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Fidelity

What is Fidelity?

Though commonly used, the term "fidelity" is not consistently applied in the modeling and simulation (M&S) community. An ordinary dictionary characterizes fidelity as follows[1]:

- **Synonyms –** allegiance, ardor, devotion, faithfulness, fealty, loyalty, piety
- **Related Words –** constancy, staunchness, steadfastness; dependability, reliability, trustworthiness
- **Contrasted Words –** disloyalty, falseness, falsity, perfidiousness, traitorousness, treacherousness, treachery; undependableness, unreliability, untrustworthiness
- **Antonyms –** perfidy; faithlessness

This characterization certainly leaves the impression that fidelity is good and that more of it is better. However, to be of use to the verification, validation and accreditation (VV&A) community, this generic concept of fidelity must be more precisely interpreted, considering the context of modeling and simulation.

The M&S community uses the term fidelity at least in some commonly understood, if general, sense.

- ***Developers*** discuss fidelity tradeoffs between modeling approaches during simulation design.
- ***Users*** inextricably associate fidelity with the simulation's fitness for its purpose, such as analysis, design, training, etc. It is the rare User that desires a lower-fidelity solution – despite the fact that fidelity is understood to be a large cost driver for simulation.

"High" fidelity is expensive both to buy and to own, as exemplified by full-motion platforms and sophisticated visual systems.

The Department of Defense (DoD) M&S Glossary provides a formal definition within the context of modeling and simulation:[2]

> **Fidelity:** the accuracy of the representation when compared to the real world.

Armed with this background, and moving toward a more detailed definition, the Simulation Interoperability Standards Organization (SISO) adopted the following formal definition:[3]

Fidelity: 1. The degree to which a model or simulation reproduces the state and behavior of a real world object or the perception of a real world object, feature, condition, or chosen standard in a measurable or perceivable manner; a measure of the realism of a model or simulation; faithfulness. Fidelity should generally be described with respect to the measures, standards or perceptions used in assessing or stating it. 2. The methods, metrics, and descriptions of models or simulations used to compare those models or simulations to their real world referents or to other simulations in such terms as accuracy, scope, resolution, level of detail, level of abstraction and repeatability. Fidelity can characterize the representations of a model, a simulation, the data used by a simulation (e.g., input, characteristic or parametric), or an exercise. Each of these fidelity types has different implications for the applications that employ these representations.

The basic connotation of simulation fidelity is clear even when there are differences of opinion about its precise definition. Simulation fidelity is focused on how closely the simulation representations represent the real world (e.g., the simuland). Furthermore, validation and accreditation of a simulation are achieved by assessing the fidelity of a simulation relative to the referent and the intended use.

The Role of the Referent in Defining and Measuring Simulation Fidelity

All these definitions of "fidelity" share a particularly difficult-to-measure term, "real world." This term poses two obstacles to any standard for fidelity measurement:

- A definition of the real or imagined world that is sufficient to measure the difference between it and the simulation must exist.
- The simulation must be defined in terms similar to that definition.

An important distinction exists between what the simulation is **intended** to represent (the simuland), and what it is **able** to represent. The simuland is often casually referred to as the "real world" or as reality, actuality, or truth. However, no simuland actually achieves equivalence with the "real world." Many simulations do not intend to represent all the possible situations of current reality. Valuable simulations represent only pieces of the electromagnetic spectrum or predict the performance of proposed weapon systems in a hypothetical battlefield. Selection of a subset of reality or extending it with hypothetical systems should not invalidate the notion of valid simulation results.

Furthermore, simulations cannot **directly** represent their simulands because much about them is not known, and may not even be knowable. Every simulation developer has had the experience of developing a model that faithfully represents all known physics about a vehicle, but still requires "tweaking" to match data collected in field experiments.

Simulations actually represent an abstraction drawn from the sum total of what is known, assumed, or projected about the simuland, called a ***referent***. A typical

simulation program captures the referent in a combination of simulation requirements and a conceptual model.

How "well" the simulation represents this referent precisely defines its fidelity, and is often described by terms such as the "degree to which …," "similarity between …," "accuracy," "precision," etc.

The first obstacle explains why essentially all the fidelity literature calls for the establishment of some common referent – the "real world" is not a good ruler to measure fidelity.[3] Some claim the world is too large and complex, and too poorly understood, to be a practical referent, concluding that a commonly understood standard against which to measure fidelity for a specific simulation problem is the most that can be achieved. Others go farther to claim that the fidelity of a simulation needs to be assessed only against those aspects of the simuland it was intended to simulate, arguing that if the simulation represented all aspects of the simuland it would **be** the simuland. This approach makes the only measure of interest how well a simulation represents a behavior against the behavior it was intended to represent, its referent. However, in order to use this approach to measuring a simulation's fidelity, the referent must be carefully defined in terms of how much is to be simulated (i.e., entities and characteristics) and what interactions are involved (i.e., relationships between entities in the referent).

Even with a well-understood and specified referent, defining the simulation in a way that can be measured becomes the second obstacle. The metric of fidelity will measure the difference between the referent and the simulation, because it describes how well the behavior of the simulation matches the simuland for the characteristics of interest in the simulation problem.

The specification for a simulation reads very much like the specification for a computer program or visual display; with requirements for controls and displays, functional performance, safety concerns, and so forth. But in addition to typical computer system requirements, a simulation specification uniquely addresses the particular abstraction of the simuland that is of interest for this particular simulation – in other words, it defines what this simulation is to simulate. These representational requirements sometimes appear as an extensive discussion, and sometimes as a brief reference to other design criteria, but they are always there. In turn, the simulation design and the eventual implementation aim to create a simulation with the specified level of abstraction. In every phase of simulation development, the unique measure of "goodness" that describes how "well" or closely the simulation represents its simuland is its fidelity.

Qualitative and Quantitative Fidelity Descriptions

A variety of ways for describing simulation fidelity currently exist in the simulation literature, as surveyed in the *Report from the Fidelity Definition and Metrics Study Group*.[3] These descriptions can be grouped into three basic categories: **short**, **shorthand**, and **long.**

- **Short descriptions** of simulation fidelity, including qualitative labels such as “high,” “medium,” or “low” fidelity. Such dimensionless characterizations tend to have more public relations utility than technical value in that they frequently lack the information content necessary to support technical decisions about simulation fitness.
- **Shorthand descriptions** of simulation fidelity, including checklists, indicate that a simulation satisfies multiple, bundled attributes. For example, the Federal Aviation Administration’s “Level D Flight Simulator” certification requires satisfaction of more than 100 specific attributes.[4]
- **Long descriptions** of simulation fidelity typically describe simulation fidelity in terms of multiple explicit attributes. The number and kinds of attributes considered varies with the construct being employed for simulation fidelity. Most constructs consider either the scope of the simulation’s treatment of significant factors in the application domain (this usually involves some kind of *enumeration*), the quality of treatment of factors within the simulation (as indicated by parameter accuracy, resolution, etc.), or both.

Despite its apparent importance for simulation, fidelity has proved difficult to apply in practice. Short descriptions that capture the qualitative nature of fidelity are generally understood and assigned. The typical practice is to default to qualitative terms such as high, medium, and low. This is unsatisfactory in many cases because these terms are highly subjective and abstract. Since fidelity is regarded as a primary measure of goodness for simulations, developing an objective fidelity measure offers substantial benefit for describing and choosing simulations.

Very few applications attempt to describe fidelity objectively, that is, with shorthand descriptions. Long descriptions that involve the quantitative nature of fidelity delineated in the SISO definition are often neglected as impractical. However, it is often possible to decompose all or part of a qualitative assessment into a collection of quantitative assessments.

Example:

Qualitative characteristics can certainly be perceived – such as a good musical performance, a good meal, a bad experience, etc. But each of these qualitative assessments has quantitative corollaries. The good musical performance was one in which the performer closely followed the timing, frequency (pitch), and so forth specified by the composer. The good meal was one in which the amount of ingredients was as specified in the recipes, and prepared accordingly.

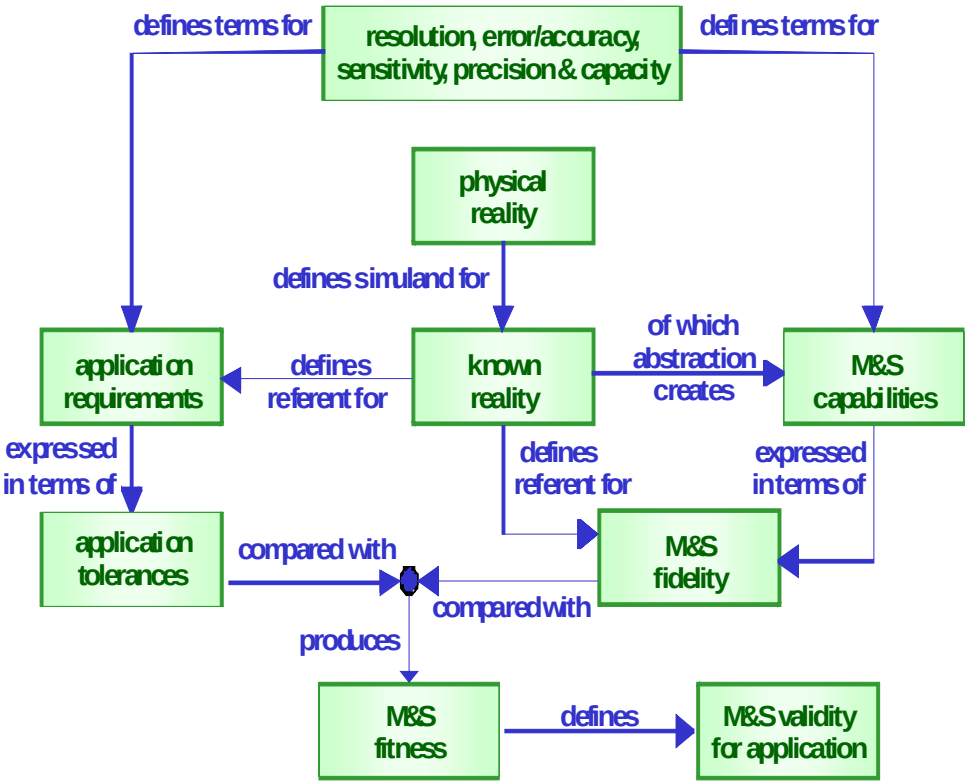
Quantitative descriptions of simulation fidelity are required when specific, objective characteristics of a simulation need to be evaluated. If a simulation must produce critical parameters to specified levels of accuracy and precision, then only quantitative descriptions can suffice.

Example:

Consider a simulation that is intended to be used to determine the best missile configuration by simulating missile flyout in order to find the miss distance. In such a case, only a quantitative description of the flyout model's fidelity will satisfy the need.

A Fidelity Framework

There are many terms related to fidelity, such as accuracy, precision, resolution, and so forth, whose casual use adds to the general confusion limiting the practicality of fidelity. The SISO Fidelity Implementation Study Group (ISG) was formed in 1999 to provide clarity to the concept of fidelity as applied to simulation. One of the products from that group is the Fidelity Conceptual Framework. This framework asserts that physical reality, either material or imagined, provides the basis from which all that is knowable about reality can be obtained. Known reality manifests this body of knowledge. Known reality also provides the source both for referents (through which application requirements are understood) and for abstractions of reality (through which a model or simulation's fidelity is understood). The Fidelity Conceptual Framework, depicted in the figure below, defines the semantic relationships among these terms.[5]



Fidelity Conceptual Framework

The formal definitions for the terms defining the fidelity framework that emerged from the SISO Fidelity ISG are:[5]

Accuracy – The degree to which a parameter or variable or set of parameters or variables within a model or simulation conform exactly to reality or to some chosen standard or referent. See resolution, fidelity, precision.

Capacity – The number of instances of an object or detail that are simultaneously represented by a model or simulation; cardinality.

Error – The difference between an observed, measured, or calculated value and a correct value.

Fitness – Providing the capabilities needed or being suitable for some purpose, function, situation or application.

Precision – 1. The quality or state of being clearly depicted, definite, measured or calculated. 2. A quality associated with the spread of data obtained in repetitions of an experiment as measured by variance; the lower the variance, the higher the precision. 3. A measure of how meticulously or rigorously computational processes are described or performed by a model or simulation.

Resolution – 1. The degree of detail used to represent aspects of the real world or a specified standard or referent by a model or simulation. 2. Separation or reduction of something into its constituent parts; granularity.

Sensitivity – The ability of a component, model or simulation to respond to a low level stimulus.

Tolerance – 1. The maximum permissible error or the difference between the maximum and minimum allowable values in the properties of any component, device, model, simulation or system relative to a standard or referent. Tolerance may be expressed as a percent of nominal value, plus and minus so many units of a measurement, or parts per million. 2. The character, state or quality of not interfering with some thing or action.

Validity – 1. The quality of being inferred, deduced, or calculated correctly enough to suit a specific application. 2. The quality of maintained data that is found on an adequate system of classification (e.g., data model) and is rigorous enough to compel acceptance for a specific use. 3. The logical truth of a derivation or statement, based on a given set of propositions.

The formal definition of these terms provides for careful consideration of their interrelationships. While these specific definitions may not be completely consistent with the definitions used by other authors, they represent the consensus of a broad cross-section of the M&S community. This consensus evolved during two year-long discussions in the SISO Fidelity ISG in which many differing viewpoints were aired, and these definitions have since continued to be used by the M&S community.

The Fidelity Conceptual Framework clarifies the difference between the fidelity required by the application (captured in the simulation requirements), and the

fidelity present in a specific model or simulation (contained with the M&S capabilities). Both the fidelity required and the fidelity present are characterized in terms of resolution, error/accuracy, sensitivity, precision, and capacity, and they are deduced from the referent.

Finally, the fidelity present in a model is a knowable quantity, whereas the fidelity required is generally discussed in terms of tolerances. These tolerances define the acceptability criteria for the dependent and independent variables needed to address the intended use of the simulation. Comparing acceptability criteria with the fidelity presented by a simulation enables validation assessment. If a model or simulation meets all of the acceptability criteria, then it is valid for the intended use.

The Role of Simulation Fidelity in Validation

Validation is the process of determining the degree to which a model or simulation is an accurate representation of the real world, or some other meaningful referent, from the perspective of the intended uses of the model or simulation. Restated, validation is the process of determining the fidelity of a simulation from the perspective of the intended uses.

> Example:
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> Qualitative characteristics can certainly be perceived – such as a good musical performance, a good meal, a bad experience, etc. But each of these qualitative assessments has quantitative corollaries. The good musical performance was one in which the performer closely followed the timing, frequency (pitch), and so forth specified by the composer. The good meal was one in which the amount of ingredients was as specified in the recipes, and prepared accordingly.

In revisiting this example, it is clear that the musical performance and the meal would be described as having high fidelity when measured against the referent (music metrics, recipe instructions). However, a “good meal” is not necessarily the one prepared according to the recipes – the concept of a good meal varies with the one consuming it (i.e., the User): it may have lots of salt or be salt-free, contain a lot of protein and no carbohydrates or be vegetarian, etc. In this case, using only correspondence with a recipe as the metric to measure the fidelity of the meal is inadequate. A good musical performance may be one that does not cause the listener to fall asleep –- or it may be one that relaxes the listener enough to do so! The referent must include measures relative to the intended use. A model (performance, meal) is only deemed valid if it satisfies all of the acceptability criteria, which should include criteria that address the intended use of the simulation.

Characterizing the fidelity of a simulation captures the accuracy of the representation of the referent and the resolution of the representation of the simuland, but takes only the first critical step toward its validation. In addition, many characteristics of a simulation do not directly relate its fidelity but instead

describe the nature, behavior, and character of the simulation independent of the simuland. Goncalves[6] proposed measuring fitness using three measures of simulation effectiveness: fidelity, time-to-answer, and resource usage. Obtaining balance between these characteristics such that the simulation satisfies the intended use establishes simulation validity. As such, fully describing a simulation requires a multidimensional set of measures. If such a multidimensional simulation description, including fidelity, were to be defined, then it could be used to assess the fitness of the simulation for the intended use, i.e. validation. Carefully specified and measured fidelity is important; but it is only one aspect of measuring that fitness.

Recommend Practices for Addressing Simulation Fidelity

Because any model or simulation is, by definition, an abstraction or representation of some part of reality (material or imagined), fidelity is interwoven with all facets of model and simulation development. Indeed, most of the value of a simulation comes from its ability to simplify the complexity of the real world through abstraction into a tractable form. Since the model will always differ from its referent, the model's fidelity to that referent will always be of interest. Despite the fact that fidelity is intrinsic to the nature of simulations, however, it is rarely formally addressed. The Fidelity Conceptual Framework presented in this document represents some initial steps by the M&S community to develop a formal approach for specifying and measuring fidelity.

A number of recommended practices can be made on the basis of the foregoing discussion:

- **Use the terms "fidelity," "simuland," "referent," "representation," "verification," and "validation" precisely.** These terms reflect ideas proven in years of simulation practice. While the general vocabulary overlaps with other software disciplines, these terms present the unique challenges of simulation. A software program might view a "bug" as undesirable, whereas a simulation of the software without the same "bug" would likely be invalid.
- **Recognize that fidelity is a core concept spanning every issue in simulation, especially issues related to verification and validation (V&V).** The distinguishing characteristic of simulations is that they are systems that contain within themselves a model of another system. Fidelity is at the core of understanding how to specify the representational requirements and validate that the requirements and eventual model suitably represent that "other system." Users, M&S Program Managers, Developers, V&V Agents, or Accreditation Agents can and should think about fidelity impacting their projects in terms of the Fidelity Conceptual Framework.
- **Beware single point or qualitative fidelity descriptions.** While fidelity is a unified concept, it has little or no meaning when expressed

as a single point or qualitative description (e.g., low, medium, or high). Simulation fidelity can and should be decomposed into its constituent components of resolution, error/accuracy, sensitivity, precision, and capability. When presented with single point or qualitative fidelity descriptions, a User, M&S Program Manager, Developer, V&V Agent, or Accreditation Agent should seek meaningful insights by asking about the model's resolution, error/accuracy, sensitivity, precision, and capability. Likewise, they all should push toward specificity in representational requirements, which will inevitably address resolution, error/accuracy, sensitivity, precision, and capability needed, rather than requiring "goodness".

- **Use comparison as a basis for defining the fidelity aspects of representational requirements.** Without resorting to the various quantitative methods being proposed in the research community, in practice, the fidelity of the proposed simulation can be compared with simulations meeting similar purposes in order to gauge its fitness for purpose.

> Example:
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> If the problem is about pilot training, one could compare the fidelity of models proposed to the fidelity of models in other pilot trainers to confirm fitness. While this may not result in the minimum acceptable fidelity, it should result in an acceptable level of fidelity.

- **Seek to limit the fidelity required and implemented to that which is actually needed.** Frequently simulations projects seek to include all the fidelity they can afford, without realizing the burden that creates and the reduced benefit that results. Higher-fidelity simulations cost more time and money to build, more to verify and validate, and more to operate. Furthermore, the perceived increase in quality with higher fidelity is sometimes illusory.

  In a trivial example, a high fidelity training simulation may in its complexity obscure the real issues for which training is required. After all, perfect fidelity in a simulation is a degenerate case that means the simulation matches the real system in all details, including the environment. This raises the question of why the original system was not used in the first place, thus saving the cost of constructing the simulation. In contrast to intuition, the real value of simulations comes from abstracting away irrelevant details, thus lowering the fidelity of the simulation in at least some ways. A User, M&S Program Manager, Developer, V&V Agent, or Accreditation Agent offered a "higher" fidelity solution should assume a skeptical point of view, until it has been demonstrated that the increased costs are justified by real benefits.

References

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Acronyms

AC	Advisory Circular
DMSO	Defense Modeling and Simulation Office
DoD	Department of Defense
FAA	Federal Aviation Administration
M&S	Modeling and Simulation
RPG	Recommended Practices Guide
ISG	Implementation Study Group
SISO	Simulation Interoperability Standards Organization
SIW	Simulation Interoperability Workshop
V&V	Verification and Validation
VV&A	Verification, Validation, and Accreditation

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