Part One

Principles of Modeling and Simulation: A Multidisciplinary Approach

Chapter 1

What Is Modeling and Simulation?

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INTRODUCTION

Modeling and Simulation, or M&S as it is commonly referred, is becoming one of the academic programs of choice for students in all disciplines. M&S is a discipline with its own body of knowledge, theory, and research methodology. At the core of the discipline is the fundamental notion that *models are approximations for the real-world*. To engage M&S, students must first create a model approximating an event. The model is then followed by *simulation*, which allows for the repeated observation of the model. After one or many simulations of the model, a third step takes place and that is *analysis*. Analysis aids in the ability to draw conclusions, verify and validate the research, and make recommendations based on various iterations or simulations of the model. These basic precepts coupled with *visualization*, the ability to represent data as a way to interface with the model, make M&S a problem-based discipline that allows for repeated testing of a hypothesis. Teaching these precepts and providing research and development opportunities are core to M&S education. M&S also serves as a tool or application that expands the ability to analyze and communicate new research or findings.

There has been much attention paid to M&S by the National Science Foundation (NSF). In 1999, then Director Dr. Rita R. Colwell declared simulation as the *third branch* of science at the fall meeting of the American Geophysical Union [1]. In a more recent report entitled, "Simulation-based Engineering Science: Revolutionizing Engineering Science through Simulation," the NSF drew on the expertise of an esteemed cadre of scientists to discuss the challenges facing the United States as a technological world leader. The group made four recommendations that they

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believed would help restore the United States to its leadership role in this strategically critical technology (simulation). One recommendation went straight to the study of M&S:

> *"The Panel recommends that NSF underwrite an effort to explore the possibility of initiating a sweeping overhaul of our engineering educational system to reflect the multidisciplinary nature of modern engineering and to help students acquire the necessary modeling and simulation skills."* [2]
>
> Simulation-Based Engineering Science: Final Report, May 2006

The intent of this text is to introduce you to M&S education and research from a multidisciplinary approach so that you can acquire the skills necessary to this critical technology.

Fundamental to a formal engineering M&S program of study is its curriculum built upon four precepts—modeling, simulation, visualization, and analysis. Students study the basics of **modeling** as a way to understand the various modeling paradigms appropriate for conducting digital computer simulations. They must understand **simulation** and the methodology, development, verification and validation, and design of simulation experiments. Students who are able to engage **visualization** are able to provide an overview of interactive, real-time 3D computer graphics and visual simulations using high-level development tools. Important to any student research is the **analysis** of the findings; and included in any good analysis is an observation of the constraints and requirements of applying M&S. In other words, analysis also includes making known the limitations of the research.

It was political scientist Herbert A. Simon (1916–2001) who introduced the notion of *learning by doing* (also known as experiential learning).[1] M&S can be just that. It is the simulation of a model that allows for the imitation of the operation of a real-world process or system over time. To imitate an operation over time one must generate a history, real or artificial, to draw inferences concerning the operating characteristics of the real system that is represented [3]. The art and science of M&S has evolved very rapidly since the mid-1980s, so much so that it easily parallels the technological advances of mainframe and desktop computers and the ever-increasing emergence of the internet and World Wide Web (www).

[1] **Herbert A. Simon** was a political scientist who conducted research in a variety of disciplines including cognitive psychology, computer science, public administration, economics, management, and philosophy of science. Dr. Simon was among the founding fathers of several of today's most important scientific domains, including artificial intelligence, information processing, decision-making, problem-solving, attention economics, organization theory, complex systems, and computer simulation of scientific discovery. He was the first to analyze the architecture of complexity and to propose a preferential attachment mechanism to explain power law distributions. He introduced the notion of *experiential learning, bounded rationality*, and *satisficing*. Dr. Simon's research at Carnegie Mellon University resulted in numerous cited publications. He remains one of the most influential social scientists of the 20th century.

MODELS: APPROXIMATIONS OF REAL-WORLD EVENTS

A *model* is a representation of an event and/or things that is real (a case study) or contrived (a use-case). It can be a representation of an actual system. It can be something used in lieu of the real thing to better understand a certain aspect about that thing. To produce a model you must abstract from reality a description of a vibrant system. The model can depict the system at some point of abstraction or at multiple levels of the abstraction with the goal of representing the system in a mathematically reliable fashion. A *simulation* is an applied methodology that can describe the behavior of that system using either a mathematical model or a symbolic model [4]. Simply, simulation is the imitation of the operation of a real-world process or system over a period of time [3]. As you will see there are many uses of M&S. M&S can be used to determine the ordering policies of Wal-Mart's extensive inventory system, or it can be used to analyze the prospects and rate of rehabilitation of a patient who just underwent knee-replacement surgery, or it can be used to evaluate ocean currents and waves to better understand weather patterns.

M&S begins with 1) developing computer simulation or a design based on a model of an actual or theoretical physical system, then 2) executing that model on a digital computer, and 3) analyzing the output. Models and the ability to act out with those models is a credible way of understanding the complexity and particulars of a real entity [4]. From these three steps you can see that M&S facilitates the simulation of a system and then a testing of the hypothesis about that system. For example, if you wanted to determine how many cashiers are needed to process a certain number of customers during rush hour with the assurance that the store's high level of quality service was not compromised, you must first research the current system of processing customers.

You will no doubt review the work schedule and note that the manager has scheduled more cashiers during peak times. You will then assess how many customers are processed during peak times based on the cashier tapes. Also, you might want to see how long it takes to process a customer at slow periods and at heavy traffic periods—you might be surprised to find that customers are processed in shorter exchanges at busy times. Do the customers feel rushed? How many errors are made? Do the customer lines flow smoothly? Are the cash registers placed in good locations? All of this is part of the initial research you will do to develop your model. Once you have sufficient data you can create your model. It is important to note that *models are driven by data* and so your data collection must be done with great accuracy.

Once the model is created you can craft a fairly well-thought-out and credible hypothesis such as, *if the store manager does this, this will be his result*. But are you certain? There may be unexpected changes to the model—a cashier is out sick, a cash register breaks, the power goes out and stops all transactions. What can the manager do to accommodate these unforeseen occurrences? You can assist the manager by creating a number of simulations or iterations of the model to ascertain the "what if." Upon reviewing the output of your simulations, you can provide that data to the store manager so that he or she can make well-informed decisions about the scheduling of cashiers and distribution of registers to meet the goal of high-quality service. As you can see from the example, M&S gives you many opportunities to repeat a simulation of the hypothesis. In essence, you have the ability to repeat the testing of the hypothesis through various simulations. Let's take a closer look at simulation.

First, we must appreciate that defining simulation is not as clear-cut as defining model. Definitions of simulation range from:

- a method for implementing a model over time
- a technique for testing, analysis, or training in which real-world systems are used, or where real-world and conceptual systems are reproduced by a model
- an unobtrusive scientific method of inquiry involving experiments with a model rather than with the portion of reality that the model represents
- a methodology for extracting information from a model by observing the behavior of the model as it is executed
- a nontechnical term meaning not real, imitation (the correct word here is the adjective simulated)[2]

Simulation is used when the real system cannot be engaged. The real system may not be engaged because 1) it may not be accessible, 2) it may be dangerous to engage the system, 3) it may be unacceptable to engage the system, or 4) the system may simply not exist. So to counter these objections a computer will "imitate" operations of these various real-world facilities or processes. Modeling depends on computational science for the visualization and simulation of complex, large-scale phenomena. These models may be used to replicate complex systems that exhibit chaotic behavior and so simulation must be used to provide a more detailed view of the system. Simulation also allows for virtual reality research whereby the analyst is immersed within the simulated world through the use of devices such as head-mounted display, data gloves, freedom sensors, and forced-feedback elements [4]. *Artificial Life* and *Computer Animation* are offshoots of computational science that allow for additional variations in modeling.[3]

Now that we know what comprises a model and what constitutes a simulation, we then couple these steps with visualization. M&S coupled with visualization refers to the process of developing a model of a system, extracting information from the

[2] Additional information and definitions can be found at the U.S. Department of Defense, Defense Modeling and Simulation Office (DMSO) online glossary at http://www.dtic.mil/whs/directives/corres/pdf/500059m.pdf.

[3] *Artificial life* enables the analysts to challenge the experiment by allowing the computer program to simulate artificial life forms. *Computer animation* is emphasized within computer graphics and it allows the modeler to create a more cohesive model by basing the animation on more complex model types. With the increased use of system modeling there has been an increased use of computer animation, also called physically based modeling [4].

model (simulation), and using visualization to enhance our ability to understand or interpret that information. We have mentioned "system" a number of times. Let's take a look at what constitutes a system.

An accepted definition of "system" was developed by the International Council of Systems Engineering (INCOSE). A **system** is a *construct or collection of different elements that together produce results not obtainable by the elements alone*.[4] The elements can include people, hardware, software, facilities, policies, documents—all things required to produce system-level qualities, properties, characteristics, functions, behavior, and performance. Importantly, the value of the system as a whole is the relationship among the parts. There are two types of systems: 1) *discrete* in which the variables change instantaneously at separate points in time and, 2) *continuous* where the state variables change continuously with respect to time. There are a number of ways to study a system:

- the actual system versus a model of the system
- a physical versus mathematical representation
- analytical solution versus simulation solution (which exercises the simulation for inputs in question to see how they affect the output measures of performance) [5]

As you will learn, M&S holds a significant place in research and development due to its inherent properties of modeling, simulating, analyzing, and visualizing (communicating). It is becoming the training apparatus of choice. In fact, M&S is considered a new tool of choice in the fields of health services, education, social sciences, business and industry. Many folks in the M&S community (researchers, academicians, industry, and military) were introduced to M&S as a tool that evolved with the modern military of the 20th century. But its origins can be traced to an ancient military whose use of wargames made it one of the most efficient armies in military history.

A BRIEF HISTORY OF MODELING AND SIMULATION

The act of wargames and challenging or outwitting an opponent on the battlefield is centuries old. In ancient Rome, the then world's largest empire was secured by the world's largest military. The Roman Army conducted live training between two contingents of its military (red team versus blue team). Their training battlefield reflected an environment the troops would encounter somewhere within the expansive Roman Empire that spanned the Scottish border in northern Europe throughout North Africa into the Near East (Afghanistan). The Roman Army had to learn how to fight in unknown regions against armies with diverse warring techniques. Although their training exercises were not intended to draw blood, their training honed a mili-

[4] Additional information and definitions can be found at the INCOSE online glossary at http://www.incose.org/mediarelations/glossaryofseterms.aspx.

tary prowess that made the Roman Army the greatest military the world had known for centuries (circa 500 B.C.E.–1500 C.E.). Significant as they were with Rome's legions, models were not restricted to the art of wargames and military training.

During the age of the Renaissance (1200–1600 C.E), or rebirth of learning, artists and scientists were using models in their designs of statuary or edifices. These models were presented to the artist's patron or commissioner as a way of seeking approval of a design before beginning an expensive project such as a marble bust or sarcophagus. One of the most notable scientists of the time was Leonardo DaVinci. He is famous for his paintings, sculptures, building designs, and scientific experiments. His projects include the design of advanced weaponry (to include tanks and submarines), flying machines, municipal construction, canals, and ornamental architecture (churches and fortresses), as well as his famous anatomical studies. Among his many assignments Leonardo worked as a military engineer where he was called upon to design a bridge to span the Golden Horn (a freshwater waterway dividing the city) in Constantinople (modern day Istanbul). Leonardo was also commissioned to do a life-sized equestrian statue (which was later changed to be four times larger). To do this he studied the movement of horses, made countless sketches, and devised new casting techniques. He did not complete the project, but he had succeeded in making a 22-foot clay model.

Leonardo made repeated uses of modeling to test the design of many of his inventions and projects. He determined that by understanding how each separate machine part functioned, he could modify it and combine it with other parts in different ways to improve existing machines or create new machines. He provided one of the first systematic explanations of how machines work and how the elements of machines can be combined. Fortunately, his studies and sketches have been collected into various codices and manuscripts that are available for our review. Around this same time a new competition was introduced in Europe. It came in the form of a game that required intellect and prowess—chess.

The current game of chess, as most westerners know it, had its origins in southern Europe in the second half of the 15th century. That game was a derivation of a 7th century game of Indian origin. Included on the chessboard are the King, Queen, Bishop, Knight, Rook, and Pawn. The object of the game is to checkmate the opponent's King by first placing that King under immediate duress or "check" with such maneuvering that there is no way for your opponent to remove his King from attack. Think about what is created on the chessboard: a simulated battlefield with two armies who possess equal strength of force. It is now up to the human commander (the chess player) to conduct his simulations: what if I move this way? What will happen if I do this? How will my opponent respond? What is he planning? The ultimate "checkmate" is rewarded by winning the war (the game). But what if you are playing a computer? Can it outwit a human opponent? Yes, it can.

In 1997 an IBM chess playing computer named Deep Blue won a short six-game exhibition match (not a world title match) by two wins to one with three draws against the Russian world champion Garry Kasparov after he made a blunder in the opening of the last game. Kasparov accused Deep Blue—IBM—of cheating and demanded a rematch, but officials at IBM declined. His accusation stemmed from the fact that he saw deep intelligence and creativity in the machine's moves suggesting that during the second game human chess players, in violation of the rules, intervened. IBM's response was that the human intervention occurred only between games as the rules provided so the developers could modify the program between games. This gave IBM an opportunity to modify for weaknesses in the computer's play as it was displayed during the game. Doing these modifications precluded the computer from falling into previous traps set by Kasparov [6]. There are a number of theoreticians who have developed extensive chess strategy and tactics. Many who play the game cite chess as one of the first wargames. By the 18th century military modeling, simulation, and training took on a new perspective.

In the 1780s, with England at the height of its naval power, a Scotsman named John Clerk developed a method of using model ships to gain tactical insights. He used his ships to step through battles analyzing the influence that geometry of the combatants had on their combat power. While a military simulation, Mr. Clerk's work was not considered a wargame because it did not provide a way to measure or apply the effects of actions—the reward and risk from game theory [7]. On the European continent, however, wargames were being formally developed by the Prussians (modern-day northeastern Germany).

Prussia attained its greatest importance in the 18th and 19th centuries. In the 18th century during the reign of the Soldier King Frederick I (1713–1740), Prussia instituted a *standing army*, or an army composed of full-time professional soldiers who *stand over* and never disband, even during times of peace. As a result of this significant military capacity, Prussia became a great European power during the latter half of the century under the reign of Frederick II (1740–1786). The Prussians saw the advantages to playing wargames and by 1824 games were incorporated as part of the training throughout the Prussian army. It was during the 19th century that Prime Minister Otto von Bismarck pursued a policy of uniting the German principalities into a "Lesser Germany" that would exclude the Austrian Empire. This led to the unification of Germany in 1871. Wargaming no doubt contributed to the outstanding military capability of Prussia's standing army and its success on the battlefield during the 19th century.

In the United States, Major W. R. Livermore of the Army Corps of Engineers introduced modern wargaming to the American military [7]. In 1883 he translated the German rules to a wargame they had developed based on the American Civil War and Prussia's own wars of 1866 and 1870–1871. Livermore found that when he compared the German attrition tables to actual statistics errors were made. Livermore determined that the German attrition tables usually predicted lower casualties than the historical record indicated. He adjusted his tables accordingly. Upon improving the wargame with the historically accurate data, Livermore sought official acceptance of wargaming for the U.S. military. Much to his surprise he was blocked by General William T. Sherman who was serving as the U.S. Army's Chief-of-Staff. Sherman felt wargames depicted men as blocks of wood rather than human beings. He therefore refused the integration of wargames into military training. Four years after Sherman's refusal to use wargames, the Naval War College decided it would use Livermore's model. In 1887 the college introduced its first Army-Navy field exercise. By the turn of the 20th century wargames made their way into U.S. military exercises and training. These games, however, lacked the capability and the complexity to model an event with the accuracy we now see in military modeling, a change that came about with the introduction of technology.

M&S can trace its technical origins to the first flight simulator, the *Link Flight Simulator*, which was patented in 1929 by American Edward Link. The pilot trainer resembled a toy airplane from the outside with short wooden wings and fuselage mounted on a universal joint. Link used organ bellows driven by an electric pump to make the trainer pitch and roll as the pilot worked the controls. The *Link Flight Simulator* was used in both government and private sectors [8]. In 1931 *Link Flight Simulator* was fully instrumented and sold to the Navy. The Army took delivery of *Link* trainers three years later. And on the home-front, the *Link Flight Simulator* was used in amusement parks during the 1930s. This was no doubt great fun for those young at heart who enjoyed pretending to be a pilot. But importantly, the *Link Flight Simulator* was great economy for the military as vast sums of money and time were saved with the training of Navy and Army pilots in simulators replicating air flight. This is a good example of how using simulation allows the military or any other company or organization to test a system before investing in the full-scale model, or to train an individual in a less expensive environment.

In the post–World War I period the Navy and the Marine Corps both employed wargames as part of their training. This training proved useful with the coming of the Second World War. Under the leadership of General George C. Marshall live simulation was introduced into military training. As a result, military M&S was making quick inroads into training the military of a new world power and that was by no accident. With the end of two World Wars a new period of military engagement was beginning, one that brought with it weapons of mass destruction that required computer-assisted air defense systems to interfere with their delivery. This post–World War II period is called the *Cold War*. The Cold War took place between the two world powers: the United States and the Soviet Union, and it would last almost a half century (1945–1989) as a military competition between the two.

On 29 August 1949 the Soviet Union detonated an atomic device at the Semipalatinsk Test Site in Kazakhstan, making it the second nation in the world to detonate a nuclear mechanism. This action served as the impetus for the U.S. government to give grave consideration to the threat of another nation possessing nuclear military capability. As a result, the Department of Defense was given the approval to invest funds for research in air defense systems. By the winter of 1949 digital computers were engaged in creating simulated combat. Developed by the U.S. Air Force, a semi-automated ground environment—SAGE—simulated combat from the perspective of more than one combatant. This type of simulation provided military training that now incorporated an air-defense system.

By the 1950s computers were being used to generate model behavior followed by simulation programs. These computers were then required to process the results of the elements of the simulation-based problem solving environments [9]. Digital radar was now able to transmit from the newly developed Microwave Early Warning (MEW) radar. This innovative research was being conducted by engineers at the

Massachusetts Institute of Technology (MIT). Significant to the research was a transmission that tied together the MEW located at Hanscom Field to the digital computer named *Whirlwind* located at MIT. Also at this time a scaled-down version of SAGE was being developed. Dubbed the *Cape Cod System*, this simulator was introduced in 1953. It allowed radar operators and weapons controllers to react to simulated targets presented to them exactly as these targets would appear in an engagement. The country was becoming embroiled in a military contest that called for technology far beyond the imagination of the average citizen.

Interestingly, some of that same technology was making its way into the homes of so many families in everyday, ordinary appliances and communication devices that brought a new definition to the post-modern age. In essence, as the country was developing militarily, and so was every other aspect of technology—that is why the 1950s were so progressive. This was a unique time in the social history of the country. It was both an age of innocence and a post-modern world with technical advances that would send men into outer space. Ironically, it was the newly invented *RCA FlipTop* television and *Regency TR1* transistor radio that delivered fear and talk of war with the Soviets into the American family living room.

At the close of his two-term presidency (1953–1961), Dwight D. Eisenhower gave an address to the American people about the effects of the ongoing military competition with the Soviet Union. Eisenhower's Military-Industrial Complex Speech made Americans aware that *a vital element in keeping the peace is our military establishment*. The president emphasized that *U.S. arms must be mighty, ready for instant action, so that no potential aggressor may be tempted to risk his own destruction* [10]. To do this the federal government would support and fund research that would make the military state-of-the-art, always ahead of the opposition. The president's speech referred to the increasing military buildup in the United States throughout the 1950s. That build-up fueled the nation's growing economy and many were living quite comfortably during this time. Perhaps somewhat oblivious to what was truly happening, Eisenhower was compelled to explain to his fellow citizens the ramifications of coupling an immense military establishment with an expanding arms industry. This was a new concept for Americans. In fact, the **Military-Industrial Complex** was a new American experience with an economic and political influence that reverberated throughout the country. By 1960 the increased spending for this complex amounted to more than half of the U.S. federal expenditure. And, as the complex grew so did the workforce. From the close of World War II (1945) to the end of Eisenhower's second term (1961), an expansive workforce of civilian employees constituted much of the defense industry. Additionally, many universities thrived on the increased research opportunities.

Throughout the 1960s military wargames became much more sophisticated, moving from strictly tactical training to strategic commands. Games were now incorporating things like the political capacity of a state or leader. They also became technically mature. This became apparent with work done at the universities. In 1961 a student at MIT created an interactive computer game called *Spacewar* [11]. The game required the player to operate his spaceship during a conflict that was fought with the firing of torpedoes. Pilots of the spaceships scored points by launching missiles that inflicted damage on the opponent, avoiding direct hits by the opponent, and maneuvering the spaceship to avoid the gravitational pull of the sun. This computer game was one of the first *interactive* games in the country. The president and Congress were also pushing forward a research agenda at government institutions. Just over a decade after Spacewar, two engineers at the National Aeronautics and Space Administration (NASA) in Moffett Field, California, developed another computer game, one a bit more complex called *Mazewar* [12]. This game was networked and it introduced the concept of online players as **avatars** (a graphical image of a user or a graphical personification of a computer or a computer process) in the form of an eyeball chasing other players around a maze.[5] Mazewar's development in 1974 served as a catalyst for a number of versions on various programs.

The military was also making contributions to M&S by formalizing simulation as a training tool. In 1971 the Navy's *Top Gun* school opened to train fleet fighter pilots in air combat tactics. In 1975 the Tactical Advanced Combat Direction and Electronic Warfare (*TACDEW*) simulator was being used for team training. The simulator created 22 separate shipboard mock-ups with the ability to generate a virtual (also called synthetic) threat environment [13]. There was also work done with linking training simulators. Fighter plane cockpits like the B-52 (long-range, heavy bomber aircraft) were simulated so that they could operate with tanker (refueling aircraft) simulators to facilitate training plane/tanker rendezvous.

By 1983 simulator networking was advancing rapidly. The *Defense Advanced Research Projects Agency (DARPA)* had initiated simulator networking—*SIMNET*— with an emphasis on tactical team performance on the battlefield. The U.S. Army supported the idea of incorporating armor, mechanized infantry, helicopters, artillery, communications, and logistics into the model for a much more expansive simulated training experience. Combatants could now see each other and communicate over radios. The SIMNET simulator was introduced at the First-Platoon Level in 1986. By 1990 over 250 networked simulators at 11 different sites were delivered to the U.S. Army [14]. It wasn't long before the benefit of SIMNET training was realized.

On July 25, 1990, Saddam Hussein convened a meeting with U.S. Ambassador to Iraq April Glaspie expressing his contempt for two of his Persian Gulf neighbors, Kuwait and the United Arab Emirates. He specifically accused Kuwait of exceeding the Organization for Petroleum Exporting Countries (OPEC) production limits and thus driving down oil prices. This lowering of prices was having a negative affect on the Iraqi economy and he faulted the United States for encouraging this high level of production. Additionally, his aggressive behavior earlier in the year resulted in the cessation of American aid—no more American aid meant he would look elsewhere, and that elsewhere was Kuwait. Within two weeks of his meeting with Ambassador Glaspie, Saddam ordered his troops into Kuwait. Iraqi troops entered

[5] Please note the difference between a GAME and a SIMULATION. A game is more concerned with entertaining and there is much more player participation. A simulation is more focused on getting the details of the model and system correct. A simulation does not require a participant or player, but a game does.

Kuwait on August 2, six days later an international coalition that included U.S. ground forces was conducting *Operation Desert Shield* to counter the Iraqi invasion of Kuwait. By January 1991 the U.S.-led international coalition's mission changed to include offensive air attacks. A seamless transition from *Operation Desert Shield* to *Operation Desert Storm* was underway.

In February a decisive tank battle was in progress. The *Battle of 73 Easting* was fought between armored forces of the U.S. Army and the Iraqi Republican Guard. The U.S. ground unit was outnumbered and outgunned; yet, it was able to affect the enemy by destroying 85 tanks, 40 personnel carriers, and 30 wheeled vehicles carrying anti-aircraft artillery. Why was this outnumbered and outgunned U.S. armored unit able to conduct itself with such precision and success? The answer is because this unit had trained intensively before the engagement using SIMNET. The *73 Easting Project* was a collaborative study conducted jointly by the *Institute for Defense Analyses (IDA)*, DARPA, and the U.S. Army. With the development of a database and the use modern computer simulation technology, the soldiers were able train in a virtual re-creation of the minute-to-minute activities of each participating tank, armored vehicle, truck, and infantry team.

After the engagement more information was collected by extensive engineering surveys of the battlefield immediately after the fighting. Exhaustive participant interviews were included. This information was further integrated into the simulation of the battle for future training. The Battle of 73 Easting and the post-analysis proved the significance of computer simulation training in and of itself and with future training with its ability to test alternative cause-and-effect hypotheses with factual and counterfactual analysis. SIMNET would now include conducting controlled experiments by changing key characteristics of the historical event, then re-fighting the simulated battle and observing the effects on the presumed outcome.

Tied to the events in Iraq was the establishment of the *Executive Council on Modeling and Simulation* by the U.S. Department of Defense in 1990. In 1991 a Defense Modeling and Simulation Office was established with large investments to advance *Modular Semi-Automated Forces—ModSAF*. ModSAF is a set of software modules and applications used to construct *Advanced Distributed Simulation* and *Computer Generated Forces* applications. ModSAF modules and applications allow a single operator to create and to control large numbers of entities that are used for realistic training, testing, and evaluating on the virtual battlefield. Funding also went into the advancement of the *Joint Simulation System (JSIMS)* to develop training tools and future M&S capability, in particular simulation improvement.

Advancements in computer software and hardware as well as artificial intelligence and software agents have hastened the pace of the maturation of M&S as a discipline and tool. These additional elements that now comprise M&S enhance the capabilities of simulation for more complex phenomena such as the human personality in social and conflictual simulations. In the early 1990s, military M&S practitioners began to explore ways to link stand-alone simulations used to model and represent distinct real-world functions into a federation of simulations where simulation entities were given semi-automated behaviors. This is commonly called *semi-automated forces (SAF)*. The initial efforts to link simulations showed promise and led to standards in simulation data exchange and the establishment of protocols for creating simulation federations [9].

As semi-automated behaviors were being explored, a closer look at human behavior was underway. It was during this time that a new type of modeling was taking form—**behavioral modeling**. A behavioral model is a model of human activity in which individual or group behaviors are derived from the psychological or social aspects of humans. Behavioral models include a diversity of approaches; however, the computational approaches to human behavior modeling that are most prevalent are social network models and multi-agent systems.[6] Behavioral modeling can be used to provide qualitative analysis of a specific foreign leader, or assess the movement of civilian populations in duress, or understand how culture and religion can affect social behavior [15]. Behavioral modeling allows for the incorporation of socially dependent aspects of behavior that occur when multiple individuals are together. This type of modeling is now being used in fields of study that include observations of human behavior be they individual, group, or crowd behaviors. Education, psychology, industry, and transportation are just some examples of behavioral modeling users. (A more detailed discussion on the social sciences and behavioral modeling can be found in Chapter 8.)

The Department of Defense has also made use of the behavioral modeling. In fact, behavioral modeling research would become a significant component of military M&S. The M&S academic community and the Department of Defense analysis community had begun expanding its research to include social network analysis and crowd modeling. However, the M&S industry stayed close to military applications focusing their work on meeting the needs of the U.S. military's *Simulation, Training, and Instrumentation Command (STRICOM)* in Orlando, Florida; the *Air Force Research Laboratory* in Dayton, Ohio; the *National Simulation Center*, and the *U. S. Army Training and Doctrine Command (TRADOC)* both at Fort Leavenworth, Kansas. The *U.S. Joint Forces Command (USJFCOM)* in Suffolk, Virginia, also became very involved in M&S. In 1997 the USJFCOM partnered with Old Dominion University in establishing the Virginia Modeling, Analysis and Simulation Center—VMASC.[7]

It was not long, however, before the explosive growth of computer games for entertainment and the emergence of new uses for M&S shifted the focus of the industry. By the latter half of the decade, the companies that grew the military M&S

[6] A Social Network Model is a model of social behavior that takes into account relationships derived from statistical analysis of relational data. A Multi-Agent System focuses on the way in which social behavior emerges from the actions of agents [15].

[7] The Virginia Modeling, Analysis and Simulation Center (VMASC) is a multi-disciplinary modeling, simulation and visualization collaborative research center managed through the Office of Research at Old Dominion University. VMASC supports the University's Modeling and Simulation (M&S) graduate degree programs, offering multi-disciplinary M&S Masters and Ph.D. degrees to students across the Colleges of Engineering and Technology, Sciences, Education, and Business. With numerous industry, government, and academic members, VMASC furthers the development and application of modeling, simulation, and visualization as an enterprise decision-making tool and promotes economic development. http://www.vmasc.odu.edu.

industry began exploring a variety of new uses for M&S. Today, M&S can be found in just about every research and training institution or venue. M&S is being used in medical and health-care fields, logistics and transportation, manufacturing and distribution, communications, and virtual reality and gaming applications for both entertainment and education. As you will see, M&S has expanded into many application areas.

APPLICATION AREAS

Once a primary training mechanism for the military, modeling and simulation is now being used in a variety of domains to include medical modeling, emergency management, crowd modeling, transportation, game-based learning, and engineering design—to name a few. Within various forms of media, M&S has already made inroads in a number of liberal arts disciplines. With the advent of modeled and simulated historic events, television has made significant strides in portraying the Ancient World as historians have researched and perceived it to be. Advertisements for complex wireless telephone systems have employed simulated, visualized geographic data that scans large crowds then zeroes in on the individual user all in the name of selling the most extensive wireless phone service. Avatars have replaced humans for interfacing within complex communication systems. These applications of M&S have all come to pass in a somewhat indirect fashion and they are a part of our lives, although we may not recognize or even realize—this is M&S. However, as an academic tool, which is what we are endeavoring to understand, M&S has a more formal role.

M&S applications are used primarily for analysis, experimentation, and training. *Analysis* refers to the investigation of the model's behavior. *Experimentation* occurs when the behavior of the model changes under conditions that exceed the design boundaries of the model. *Training* is the development of knowledge, skills, and abilities obtained as one operates the system represented by the model. As we can see, M&S is multi-faceted and it can be used as a tool, an enabling technology. It is this property that allows us to use M&S in many disciplines. What is becoming more and more apparent to traditional producers and users of M&S is that there is a "richness of the possibilities … and synergies with related disciplines" [16].

M&S can be applied in any field where experimentation is conducted using dynamic models. This includes all types of engineering and science studies as well as social science, business, medical, and education domains. As we have learned, the military were the first users of M&S and their applications ranged from the early models of traditional wargames to scene generation (battlefield simulation) to missile defense. The military continues to be the largest consumer of modeling and simulation; however, there has been an additional component to military decision-making via modeling and simulation that incorporates modeling the intangible aspects of a military intervention. Things like the politics of the region, the effect of war on the regional economy, and the outcome of diplomatic exchanges. M&S is often the only tool capable of solving complex problems because it allows for an understanding of system dynamics and it includes enabling technology both of which provides a means to explore credible solutions.

There are two types of modeling and simulation activity that can be distinguished depending upon whether or not the simulation program runs independently from the system it represents. **Stand-alone simulation** follows the H.A. Simon notion of *learn by doing* or train as your operate. **Integrated simulation** is used to enrich and support real systems. For many non-engineering and non-science students, Stand-alone Simulation may be best suited for your needs. Often, stand-alone application areas are grouped into five categories [9]:

- *Training*—goal is to provide real-world experience/opportunities in a controlled environment
- *Decision Support*—to provide a descriptive, explanatory, predictive tool or to provide an evaluative, prescriptive tool
- *Understanding*—this type of modeling and simulation facilitates testing a hypothesis relative to the structure and function of a complex system
- *Education and Learning*—used for teaching and learning systems with dynamic behavior and with serious gaming (this is also called game-based learning)
- *Entertainment*—simulation provides a realistic representation for elements possessing dynamic behavior

Training, Decision Support, and *Understanding* aim to provide a level of proficiency. An example of Stand-alone Simulation for *Training* is a simulation used to create an environment that focuses on game theory. Because it is focusing on game theory, the simulation may be a **zero-sum simulation** intent on honing the user's decision-making and communication skills. This is done by enveloping the user in battle simulations at different levels, or in peace operations, or in conflict management and allowing him to negotiate a solution. Another example of Stand-alone Simulation for *Training* is the **virtual simulation** with limited environmental interactions used to develop the motor skills of the user.

Whether it is *Training, Decision Support, Understanding*, or *Education and Learning*, M&S applications can be found in a number of research areas. Below are brief descriptions of four of the M&S application areas being developed at the VMASC. (The application areas introduced below will be addressed in greater detail in Chapter 8.)

Transportation M&S

Almost everyone is touched by some form of transportation every day of their lives. We rely on both public and private systems to get us to work, school, shopping, or to our favorite form of recreation. We take for granted the underlying system supporting this complex network of roadways, rail, and public transit routes. And these systems are very complex. They consist of miles of road surface and track with multiple control mechanisms to regulate the flow of vehicles. The systems have become so complex that a seemingly minor adjustment to the timing of a traffic light in one part of the city can have a drastic effect on traffic movement miles away.

Traffic engineers employ simulation to test these adjustments for just this reason. It is far better to see the results in a simulation and watch traffic back up there than it is to have hundreds of frustrated motorists wasting valuable time traveling at a speed far below their expectation. Large-scale regional traffic simulations, known as *Macroscopic Traffic Simulations*, are capable of showing the effects of these changes on very complex networks of roadways covering large regional areas.

Microscopic Traffic Simulations, those that model the individual movement of cars based on physics parameters such as velocity and acceleration, are employed to study smaller sections of roadway such as a particular intersection or a certain road corridor. These simulations provide exceptional detail to understand how individual cars will be affected if a new off ramp is added or lane configuration is changed. Using simulation for transportation planning is significant for understanding the implications of change in these very complex systems in today's environment.

Business M&S

Also known as Decision Support or Enterprise Engineering, Business M&S can be defined as a system of business endeavors within a particular business environment created to provide products and services to customers. Most enterprises are an integration of businesses, processes and infrastructure, and resources. M&S can assist in investigating, designing, and implementing solutions to complex enterprise issues such as optimally allocating scarce resources while considering stochastic (characterized by *conjecture* and *randomness*) and ill-posed environments. To address diverse complex and relevant enterprise issues it is necessary to bring together a multi-disciplinary team having expertise in operations management, operations research, industrial engineering, modeling and simulation, marketing, economics, decision science, and mathematics. Here are some of the core research areas:

1. *M&S in Manufacturing Enterprise Engineering (M&S-MEE)* addresses research on design, planning, and control of operations in manufacturing enterprises. Contributions extend the range of analytical and computational techniques addressed to these systems, and novel models offering policy knowledge of applicable solutions in manufacturing environments.
2. *M&S in Operations Research (M&S-OR)* addresses research on progress in the structures and properties of models and procedures derived from studying operations. The focus of the cluster is on researching, creating, and/or improving analytical and computational techniques while emphasizing the relevance of the work in significant applications.

3. *M&S in Service Enterprise Engineering (M&S-SEE)* addresses research on design, planning, and control of operations and processes in commercial and institutional service enterprises. As in M&S-MEE, contributions extend the range of analytical and computational methods addressed to these systems and novel models offering policy knowledge of applicable solutions. Research areas include: supply chain management, health care operations, retailing, and hospitality.

Medical M&S

M&S can assist many fields within the medical profession including training, treatment, and disease modeling. To address these problems VMASC and Old Dominion University (Norfolk, Virginia) have assembled a diverse, multi-disciplinary team having expertise in clinical medicine, modeling and simulation, engineering (mechanical, electrical, biomedical), exercise science and athletic training, human factors psychology, computer science, epidemiology, biology, mathematics, and tumor biology. The research program is a collaborative effort to develop innovative solutions to the aforementioned problems through a series of targeted research projects in core areas such as:

1. *M&S for Improved Training of Medical Professionals* Several recent studies have shown that the U.S. health care system is not as safe as it should be. It has been estimated that medical errors contribute to as many as 98,000–195,000 deaths annually in U.S. hospitals with a cost to society of $37 billion. Simulator systems for training healthcare providers have only become commercially viable within the last ten years. These systems allow trainees to learn fundamental procedures without putting patients at risk, can expose trainees to rare or unusual conditions, and reduce the need for cadavers and animal models. Unfortunately, there are large gaps between training systems currently available and the needs of educators across medical specialties. For instance, there are few systems for training in specialties such as family medicine or obstetrics and gynecology. Further, there are virtually no systems available that address the problem solving and decision-making skills of more advanced trainees. Research in Advanced Surgical Skills, Virtual Pathology, Standardized Patients, and Labor and Delivery are just a few of the areas being addressed.
2. *M&S to Improve Treatment* The treatment of disease and injury is primarily based on the experience of the physician who is treating the problem, which may result in treatment failures, unsatisfactory results, and unnecessary treatments. M&S can be used to develop new treatments, assist in decision making, and to optimize treatment. It is believed that M&S will be most beneficial in developing nonoperative and nonpharmaceutical methods to treat and prevent the progression of osteoarthritis, optimizing hardware and hardware placement for implanted devices used in orthopedic surgery, developing novel, virtual reality–based rehabilitation methods, and minimizing the

dose of radiation that healthy tissue is subjected to during cancer treatment. Research in Osteoarthritis Treatment, Optimization of Orthopedic Fixation Device, and Radiation Beam and Dosage Profiling are some of the projects underway.

3. *Disease Modeling* Multi-scale simulation models can provide opportunities to develop theories to explain the spread of disease, tumor metastasis, and the effectiveness of vaccination. Key to this is researching the dynamics and control of infectious diseases using mathematical modeling and computer simulation. Disease modeling also requires an understanding of how spatial heterogeneity impacts the spread of a given disease and the implications that brings to controlling the disease. Simulations that prescribe the optimal control techniques needed to identify the most effective disease intervention strategies are an integral part of disease modeling.
4. *M&S of Hospital Management in situations that involve Homeland Security* Hospitals today are facing an ever-increasing demand for their services. They are at capacity or near capacity on a daily basis. But what if some type of mass casualty event like a terrorist attack or a major chemical spill should occur? These events could produce hundreds or even thousands of casualties. How will the public health system and hospitals respond? What should they have in place to support this type of disaster? Hospitals and public health officials have turned to M&S to answer these questions. Researchers have built simulations that play out these mass casualty events to see the extent to which the public is affected. They have also built simulations of hospital systems to investigate the most efficient way to treat these large volumes of patients and still provide the level of care expected of them. In short, M&S has provided significant insight to the health care industry for these catastrophic events. They are now better able to understand the implications of these events and properly prepare for them. These and other projects engaging the medical profession with M&S tools are the future of medical research and training.

Social Science M&S

For social scientists the traditional methods of modeling include statistical modeling, formal modeling, and agent-based modeling. *Statistical modeling* is the traditional method for the discovery and interpretation of patterns in large numbers of events. *Formal modeling* is a method that provides a rigorous analytic specification of the choices actors can make and how those choices interact to produce outcomes. *Agent-based simulation modeling* allows for the observation of aggregate behaviors that emerge from the interactions of large numbers of autonomous actors.

Integrating this traditional modeling and analysis capacity with other forms of modeling (simulation and visualization) serves as a tool for expanding and communicating the social scientist's grasp of the subject area being investigated and for providing a much denser schematic for the engineer's model. This relationship will accelerate interdisciplinary research efforts on the part of engineers and social scientists and it is a very good response to changing research requirements.

Every branch of the U.S. military has recognized the need to integrate historic, cultural, and political awareness into its decision-making capacity. In fact, much of the federal government research funding is coming from the analysis sector of the military and the *Department of Homeland Security (DHS)*. The social sciences are now integral to problem solving and decision-making for every aspect of governance to include the U.S. military, DHS, and Nongovernmental Organizations (NGOs). All of these institutions must react and/or respond to disturbances that are the result of insurgencies, military action, terrorist attack, and natural disaster.

Research from the Department of Defense is now requiring the incorporation of geopolitics, culture, religion, and political economy to better understand how Diplomatic, Intelligence, Military, and Economic (DIME) factors affect real-time, tactical decision-making. A growing area of research for the Department of Defense is centered on Political, Military, Economic, Security, Information, and Infrastructure (PMESII) aspects.

As we have learned, the U.S. military employs simulation to train all levels of its service personnel and to analyze complex policy and warfighting plans. Most of these simulations represent only the military aspects of warfare and ignore the political, social, and economic aspects that are vital to understanding **Effects-based Warfare** currently employed by combatant commanders.[8] Without accurate models of these social science areas combatant commanders are unable to test effects-based strategies and plans beyond tabletop exercises. These tabletop exercises do not provide the breadth of results for commanders to gain significant insight into the consequences of their decisions. Simulations that contain social science models will much better represent real-world consequences of military actions that often spill over into the political, social, and economic areas of a country or region. The Department of Defense is aware of this and, as mentioned above, is expanding its research efforts to include this type of data.

As the need for social science qualitative and quantitative analysis expands into the military and homeland security domains, a number of other equally challenging nonmilitary areas can be explored such as:

Foreign policy issue of sanctions—a system dynamics approach to measuring the effects of failed sanctions on the behavior of the civilian population, the insurgency, and/or the controlling regime

Global and national issue of energy dependency—a U.S. and/or European study of the economic, political, and social capacity to manage energy crises

[8] U.S. Joint Forces Command defines Effects-based Warfare as the application of armed conflict to achieve desired strategic outcomes through the effects of military force. http://www.jfcom.mil/about/glossary.htm#E.

National issue of immigration—the layered effects (labor, education, healthcare) of illegal immigrants in a specific community (state, region, or national analysis)

National education issue of game-based learning—creating educational games in the subjects of history and geography

Voting habits in countries with dubious election processes—develop a model that couples statistical data with empirical findings to address voter participation

Local government issue of urban design—continued research in modeling urban development to prescribe improvements in land use, transportation, and infrastructure

These lists are in no way exhaustive, but serve to introduce you to just some of the different M&S applications in the areas of transportation, business, medical, and social science M&S. You can be sure, however, that there are many, many uses of M&S. As you read ahead, you will come to appreciate that there are also many advantages to M&S.

USING MODELING AND SIMULATION: ADVANTAGES AND DISADVANTAGES

In 1998 the Institute of Industrial Engineers (IIE) listed the advantages and disadvantages to using modeling and simulation [1]. From their list it is easy to see why many would choose to apply M&S to research and training. Here are some of the advantages to using modeling and simulation:

- the ability to *choose correctly* by testing every aspect of a proposed change without committing additional resources
- *compress and expand time* to allow the user to speed up or slow-down behavior or phenomena to facilitate in-depth research
- *understand why* by reconstructing the scenario and examining the scenario closely by controlling the system
- *explore possibilities* in the context of policies, operating procedures, methods without disrupting the actual or real system
- *diagnose problems* by understanding the interaction among variables that make up complex systems
- *identify constraints* by reviewing delays on process, information, materials to ascertain whether or not the constraint is the effect or cause
- *develop understanding* by observing how a system operates rather than predictions about how it will operate
- *visualize the plan* with the use of animation to observe the system or organization actually operating

- *build consensus* for an objective opinion because M&S can avoid inferences
- *prepare for change* by answering the "what if" in the design or modification of the system
- *invest wisely* because a simulated study costs much less than the cost of changing or modifying a system
- *better training* can be done less expensively and with less disruption than on-the-job training
- *specify requirements* for a system design that can be modified to reach the desired goal

It is obvious that there are many uses and many advantages to using M&S. The IIE also made note of some of the disadvantages to using M&S. The list is noticeably shorter and it includes things such as the *special training* needed for building models; the *difficulty in interpreting results* when the observation may be the result of system inter-relationships or randomness; *cost in money and time* due to the fact that simulation modeling and analysis can be time consuming and expensive; *inappropriate use* of modeling and simulation when an analytical solution is best.

CONCLUSION

Let's review what has been introduced in this chapter. *Models* are approximations of events, real events as in case studies, or contrived events as in use-case studies. We create models from data so our research of the event or details that go into the use-case must be accurate to ensure that the model is sound. With a reliable model we can develop a hypothesis or research question that requires our observation of the model. We observe the model via *simulation*, and as we have learned we can modify and repeat the simulation. Often, models include *systems* or collections of different elements that together produce results not obtainable to the elements alone. We then conduct our *analysis* of the simulations to draw our conclusion or verify and validate the research. The ability to apply visualization allows us to communicate or present the model, the simulation, and the conclusions we have drawn. All of this is *learning by doing*.

As we have seen the *history of M&S* is quite lengthy, especially if we start with the modeled battlefields and wargames of the Ancient World. Let's not forget the mini theatre of operations that the game of chess models. Scientists like Leonardo DaVinci modeled everything from government edifices, to life-size busts, to bridges. He also tested his inventions and, in doing, so left us with the first systematic explanation of how machines (or systems) operate.

The military no doubt engaged M&S to the fullest during the 19th and 20th centuries. By the 1990s *behavioral modeling* was integrated into military applications of M&S. Behavioral modeling is also present in many other research fields because it focuses on human activity and behavior derived from the psychological and social aspects of humans.

We were also introduced to a few of the many applications of M&S such as transportation, business, medical, and the social sciences. The many advantages to conducting research with the use of M&S are also noted. Some of these advantages are exploring possibilities, diagnosing problems, visualizing a plan, training, and specifying requirements.

The multidisciplinary approach to the principles of M&S that are outlined in the following chapters will help you understand the theoretical underpinnings of M&S, explore M&S practical domains, and observe real-world M&S applications. As with many other students you, too, may decide that M&S education and research will be your discipline of choice.

KEY TERMS

modeling
simulation
visualization
analysis
system
Military-Industrial Complex
avatars
behavior modeling
stand-alone simulation
integrated simulation
zero-sum simulation
virtual simulation

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