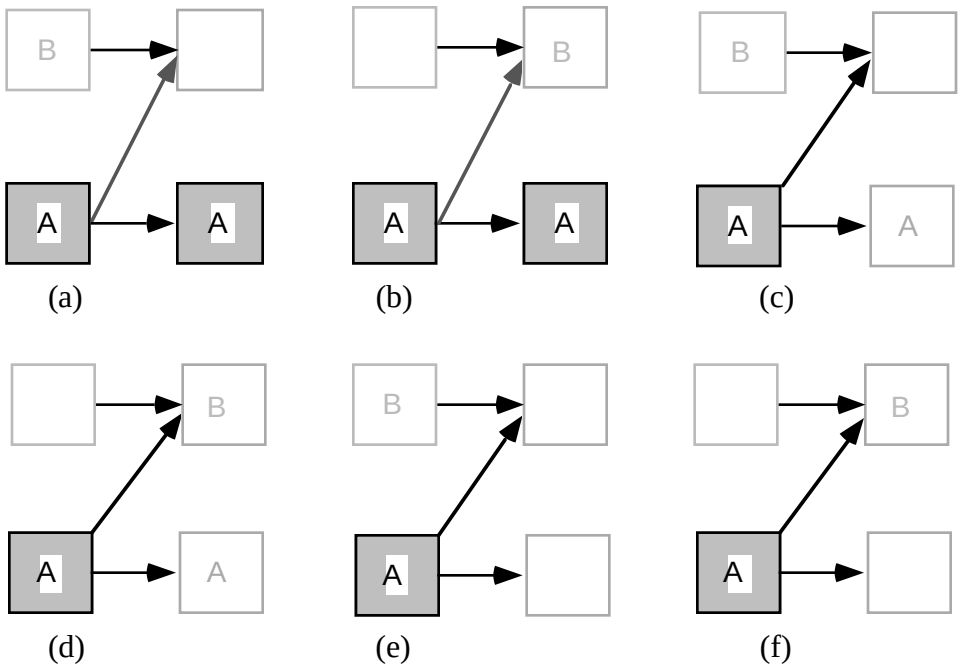

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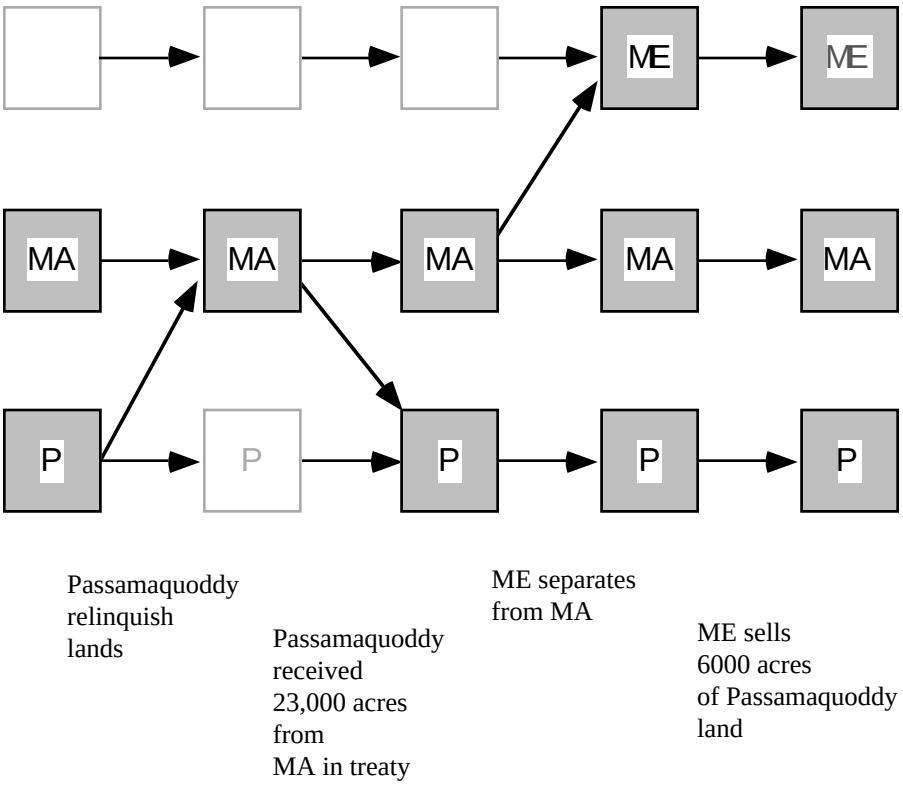

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