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Foundations for system measurement

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Abstract

A system can be defined as a set of elements that interacts with its environment, where relationships exist between the elements. Numerous disciplines in the sciences including physical, social, and behavioral, as well as the realms of engineering, business, and economics are concerned with objects, processes, and phenomenon that satisfy this generic, system definition. These fields and others have a need to understand systems within their domain. Key to understanding a system is being able to measure it. This paper presents fundamental concepts and an empirically feasible methodology for system measurement.

Keywords: System measurement; Measurement frameworks; Measurement guidelines

1. Introduction

Measurement is an integral part of modern life. We measure our surroundings, ourselves, and the passage of time. Measurement is needed to characterize the universe and everything in it [36]. Some have even suggested our advancement as a civilization is a direct consequence of our ability to measure [47]. Despite its seemingly overwhelming importance, measurement is often regarded with a 'just look and see' attitude and the complexities surrounding measurement escape critical analysis [28]. This phenomenon is largely due to the concept of measurement being closely aligned with the physical sciences where measurement is relatively straight forward. Other disciplines do not enjoy this level of objectivity. Fields in the social and behavioral sciences examine events, processes, and other complex phenomenon that are difficult to understand, let alone measure [16].

A system, which interacts with its environment, can be defined as a set of elements where relationships exist between the elements [13]. This generic definition allows the system concept to be applied to a wide spectrum of endeavors to include both physical and abstract interests. Systems are often studied to explain behavior or track and predict progress. Regardless of purpose, systems communicate physical and behavioral information through relevant attributes [1]. System measurement is the process of identifying these attributes and retrieving this information.

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This paper begins by examining the foundational aspects of measurement in general. The examination includes a brief history of measurement, to help establish a context for the many views of measurement, as well as an introduction to measurement theory. After the theoretical foundation is established, attention turns to application of measurement, measurement constructs, and concepts specific to system measurement.

2. Measurement fundamentals

Measurement is the objective representation of objects, processes, and phenomenon [14]. Measurement captures information about these systems (a set of interconnected elements [13]) through their attributes (also known as characteristics, features, or properties), which are either directly or indirectly observable [10]. Thus, a system $\boldsymbol{X}$ is defined by the attributes x_i chosen to represent it:

$$\boldsymbol{X} = \langle x_1 x_2 \ldots x_i \rangle \tag{1}$$

Although objective, an important distinction is that measurement is also an abstraction. This is because measurement does not directly represent the system but addresses the attributes selected to represent it [35]. In this light, measurement can be thought of as the process of assigning symbols to an attribute of a system such that the assigned symbols reflect the underlying nature of the attribute [9]. The assigned symbols can take on any form as long as the set of symbols reflect or can take on the same underlying structure as the attribute being measured (i.e. homomorphic). Typically, the symbols assigned are numerals, thus allowing the formal language of mathematics to be applied, enabling further insight into the system of interest [48].

All measurement is carried out within a context [31]. This context is shaped by a purpose, existing knowledge, capabilities, and resources; all of which influence the measurement process [5]. Within this context, measurement begins by identifying the system and the attributes to be used to define the system as depicted in Fig. 1. Attribute selection is critical since the validity of system measurement is influenced by the number of attributes used in the measurement [36]. Although fewer attributes will simplify the measurement process, too few can result in poor and/or misleading insights about the system [41]. Once the attributes are identified, observations, or measurement, of the attributes can take place.

Measurement can be made through the human senses or through a measurement instrument. Instruments can be simple like a 'tape measure' or complex like a derived mathematical model. Regardless of form, the instrument must be based on a scale having the same underlying relationships as the attribute being measured [30]. A scale (Fig. 2) is a predefined mapping, representing empirical relationships from one domain to another [39]. Because of this, measurement is closely tied to definition [9] and the family of mappings for attributes of a system can be considered a mathematical model of the system.

Referring back to Fig. 1, scales can be a source of error since a measure will always contain any error inherent to the construction of the scale. In addition

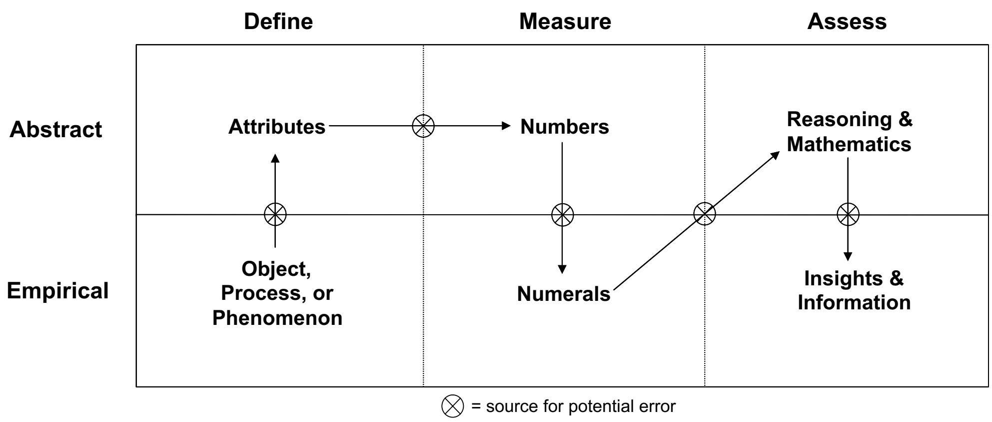


Fig. 1. Stages of measurement.

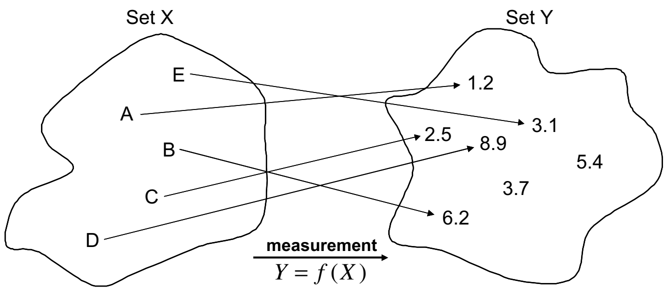


Fig. 2. Measurement scale.

to scale error, each observation itself is a random variable with an underlying distribution [36]. A key issue in system measurement, as suggested in Fig. 1, is the sources for error in the process from selection of system attributes to assessment insights.

There are three primary sources of error: random, systemic, and observational. Random error is 'noise' variation from any source impacting the system including the system itself. Systemic error derives from construction of the attribute measures and comes in the form of measurement bias. Finally, observational error is the oversight of a key system attribute requiring measurement or using the wrong measure for an identified system attribute. These errors are an inescapable feature of measurement [15] and will be part of the measurement process even when the system is well-defined [25].

In many contexts, there is a 'Catch-22' with regard to system measurement. In order to properly measure a system, one needs to know something about it; however, the very reason one may want to measure a system is to gain an understanding of it [16]. Additionally, for complex objects, processes, and phenomenon with intricate networks of connections, the attributes that best define the system may be unknown, inaccessible, or only visible as an outcome. These systems require a proxy, or indirect measuring method [36], where a proxy measure is essentially a model or approximation of an attribute of interest. Quantification is the process of developing these indirect measures [30], or in other words, the process of converting empirical relations into logical operations. Although there is no universal approach for deriving proxies, the process typically involves decomposing complex aspects of the system into simpler, more understandable elements.

By one definition, measurement is the assignment of numerals to a system according to a rule [45]. However, not all assignment techniques are useful and some techniques have constraints on how the results can be assessed. Although there is not a standard of measure for complex objects, processes, and phenomenon [7], a set of axioms for approaching measurement of these systems can help avoid deriving erroneous insights. Such a set of axioms is embodied in measurement theory.

3. Measurement theory

Formalisms regarding measurement are evident in Ancient Greek culture dating back to the 4th century BC, but the initial foundations for an axiomatic approach to measurement did not emerge until the late 1800s [14]. Much of this early work concerned the physical sciences, however. It was not until the mid-1900s, as efforts to measure abstract concepts such as preferences and aspects associated with psychology, that a more robust set of principles regarding measurement evolved [32]. These principles are captured in measurement theory.

Measurement theory is "a branch of applied mathematics that attempts to describe, categorize, and evaluate the quality of measurements, improve the usefulness, accuracy, and meaningfulness of measurements, and propose methods for developing new and better measurement instruments" [2]. Within measurement theory, the most common view is the representational view which asserts that the symbols assigned to the system represent perceived relations between the system's attributes as well as between the system and its environment [46].

Many of these system attributes can be measured directly. These are termed extensive attributes [33]. Other measurements may be based on assumed relations or by arbitrary definition [48]. However, as already noted, not all system attributes are easily measured. For these intensive attributes, indirect measures may not be empirically significant. Systems with such attributes are characterized by ill-defined representation, uncertainty about relational aspects within the system, and have little theory supporting the underlying nature of the system. For attributes of these systems, measurement often precedes definition working in an exploratory, recursive process where measurement leads to definition and definition, in turn, leads to refined measures [15].

As already suggested, all measurement is carried out within a context. This implies some purpose for conducting measurement. This purpose is typically for system description, monitoring, and/or forecasting.

4. Application of measurement

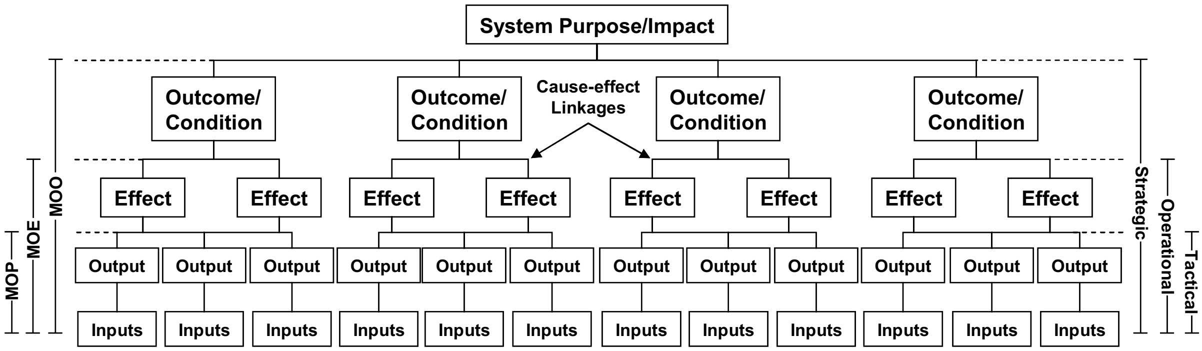
As noted, measurement is a routine, everyday process and a necessity in most fields of endeavor [38]. Measurement is fundamental to understanding, controlling, and forecasting [49]. Whether conducted explicitly or implicitly, system measurement is the mechanism for extracting information from empirical observation. However, obtaining this insight is dependent on having feasible implementation methods for system measurement [40].

Measurement is applied to a system within a specified context. The measurement context defines the need for conducting measurement. This can be for exploratory purposes such as characterizing a new system, but commonly involves resource commitment decisions. Regardless of context, a key aspect for measurement of a system is its environment. Within its environment, a system has some purpose or normative behavior. The behavior of most real world systems is the result of a complex set of interactions. Measurement translates a system's complex behavior into a set of 'vital signs' indicating variations in system behavior or gauging fulfillment of a system's purpose [21]. More importantly, measures indicate when a system has fulfilled its purpose or is acting in accordance with its normative behavior [43]. Further, depending on the measures used, system measurement can yield information on when and why a system is deviating from its normative or desired behavior [21].

Retrieving this information, however, requires a framework for conceptualizing a set of system measures. Measure frameworks are typically classified as either vertical or horizontal. The vertical or hierarchical structure is associated with measures that can be directly linked to the system purpose or normative behavior. The horizontal structure, or process framework [11], on the other hand, is aligned with system processes. Further, the vertical structure is often linked with fundamental system objectives, where a fundamental objective is the overall desired or expected system end-state. Similarly, the horizontal structure is commonly linked with means objectives, where a means objective is an enabler for a fundamental objective. Typically, measures in the vertical construct are associated with system effectiveness and measures in the horizontal construct concern system efficiency. However, these structures are not exclusive of each other. They can exist at the same time for a system and additionally, a single measure can exist simultaneously in both constructs [23].

Measures of effectiveness and measures of efficiency provide different insights about a system. A measure of effectiveness (MOE) concerns how well a system tracks against its purpose or normative behavior [43]. However, a measure of efficiency, which is also known as a measure of performance (MOP), describes how well a system uses resources [41]. In other words, an MOE determines if the right things are being done and an MOP determines if things are being done right [43]. This subtlety is critical since these measures are developed from different viewpoints. An MOE can be considered invariant to means of achievement [26]. An MOP, on the other hand, characterizes system capability or the attributes of a system under a specified set of conditions and is thus, system dependent. The key distinction, however, is an MOP alone does not provide an indication of progress towards a system's purpose or indication of normative behavior. Additionally, beyond effectiveness, measures of outcome (MOO) gauge environmental conditions created by the system [12]. Fig. 3 summarizes these relations.

Another useful construct for conceptualizing a system is an input–output model (Fig. 4). Inputs can be any controllable or uncontrollable factor. These inputs enter the system and are 'transformed' into outputs. The outputs result in various effects contributing to conditions in the system's environment which lead to attainment of the system's purpose or normative behavior. The input–output concept is invariant regardless of perspective, with the only change being the type and size of the system and its associated transformations. The key task is operationalizing the relationship between the input and output [41] where 'operationalize' is the act of quantification or defining an attribute



Inputs – any controllable or uncontrollable factor that enters the system
Outputs – system transformation of the inputs
Effect – system changes resulting from the outputs
Outcome – environmental conditions created by system effects
Purpose/Impact – reason for system existence or expected system behavior

Measure of Outcome (MOO) – gauges conditions created by system effects	Strategic – directly concerns the system purpose or normative impact
Measure of Effectiveness (MOE) – measure of changes resulting from outputs	Operational – intermediate events required to achieve the system purpose
Measure of Performance (MOP) – measure of system transformation of inputs	Tactical – short-term activities necessary to attain operational level outcomes

Fig. 3. System of measures.

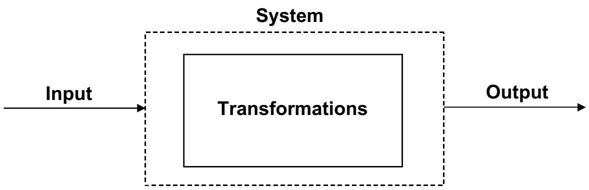


Fig. 4. Input–output model [41].

by the way it is to be measured. The input–output model provides a means for system feedback or quantifying the impact of an input, which is fundamental to understanding and control of any system [22].

Another critical task in using an input–output construct is defining the system boundaries. The boundaries of a system are where elements of the system interact with elements outside the system. Everything outside this boundary is considered the system's environment. The system environment can be described as those factors external to the system that will influence the system over the period of measurement [3]. Identification of the boundaries is critical since they define the scope of measurement [41]. Further, making accurate inferences from measurements requires an understanding of the circumstances surrounding the system when the measurements were taken [49]. This contextual information provides insight into why a system behaved the way it did; identifying pressures working with and against the system.

A useful extension of this construct is conceptualizing a network of linked input–output models, where outputs of one model are the inputs of others (Fig. 5). In fact, every system can be seen as part of another larger system [1]. Thus, the combining of systems yields a larger system with its own inputs, outputs, effects, outcomes, purpose/behavior, and boundaries. Further, within this larger system, each sub-system still has its own input, output, effect, outcome, purpose/behavior, and boundary [44]. This 'system-of-systems' view allows for conceptualizing the overall system at different levels to include strategic, operational, and tactical (Fig. 3). The strategic level directly concerns the system purpose or normative behavior. The operational level focuses on intermediate events required to achieve the system purpose or normative behavior. Finally, the tactical level addresses short-term activities necessary to attain operational level outcomes [4].

The key to successful measurement is ensuring the right measures are being used to gauge the system purpose or normative behavior [6]. The goal is to understand which inputs or environmental conditions lead to which outcomes [31]. A key challenge, however, is what we would *like* to measure and what we *can* measure are usually not the same thing [29]. Additionally, most endeavors are very situation dependent, ruling out 'one size fits all' sets of measures [37]. It is generally accepted, however, the vertical framework should be used for effectiveness

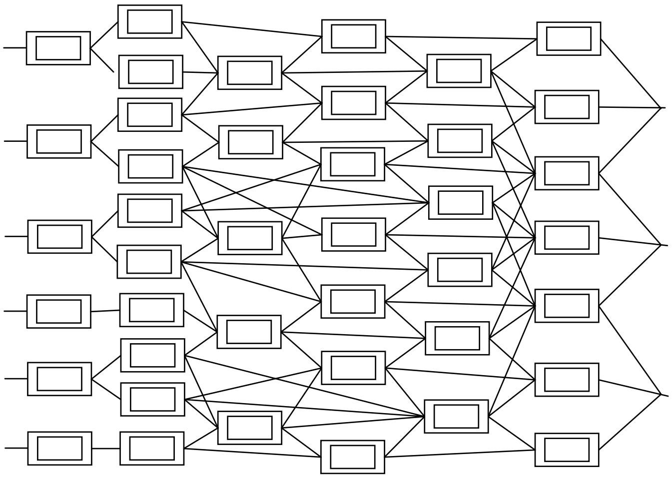


Fig. 5. System of systems.

measures where all measures are derivative of the system strategic purpose or normative behavior [6]. Thus, even operational and tactical level measures should flow from the strategic level [8].

The crux of the problem in understanding which inputs lead to which outcomes is identifying and articulating the cause–effect linkages between the strategic, operational, and tactical levels as well as the impact of inputs and environmental factors on each of these levels [41]. The difficulty in establishing these linkages is usually understated [17]. The cause–effect relationship can be difficult to discern because the output of one system may be the input of another system and some of the systems may be hidden or inaccessible [27]. Additionally, there may be a delay between a system input and when the impact of that input is seen. Further, for systems in dynamic environments, the cause–effect relationships can change [21] or the system may even adapt to being measured [34].

Approaches to developing measures vary; however, there appears to be wide agreement the starting point is defining the system's strategic purpose or normative behavior as well as associated fulfillment criteria [41]. These strategic level definitions can be abstract and difficult to quantify for real world systems. Thus, subsequent steps involve dividing the strategic level concepts into conditions or outcomes supporting the system purpose or normative behavior. An extension of this step sometimes employed is determining the relative importance, or weighting, of multiple, and possibly conflicting, conditions or outcomes [17]. These outcomes can then be further divided into effects that would bring about the conditions [6]. System outputs that would achieve the effects are subsequently identified. Finally, the inputs required to create the outputs are defined as shown in Fig. 3. In summary, the basic concept is to work backward through the cause–effect relationships iteratively decomposing abstract concepts to a point where they are so narrowly defined, a measure suggests itself [41].

Ideally, this approach will yield a direct, natural measure, or a measure with a universal interpretation that directly measures the system purpose or normative behavior. If it does not, a constructed measure may have to be used. A constructed measure is defined for a specific context and has two forms. The first is a subjective or categorically defined scale. The second form is the aggregation of several natural measures to form an index. However, if no natural measures are readily apparent and a constructed measure can not be derived, a proxy or indirect measure must be used [23].

The relationships between these measure types are summarized in Table 1. Regardless, of the type of measure, the above reductionist process assumes linear decomposition, implying the sum of the constituent parts is representative of the overall system behavior. This reductionist philosophy is based on the premise that elements of one kind are combinations of elements of a simpler kind [44].

Despite unique measures being required for most systems, and even for the same system in different environments, good measures share some common characteristics. These can be categorized as strategi-

Table 1
Measure types [24]

	Natural	Constructed
Direct	– Commonly understood measures directly linked to strategic objective – Example: profit	– Measures directly linked to the strategic objective but developed for a specific purpose – Example: gymnastics scoring
Proxy	– In general use measures focused on an objective correlated with the strategic objective – Example: GNP (economic well being)	– Measures developed for a specific purpose focused on an objective correlated to the strategic objective – Example: student grades (intelligence)

cally-linked, timely, objective, economical, complete, and measurable.

- Strategically-linked—effectiveness measures should be traceable to the system strategic purpose or behavior [20]. Additionally, strategically-linked implies a measure is responsive to change and provides an indication of how much change can be attributed to a system input [34].
- Timely—measures should be collected and processed in a timeframe required to be relevant to the context [20]. This property is at the heart of the trade-off between timeliness and measurement accuracy.
- Objective—measurements should be easy to understand, be the same regardless of the assessor, and be the same under similar circumstances [15]. Objectivity also implies credibility which concerns measure 'face-value' or whether the measure logically represents what it is supposed to represent. It should be noted, an objective measure can be qualitative, but subjective measures should be avoided [22].
- Economical—collection and processing of measurements should provide benefits that off-set the burden of measurement activities [20]. A part of an economical measurement system is ensuring the measures are unique and do not contain duplicate information [4].
- Complete—measures should address all areas of concern in enough detail to discern reasons for differences in actual and expected system results [22]. Completeness does not require identifying every relevant system attribute, however; a spanning set of measures associated with the system's purpose or behavior should be attained. Additionally, measures should be limited to those vital for assessing the system strategic purpose/behavior [18]. Completeness can be characterized by breadth and depth where breadth addresses how many of the system attributes are being measured and depth refers to the unit of analysis or 'granularity'. Unfortunately, there is no 'sure-fire' method for developing a complete set of system measures. However, achieving completeness requires both critical and creative thinking in an iterative process involving negotiation and compromise among those interested in and knowledgeable about the system [42].
- Measurable—measures should hold for the representation, uniqueness, and meaningfulness conditions of measurement theory. Additionally, measurable implies within a given context, if the measure can be feasibly obtained with available resources. This is commonly referred to as being 'operational' [23]. Further, measurable implies the collected measures are accurate and can be verified [4]. This is crucial since any system insights gleaned are only as good as the measurements [19].

5. Conclusion

The goal of this paper was to provide a framework for system measurement from both a theoretical and practical point-of-view. The generalized definition of a system used in this paper allows it to be applied to any object, process, or phenomenon. The methodology for system measurement presented in this paper is part of a disciplined approach to determining how a system is progressing towards achieving its purpose or normative impact. The intent was to develop fundamental system measurement principles and to provide theoretically-based, but practical guidelines for conducting system measurement.

Disclaimer

The views expressed in this paper are those of the authors and do not reflect the official policy or position of the United States Air Force, the Department of Defense, or the United States Government.

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