Towards an Ontology of Physics

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Abstract: *Meaningful interoperability between physics-based models requires a common understanding and standardized description of the physical laws governing physical objects, i.e., an ontology of physics and the resulting metadata. For example, currently, the Synthetic Environment Data Representation and Interchange Specification (SEDRIS) standard addresses the description of model data objects, their spatiotemporal coordinates, and many physical attributes. What is not described in SEDRIS are model dynamics, i.e., how a model evolves in time between the discrete states that are represented in transmittals. If model dynamics are not specified with the data, a data recipient will be required to infer how he/she should use the received data, making an inference that will vary depending on the recipient.*

Of the many factors that may affect model dynamics, such as military doctrine, human behavior, or physics, we focus on representing physical dynamics. This is commonly a necessary aspect of model dynamics. The key concepts in representing physical dynamics are the equations of physics, usually phrased as differential equations, and how they relate to static representations of physical objects, such as those represented in SEDRIS. This paper frames the structure of how to incorporate considerations of dynamics in an ontology of physics and begins to detail the types of physical dynamical relationships that may be modeled.

1 Introduction

Interoperability between modules in a Modeling and Simulation (M&S) framework is only meaningful to the degree that modules have an accessible description of what they are and what can be done with them. By accessible we mean that other modules, perhaps even humans, can access and interpret the description. The degree of interoperability will be determined by how well the description provides a common, unambiguous understanding. Fort the highest levels of interoperability we require common conceptual models to support semantic consistency across models [1].

Since some of the objectives of modeling and simulation are to simulate a large range of things that can happen in the real-world, the conceptual framework and language for phrasing such a description, i.e., the ontology, can conceivably cover all of human experience. Since much of what could be described, particularly that which involves mental states, is perhaps subjective, or perhaps not definitively modeled, there will be difficulties in developing standardized comprehensive ontologies for M&S. On the other hand, there are concepts that are objective. In particular, the physical environment can be objectively modeled as can projections of the physical world onto physical sensors. Since many models focus primarily on representing the physical aspects of objects, it would be advantageous to develop an ontology of the physical world. To support interoperability, a standardized ontology is required.

A common M&S system paradigm is of interlinked dynamical models passing each other datagrams representing object state information. The SEDRIS [2] standard was developed for the representation of physical, environmental objects. By its design, it is capable of representing the state of many, if not most, physical objects. In common modeling and simulation architectures, SEDRIS transmittals typically represent static snapshots of the physical state of an object (or the world) which are created by and used by algorithmic representations of object dynamics. SEDRIS supports description of model data, but the algorithmic software modules of object dynamics that pass data to each other cannot be similarly described as there is currently no standardized way to do so.

Even though domain experts may share a common background understanding of theory, when they develop dynamical models in software, various assumptions they make are usually kept hidden, even from other domain experts. If internal representations are hidden from other domain experts, there is little hope that simulation modules will be able to communicate a description to each other, module to module. The ability of software modules to communicate what they do is essential for interoperability. The problem now is, even if domain experts wanted to encode a description of the underlying dynamics and assumptions that they make in their algorithmic representations of physical object dynamics, there is no standard language or semantic reference frame for them to use to do so.

2 Ontologies

Domain experts already share an understanding of the common laws of physics; we are all taught a common set of concepts in academic physics courses. This understanding, however, is based on informal conventions; we know of no comprehensive, formal standard. For example, International Standards Organization (ISO) physics standards [3] focus on specifying physical units, measurement methods, and the values of fundamental constants. They do not focus on describing mathematical relationships between physical concepts. Because there are an arbitrary number of units for specifying the amount of mass an object has, an ISO standard specifies which unit shall be used. There is but a single concept of mass, a single concept of charge, etc.

SEDRIS references and incorporates many of the ISO physics concepts. Many of the fundamental relationships between concepts, however, such as between mass, force and acceleration, remain unstated. The underlying relationships between concepts are generally taken for granted as being commonly known. Many of these concepts are the mathematical relations specifying how the physical dynamics of objects are determined by their physical attributes and the physical relationships they have with other objects. What is required is a structure for describing these relationships: such a structure is often called an ontology.

What is an ontology? An ontology is a formal explicit description of concepts, their properties, relationships between the concepts, and the allowed values that they may take. An ontology together with a set of individual instances of classes constitutes a knowledge base [4]. An ontology provides a semantic reference frame useful for automating the communication of abstract information. The purpose of an ontology is to enable the communication of meaning for purposes of understanding. Not all ontologies are equal, however. They depend on the definitions used for “meaning” and “understanding”. The meaning of those terms is largely operational: it depends on the use we expect to make of an ontology.

In developing an ontology of physics, or any subject, it is important to consider what is unnecessary or impractical as well as what is needed or desirable. Consider that a significant effort of research in physics today is oriented towards developing a big theory of everything (BigTOE) which would unify what are separately described branches of physical theory. One could say that this should result in the ultimate ontological description of physics. Being a subject of research, though, a BigTOE is far from being settled, and, consequently, far from being a subject that can be put forth as a standard. Even though there has been considerable success towards unifying theories in physics, a practical ontology is perhaps better based upon a less unified view, e.g., a collection of sub-domains of physics, such as kinematics, dynamics, electrodynamics, heat flow, acoustics, chemical dynamics, etc. Clearly, since fundamental physical theory is still a matter of research, it would be impractical to formulate a comprehensive ontology that captured such incompletely developed concepts as unification.

What we should probably aim for in a standard is an ontology that is useful for the common uses rather than an academic ideal, however correct that may be. This suggests the question, "To what degree is it feasible to standardize a description framework, or ontology, for model dynamics?" The formulation of standards should be possible whenever there is no essential disagreement on what is being discussed or described. It should also be possible to form a standard when different descriptions of a domain of knowledge have clear equivalences, such as is the case with physical units.

Artificial Intelligence (AI) research into Qualitative Physics [5] has focused on various formal approaches to developing ontologies of physics. These ontologies have often taken a formal, axiomatic structure, exploiting the inherent mathematical nature of physical theory. They often focus in depth on a narrow class of physical problems. These formal methods approaches can lend themselves to the application of automated theorem provers which can create extensions to the ontology beyond the basic axioms. The intention of some of these ontologies might be to answer diagnostic questions such as "Why did the nuclear power plant's cooling system overheat?", or analytical questions such as "How much fuel would be required for the rocket to reach stable orbit?" Such questions reflect a desire to have computers reason deductively, as human physicists might, about physics. While it is desirable to support extensive chains of deductive reasoning that could answer such questions, it is difficult, as with any axiomatic, mathematical theory, to demonstrate that these axiomatic descriptions are self-consistent. While attempting to automate these kinds of complex reasoning is laudable, such work is still a subject of AI research. Also, while it is possible that an extended effort of development may produce these types of capabilities, it might be more fruitful to scale down the requirements we demand of an ontology so as to realize near-term results.

3 A Practical Ontology of Physics

The Department of Defense (DoD) M&S community currently has a collection of numerical models that possesses a fair degree of syntactic interoperability, thanks largely to the High Level Architecture (HLA). This means that the format for data passed between dynamical models has a standardized syntax. The meaning of that data is more open to question. The process of inserting a dynamical model into an HLA simulation framework provides little assurance that the insertion will create a meaningful outcome. As they are, DoD M&S dynamical models often lack a higher level, abstract description of the analytical model of which they comprise a numerical implementation. Even if models currently possess some abstract description, there being no standard framework for which to phrase it, the scope of utility of such a description is limited to the human technical experts who can find and understand it.

As we have discussed above, there are many important questions that might be asked that we could develop an ontology to help us answer, but perhaps we should first attempt to answer simple questions. Some of the questions that we might attempt to answer first could be: "When this federate is plugged into the simulation network, will it automatically discover those models that it may, or must, interact with?"; or, "Will the model be able to communicate to other federates the services that it can provide?"; or even "If I try to couple two models together that are incompatible, will I be alerted to a reason for the incompatibility?"

Answering such questions would be useful and does not necessarily require a great depth of reasoning. Perhaps starting with a broad, descriptive ontology would be most helpful in classifying which object dynamics are appropriate to a given situation. As requirements dictate more definition, it can be added and the ontology refined. One idea may be to focus on a process of elimination in making a determination that a given dynamic model may be appropriate for a specific object, and not expecting a single, deterministic answer. We might make better progress by first determining what dynamic models are almost certainly inappropriate for the object, and thereby eliminating them from further consideration, before trying to determine which of two feasible models makes better sense. Surely, it is easier to determine that a rigid-body dynamics model cannot predict the future state of the atmosphere than it is to determine which of two meteorological models is the better one to use. In any case, the determination of which is the better model is often a question that is still a matter for human debate, and so forming a standard which determines such a decision is not helpful. As time progresses and human debate settles such open questions, future standards could certainly be amended to incorporate the additional discriminants for enabling more finely tuned decisions of appropriateness. In order to support these kinds of reasoning it would be helpful to have an abstract classification scheme within which to describe dynamical models. In the end, we envision an ontological structure that first captures fundamental physics, then details governing equations of various branches of physics such as fluid mechanics, electrodynamics, etc. At more detailed levels, standard approximations would be characterized, such as viscous fluid flow and inviscid fluid flow, and, following that, named numerical models. Additionally, we envision describing the concepts of measurement and uncertainty and the process of state estimation.

4 The Modeling Process

To determine where we begin to start developing a standard ontology, we first synopsize the general process by which a model developer goes about developing a simulation model of physical dynamics. One may visualize these steps as various layers of abstraction, each lying above the next.

The first step a developer must take is to determine what the relevant physical concepts are that are required to model the physical objects being considered. We can call this the layer of physical semantics. An example of this is the Environmental Data Coding Specification (EDCS) in the SEDRIS suite of standards. The EDCS contains many physical concepts with some relationships between concepts as well. The EDCS also includes concepts that, while part of the physical environment, would not generally be considered concepts of physics, per se. Additionally, being intended for describing data, the EDCS does not capture physical dynamics.

Following this the developer needs to put together a mathematical formulation of the problem he wants to solve. This step begins with one or more fundamental physical equations, usually differential in nature. After determining the relevant physical equations, these equations need to be solved for the state of the physical object, within some specified space-time reference frame. By solving for the state, we usually mean that the position and velocity, and perhaps the acceleration, of an object's mass distribution are determined as explicit functions of time, although sometimes only implicit symbolic solutions are available. We can call this layer the mathematical representation layer.

Frequently the mathematical formulation has no analytically exact solutions, or the solutions are mathematically difficult to solve, and consequently a mathematical approximation to the solution may be made. This layer may be considered part of the mathematical representation layer, or an independent, mathematical approximation layer. An example of some specific mathematical constructs applicable to representation of physics may be found in the SEDRIS suite of standards, in particular the Spatial Reference Model (SRM). The SRM codifies a large range of specific spatial coordinate reference frames, with origins generally earth or solar system centered, as well as mappings to convert from one to another.

To summarize, most of the solutions so far discussed are expressed in continuous, rather than discrete, state spaces. They are typically expressed in algebraic mathematical symbols. For example, while many of the fundamental equations of physics are differential in nature, the final combined solution of an object's physical state, as a function of time, is typically an integral over continuous space and prior time of the influences of those things physically affecting the object. For the purposes of describing model dynamics in a way that can be automatically processed and manipulated, much of these formal, mathematically expressed relations between physical objects need to be standardized.

The next step in developing a computer model of object dynamics, often called a numerical solution, entails a discretization process. In this process there are frequently many choices to be made, some arbitrary, some motivated by analytical reasoning, and some motivated by practicality. (In making these choices, alternative approaches are neglected). Space and time are usually discretized. In the representation of the mathematical terms on the discretized space/time grid, differential equations are represented as finite difference equations and continuous integrals as discrete sums. There are multiple ways a single mathematical formulation may be discretized, which in a continuum limit are equivalent. For example, a one dimensional lattice derivative may be left sided, right-sided, or symmetric. These multiple choices may result in relative bias in the alternate discretized formulations.

The discretization process also affects the accuracy and precision of the resulting computations. Sometimes models may be run at "higher resolution", or closer to the continuum limit, to improve accuracy, when it is feasible. Improved accuracy is generally gained at the expense of computational resources, where cost is often expressed in the amount of time required to arrive at a solution. Additionally, for a given discretization of space and time there may be multiple algorithmic choices. For example, to compute the area under a curve, F(x), we can compute the integral by adding up the areas of a "bar-chart" representation of F(x) or by applying the Trapezoidal Rule, both using the same discrete values of x(i) and F(x(i)). The result is that different discretized solutions of the same underlying analytical equations may be considered non-equivalent. This last layer we can call the discretization layer. The nature of the discretization layer in the modeling process explains the common experience that there are as many solutions as there are developers. It is also a process that can make the computer code difficult, if not impossible, to relate back to the original mathematical description.

The best approach to standardizing a description of the discretization of the algorithm would probably be a standard for a symbolic representation of the discrete sums and finite difference equations. A description of an algorithm using this kind of standard might well resemble standard source code itself, e.g., C++ code.

We note here for purposes of contrast and comparison that the SEDRIS standard's Data Representation Model (DRM) provides a means for describing discretized data fields, where the values between grid points are supplied by user defined interpolation. SEDRIS does not discuss or prescribe discretization methods, nor does it represent the underlying mathematically continuous ideal: SEDRIS is a standard for representing things that have been discretized. Certainly the standard was developed with cognizance of the variety of typical numerical methods used by computational model implementers, and so supports them without describing them. Since we would expect a standard descriptive framework of object dynamics to complement the SEDRIS standard, we here raise the interesting question as to whether it would be desirable or feasible to design an ontology of physical dynamics that referred only to discretized models.

Finally, the solution to the mathematical expression often entails a single, modeler-selected discretization, or grid. This approach cannot anticipate the data requirements of all possible users. For many users to have access to model output, an interpolation is often required, to determine the values on the user specified (discretized) domain, or grid, instead of the modeler-selected grid. We can call this layer the interpolation, or translation layer. Ideally, the user specifies the grid that the model computes the results for and this interpolation is unnecessary, but practically speaking, interpolation is sufficiently common that we need to represent it.

While there are formal relationships that hold within each of the above described layers, transitions between layers are often not formal. Additionally, it is particularly difficult to infer the layer above from the layer below. As a rule, intrinsic meaning is lost, in a sense, as one proceeds from the physical layer downwards. Additionally, precision may also be lost. What is gained is a quantifiable result - a numerical answer. For example, mathematical expressions may be formally combined and solved without ambiguity or lack of meaning within mathematical formalism. It is difficult, however, to infer what physical principals are being represented in the equations. Without proceeding to a discretized representation, a mathematical expression may be unsolvable with current techniques. As one proceeds to obtaining a numerical answer, precision in the result may be sacrificed due to the approximations that are often made in the downward transitions.

As an alternative to the above described multilayered modeling process, one may decide that one should use exclusively discrete models, since these are what are implemented on computers, in order to preserve formal meaning within a discrete mathematical representation. The problem with this approach is that the implemented model is far removed from the semantically rich physics layer. As well, most physical models are specified in symbolic mathematical form and not for the convenience of programmers of discrete models. The real answer to this problem is continued research to create more formal transitions between these layers. In the meantime, we need to work within the established set of methods for these transitions, accepting the resultant, often unpredictable, errors incurred by doing so.

At this point we point out that there are some practical tools that may help in the modeling process we describe above. Many are familiar with the MatLab™product line, which provides an integrated development environment with the core constructs of discrete arrays and an interpreted scripting language. Other tools, like computer algebra systems such as Mathematica™, Maple™, and MuPad™, are based upon representing, manipulating, and solving formal, symbolic mathematical expressions. Additionally, these tools support the numerical evaluation of the mathematical expressions. Another effort, the development of the Modelica™language, bears examination for supporting interchange of models created with Computer Aided Design (CAD) systems. Some of these tools may be candidates for building an ontology of physics. While one should be careful in relying upon proprietary tools for standards development so that the standards do not rely upon the specific tools, these tools do provide a current capability to express many of the concepts we have discussed. It may be that wider use of these kinds of tools alone will facilitate meaningful interoperability, and should be encouraged.

While standards may be helpful in specifying each of these layers, we are focussing particularly on the physical semantics and their symbolic mathematical representations. If we believe that we can standardize the commonly accepted laws of physics, we need to determine which variation should be standardized. Because the laws of physics are mathematical, we can derive alternative equivalent formulations by algebraic manipulation. We certainly don't want to standardize each distinct permutation in the phrasing of the equations. Perhaps there is one approach to formulating the laws of physics that is better than others. For example, while most of the fundamental equations of physics are differential in nature, relating infinitesimal changes of physical state with respect to space and time, the representation of a solution to the equations is generally integral in form. Since we seek to represent a way of describing the solutions, perhaps that is the place to start.

5 Elementary Physics

We illustrate what concepts for describing dynamical models as solutions that we believe should be standardized by beginning with elementary physics, i.e., the physics of Newton and beginning college physics courses. It consists of the kinematics and dynamics of everyday objects.

5.1 Kinematics

The concept of *mechanics* includes *kinematics* and *dynamics*. Kinematics is defined as the specification of the motions of an object considered in and of themselves without reference to their causes. The concept of kinematics also includes the comparisons and relationships between different motions.

The first two fundamental concepts are *location*, or *position*, and *time*. The position of an object, $\vec{r}$, is expressed as a vector relative to the position of a *reference frame* origin at a time specified relative to a reference time origin. Any object exists at exactly one location at any given time. The location, or position, may change as a function of time, $\vec{r} = \vec{r}(t)$. The rate of change of position with respect to time is defined as the *velocity*, $\vec{v} = \frac{d\vec{r}}{dt}$. The rate of change of velocity with respect to time is defined as the *acceleration*, $\vec{a} = \frac{d\vec{v}}{dt}$

As a function of time, the position and velocity are given by the solution integrals:

$$\vec{r}(t) = \vec{r}_0 + \int \vec{v}(t)dt \ ; \quad \vec{v}(t) = \vec{v}_0 + \int \vec{a}(t)dt$$

When the acceleration is constant this gives: $\vec{v}(t) = \vec{v}_0 + \vec{a}t$ and $\vec{r}(t) = \vec{r}_0 + \vec{v}_0 t + \frac{1}{2}\vec{a}t^2$.

Kinematics represents what are the most directly observable physical properties of objects. The kinematics represents the dynamical state of an object and predicting them is what we desire. These solution integrals form the starting point of a representation of the dynamical models. Now, to solve the kinematics, if an algorithmic module is passed an object with an initial position and velocity in order to solve its future position and velocity at arbitrary time past the initial time the acceleration must be specified. For specifying the acceleration we need to proceed to dynamics, where the physics enters prominently. We note in passing that a more complete discussion of kinematics would also require a discussion of accelerating, or non-inertial, reference frames, which we do not discuss here.

5.2 Dynamics

Dynamics is the concept that encompasses the description of the causes of motion of objects, the individual causes being called *forces*. There are multiple concepts within the discussion of dynamics. We first explore these within the framework of Newtonian dynamics.

An object has *inertia*, i.e., it tends to resist a change of motion proportional to its *mass*, m, a scalar. The *momentum*, $\vec{p}$, of an object is defined as its mass multiplied by its velocity, $\vec{p} = m\vec{v}$. A force applied to an object tends to cause that object to change its momentum. The relationship between force on an object and the mass of an object is specified by Newton's Second Law:

$$\vec{F} = \frac{d\vec{p}}{dt} = \frac{d(m\vec{v})}{dt}$$

where for a constant mass,

$$\vec{F} = m\vec{a}$$

Multiple forces may act on an object. The net force is the vector sum of those forces. The object's acceleration is determined by net force divided by the object's mass. Now, as a function of time, the position and velocity are given by substituting the acceleration into the above specified solution integrals:

$$\vec{r}(t) = \vec{r}_0 + \int \vec{v}(t)dt \ ; \quad \vec{v}(t) = \vec{v}_0 + \int \frac{\sum_i \vec{F}_i(t)}{m} dt$$

This is the basic approach towards expressing the state of a physical object: determine the forces acting on the object, then integrate forward in time to solve for the velocity and position as a function of time.

When an object exerts a force on another object, it experiences an equal magnitude force in the opposite direction. This is known as Newton's 3rd law; "For every action there is an equal and opposite reaction," and is given as:

$$\vec{F}_{\text{action}} = -\vec{F}_{\text{reaction}}.$$

Now, there are fundamental forces and forces derived from fundamental forces. The most familiar fundamental force is perhaps gravity, which Newton first described, and is given by

$$\vec{F} = \frac{Gm_1 m_2 \vec{r}_{1,2}}{|\vec{r}_{1,2}|^3}$$

for the force experienced by mass m_1 gravitationally attracted to mass m_2, where $\vec{r}_{1,2} = \vec{r}_2 - \vec{r}_1$. Similarly, Coulomb's law for electric attraction is

$$\vec{F} = -\frac{kq_1 q_2 \vec{r}_{1,2}}{|\vec{r}_{1,2}|^3}$$

between charges q_1 and q_2. In addition to fundamental forces, we usually work with derived forces. Derived forces of the more familiar kind are commonly called contact forces. These include applied forces, such as when we push something across a table, tension, stress, spring forces as well as friction and drag forces. These forces are generally created at the microscopic level by fundamental forces. These fundamental forces are rarely modeled at the detailed microscopic level to represent macroscopic effects, but rather are taken as aggregate forces. Similarly, real objects are composed of microscopic elementary particles, but are mathematically modeled as solid aggregates with internal stresses and external forces.

Other important physical dynamical concepts are impulse, angular momentum, torque, energy, and power. Important related concepts pertaining to aggregates are center of inertia, moment of inertia, and potential fields.

6 Composability

Composability and composition are much discussed subjects in M&S [6], [7]. One of the reasons for developing an ontology of physics is that we need meaningful interoperability between physics-based models. In other words, we need to meaningfully compose models of physical objects. We use the term composition in the sense where one has standardized components that may need a small amount of tailoring to easily build a usable model. We also start with the premise that composition of M&S components must ultimately be de-constructed to formal notions of composition, probably of more primitive components, because only then will we have unambiguous meaning in what it means to compose. We need to keep in mind that formal structure for rules of composition will give clarity and consistency, but not meaning. Meaningful interoperability requires that the result of our composition make sense and fit an intended use [1]. A mathematical model is not necessarily physical, and so, may not have meaning. For a physics-based model to be meaningful, it must properly capture the physical properties of the underlying object.

Composition of mathematical functions is the most common formal notion of composition. By this we mean $f \circ g \equiv f(g(x))$, which is the composition of functions f and g. In composition of mathematical functions, the inputs to one function are taken from the outputs of other functions.

We might also speak of composition of data, for example, where one takes two overlapping representations of the terrain and merge them into a single one. In this case one has two functions, i.e., each data table is a set of unique elevation values defined at various locations, that one needs to merge into a single function. This frequently means defining one function over a union of the two domains. This data composition is often done, and the procedure commonly goes by the name "data assimilation". If we want to preserve the higher level, more colloquial meaning of composability in the context of M&S, composition of functions may be too narrow at a primitive level of formality to encompass the range of things meant, since we will also want to perform data assimilation.

Pure functional modeling puts an emphasis on separating functions and data. Recent trends in software engineering advocate the use of objects, which combine functions and data. Booch defines an object as having state, behavior, and identity [8]. Operationally, an object's state is represented with data elements, representing property values, and functions, representing behavior. While these functions, once defined, do not change, objects can be modified by changing their internal state. The behaviors of an object may be functions of its changing state. Objects of the same class have the same behaviors and attributes, but not necessarily the same state. Identity allows one to distinguish two otherwise identical objects, i.e., two objects in the same class with identically valued state. In summary, objects are a marriage of a data records with functions.

Objects must be composed. Software objects are commonly used to model real-world objects, with the name ”object” not accidentally being the same. Real-world objects also have both behavior and state, making software objects useful models. If in a battlespace I can land aircraft on a carrier or dis-mount infantry from armored personnel carriers, I must be able to model these activities by similarly composing and de-composing the software objects that represent these battlespace objects. The behaviors of the composed objects may not be the same as when they are not composed. This suggests that we need to develop rules of composition for objects, perhaps on a case by case basis for each pair of object classes.

Physical aggregates are composed of more primitive physical objects. Most familiar physical objects are, in fact, physical aggregates. In point of fact, the fundamental constituents of physical objects are not completely understood, be they quarks, strings, branes or whatever. What is understood about physics is the behavior of physical aggregates. So, right at the beginning of describing what it means to be a physical object, we must describe the rules of composition of physical objects in order to describe aggregates. As it happens, although not usually stated as such, the rules of composition of physical objects are generally considered to be the most fundamental principals of physics.

7 Axioms of Physical Composition

Before elaborating on the details of various branches of physical phenomena, such as fluid dynamics, solid mechanics, mixtures, chemistry, etc., there are some fundamental properties of all physical objects that should be captured, which we do here in an axiomatic form, which has a definite object-oriented flavor. What we mean by physical composition is how physical objects interact with each other and how physical objects are composed, and decomposed, with respect to other physical objects. We mean to describe the answer to questions such as “What is the physical composition of this physical object?” The focus here is centered on the intrinsic properties of a physical object, such as mass and charge, rather than on the extrinsic properties, such as the object's position. Additionally, after having described physical dynamics in the more familiar Newtonian form in the last section, here we move forward to state these properties in the more correct special-relativistic form (see, for example, [9]). First, we briefly state the properties, and then elaborate on the meaning of the properties.

Definition (Physical Object). *A physical object has the following intrinsic properties: an electric charge, q; an energy and momentum, $p^\mu = (E/c, \vec{p})$, defined in a non-accelerating reference frame; and an angular momentum, $\vec{\Omega}$, also defined in a non-accelerating reference frame.*

The rest energy of a physical object, where $\vec{p} = 0$, is mc^2. The combined kinetic and rest energies of a physical object is $\sqrt{\vec{p}^{\,2} c^2 + m^2 c^4}$, which reduces to the non-relativistic $\frac{\vec{p}^{\,2}}{2m} + mc^2$. The definition of a physical object describes the basic concept of a physical object in isolation, for example, a free particle. Conserved quantities do not here include anything specifically relating to the strong or weak forces, though they could conceivably be added. We choose to use the special relativistic representation since it gives a single basis for most physics and it is relatively straightforward to simplify to non-relativistic velocities. The energy-momentum tensor has its first component as the object's energy, E, divided by the constant speed of light, c, where $(E/c) = \sqrt{\vec{p}^{\,2} + (mc)^2}$ in relativistic mechanics. The velocity of a physical object is $\vec{v} = \frac{c^2 \vec{p}}{E}$, which at non-relativistic velocities reduces to $\vec{v} = \frac{\vec{p}}{m}$. We now state the fundamental property of physical objects.

Axiom (Conservation). *In a non-accelerating reference frame, the intrinsic properties of an isolated physical object are conserved.*

Conservation highlights the invariant properties of a physical object, the true nature of a physical object. Conservation of mass is found in the magnitude of the conserved energy-momentum four-vector, or tensor. The magnitude, or norm, of the energy-momentum tensor is $\sqrt{p^\mu p_\mu} = \sqrt{(E/c)^2 - \vec{p}^{\,2}} = mc$, or the rest mass multiplied by the constant speed of light, c.

The dynamics of physical objects in isolation are rather simple, as described previously. Having defined the properties of a physical object in isolation, we can move forward to interactions between physical objects.

Definition (Physical Interaction). *Physical objects may have a physical interaction with other physical objects. A physical interaction is defined by one of the following three occurrences:*

Physical composition; a physical object may combine with another physical object to form a new object, a physical aggregate, or;

Physical decomposition: a physical aggregate may divide to form multiple physical objects, or;

Third, a momentum exchange, also called a force interaction.

A physical object's conserved properties may change by physical interaction with other physical objects.

Interactions provide the fundamental behaviors of physical composition. By the following, we see that the composition of physical objects results in new physical objects.

Axiom (Total Conservation). *In a physical interaction, the sum over the interacting objects of each conserved quantity is conserved.*

The energy of the aggregate object is the sum of the energies of the constituents, as is the momentum of the aggregate the sum of the constituent momenta, i.e.,

$$E = \sum E_i \qquad ; \quad \vec{p} = \sum \vec{p}_i \quad .$$

The mass of the aggregate, given by the norm of the energy-momentum tensor, is

$$M = \sqrt{\frac{E^2}{c^4} + \frac{\vec{p}^{\,2}}{c^2}}$$

which in the non-relativistic limit becomes the simple sum over the constituent masses. Since the conserved properties of a physical object define it, and multiple physical objects participating in an interaction have their aggregate conserved properties also conserved, then aggregates of physical objects are themselves physical objects.

The velocity of the aggregate is $\vec{v} = \frac{c^2\vec{p}}{E}$ which is the velocity of the aggregate's relativistic *center of inertia*. The center of inertia, which can be taken as the aggregate's position, is given by

$$\vec{R} = \frac{\sum E_i \vec{r}_i}{\sum E_i}$$

summing over each constituent element of the aggregate, with $\vec{r}_i$ the constituent element's position. This reduces to the center of mass

$$\vec{R} = \frac{\sum m_i \vec{r}_i}{\sum m_i}$$

in the non-relativistic case.

As physical objects aggregate, their behavior as an aggregate is sometimes more practically described by its predominating aggregate properties. While many examples of physical objects are elementary particles, atoms, and molecules, for which we may benefit from a detailed description, other physical objects are comprised of large numbers of elementary constituents, greater that 10^{23}, such as solids, fluids, gases and plasmas. Examples of such objects are crystals, polymers, composites, missiles, tanks, ships, aircraft, etc. While in the future we expect to elaborate on the nature of the dynamics of these aggregates, we simply summarize their fundamental property as *statistical* aggregates, which, naturally, will have a statistical description.

Definition (Statistical Aggregate). *A physical statistical aggregate is a physical aggregate where the identities of the individual combined objects that the physical aggregate is composed of, are lost.*

Note that we here have occasion to make use of the notion of identity from Booch's definition of an object.

A final set of definitions introduces the important ideas of work and potential energy. The force experienced by one physical object in a system of two physical objects is $\vec{F} = \frac{d\vec{p}}{dt}$, with a corresponding force, $-\vec{F}$, experienced by the other object. Physical objects experiencing forces tend to move, and by so doing their overall energy changes, resulting from the *work* done via the force. While the change of energy is the important concept, a definition of *potential energy* is also required to define a reference energy.

Definition (Work). *Work, U, on an object is defined as the integral of the force experienced by that object along its path through space.*

$$U = \int \vec{F} \cdot d\vec{s}$$

Definition (Potential Energy). *The potential energy of an isolated system of two physical objects that have a force interaction is the negative of the amount of work necessary to separate the two objects, at rest, to be arbitrarily far apart, at rest.*

By this definition, the potential energy of two physical objects that always have an attractive force will never have a potential energy greater than zero. A system of two physical objects will have their total energy conserved, while the energy in the kinetic energy and potential energy components will vary. When two physical objects do not together possess sufficient kinetic energy to overcome the negative potential energy of due to an attractive force between them, they cannot by themselves become separated arbitrarily far apart. In such a situation, the two objects are physically bound together.

We have here merely described some of the basics to illustrate how one might proceed to develop a descriptive framework for dynamics. What we have not discussed in detail are the behavioral methods of various physical objects that we will want to describe. Their general form we discussed in our section on dynamics, but a detailed treatment is of a scope too great for this article. We can, and should, adapt formularies of physical equations [10] to create a standard database of fundamental equations and the schema necessary to generate the large number of possible solution integrals. We also note that the basic approach outlined above is most apparently useful for particle, or rigid body dynamics. Standardized representations for the concepts for gas and liquid phase as well as non-rigid solid material objects would need to be developed. Additionally, we are often interested in the physics of propagation of disturbances in media, such as acoustic or electromagnetic wave propagation. As mentioned before, the concepts of measurement, uncertainty, and the process of state estimation, too, would require representation in the set of concepts within an ontology of physics.

8 Description in Physical Context

In describing the physical attributes of an object, in order to be able to reason about what is the appropriate dynamics to apply to that object we also need to be able to describe not only the object itself, but it's context relative to other objects that may affect its dynamics. Certainly one approach is to consider everything as one single physical object, and the dynamics are all internal. This approach defeats the original notion of encouraging composition in order to partition the problem of modeling the whole world. While partitioning the world into physical objects is convenient, it is not a perfect process since an object's behavior may be modified by other external physical objects. The result is that the physical context of an object within a simulation system must be monitored so that when other physical objects come within scope of physical interaction, those interactions may be computed. To do this we also need to consider how we may specify interaction thresholds so that the monitoring may be done efficiently.

While this interaction monitoring requirement may sometimes be performed, e.g., in the current simulation practice of dynamic objects routinely broadcasting their state, it is frequently not done. In some simulation systems ships may travel on land as well as at sea, or towed array sonars may be literally dragged through the mud with no effect, all violating simple physics. Ideally a physical object would know how determine that another physical object is within interaction distance by knowing, for example, only its relevant physical parameters, such as its mass distribution, velocity, charge, energy, etc., since these are what matter in physical interactions. The fact that the object is a bullet is less relevant than it's mass, velocity, and structural properties. We cannot consider the dynamics of an object in a vacuum: commonly objects move on solid or liquid surfaces, or through gas or liquid phase media. Knowing the physical nature of the context informs the choice of appropriate dynamical modeling for interactions, be it consideration of Earth's gravitational force, contact forces with other objects or fluid drag forces.

9 Benefits

The effort required to develop a standard ontology of physics is not a small one. It will require the contributions of many, each possessing a high level of technical competence. As time passes we will need to evaluate the ontology as it is being constructed. Does it meet stated needs? Is the ability to reuse models that may be afforded by the effort worth the cost? Accordingly, the success of such an effort should address the near term benefits as a test case of value received for effort expended.

What are some of the nearer term benefits that we might expect from an ontology of physics? We anticipate some near term benefits of an ontology of physics such as the following.

We can have simulation systems that obey the ”simple” laws of physics such as “two objects cannot be in the same place at the same time”. As mentioned above, this is a commonly violated principal.

We can build decision aids for simulation developers to help in choosing dynamical models for simulation construction, encouraging a marketplace of models. Often a key discriminant in model selection is the physical representation and level of detail. Documentation of these features are usually buried.

By knowing what our physical modeling requirements are, we should be able to search a database of models more easily, perhaps with software agents, so that our selected model represents the correct mix of physical properties for our needs.

We can develop universal “animation engines” much as there are generic visualization tools for viewing static models described with SEDRIS. How frustrating is it to see a static representation of a model and not know how it can move. An animation engine would allow us to see how a model moves and explore its dynamics. Is it articulated, rigid, or flexible? While a detailed physical description can tell us this, we could opt to just test drive the model.

We can use an ontology of physics to facilitate of simulation planning with regard to the impact of the natural environment. The natural environment has many physical effects on objects. A formal physical description of the environment and the objects we want to immerse in the natural environment will allow us to enable untrained simulation operators anticipate the physical interactions that may occur.

We can enable better dead reckoning computation. Knowing the dynamical model of an object and how to interpret it can enable distributed components in a simulation system to better anticipate the future state of objects represented on remote computers.

We approach the long term objective of composability. Models are usually only able to move about and operate within a specific simulation system used as an application. Model implementations should be portable, so that they may be used in multiple simulation systems.

In sum, we anticipate that development of a standard ontology of physics, while difficult and requiring the contribution of many, can have near-term as well as long-term benefits. In any case, it is a necessary step down the road to better interoperability in M&S.

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