Certified Modeling and Simulation Professional Examination Preparation

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ALABAMA IN HUNTSVILLE

Acknowledgements

National Training and Simulation Association

- Sponsors
  - National Training and Simulation Association
  - The Boeing Company
- Guidance
  - Modeling & Simulation Professional Certification Commission (exam structure)
  - SimSummit (body of knowledge outline)
- Selected contributors (alphabetical order)
  - Wesley N. Colley, Ph.D. (questions)
  - David C. Gross, Ph.D. (topics, sources, and slides)
  - Gregory S. Reed, Ph.D. (software)
  - John A. Sokolowski, Ph.D. (question review)
  - William F. Waite (topics and sources)

Instructor

- Mikel D. Petty, Ph.D.
  - Associate Professor, Computer Science
  - Senior Scientist for M&S, Info Tech and Sys Center
- Education
  - Ph.D. Computer Science, UCF 1997
  - M.S. Computer Science, UCF 1988
  - B.S. Computer Science, CSUS 1980
- Career summary
  - M&S R&D: UCF, ODU, UAH; 1990-present
  - IT: CSUS, UTEP, GM, UCF; 1980-1990
- Research
  - Modeling and simulation, esp. distributed simulation and V&V
  - > 195 publications
  - > $16 million total research funding awarded

Part 1: Introduction, structure, and logistics

- Introduction
  - Motivation
  - Certification types
- Structure
  - Topics and subtopics
  - Questions and instances
- Logistics
  - Requirements, preparation, and examiniationn
  - Recertification

Placed first for people who must leave early; will be covered completely.

Part 2: Content survey

- Definitions and concepts
  - M&S terms and attributes
  - M&S categories
- Modeling methods
  - Survey of modeling methods
  - Discrete event simulation
  - Monte Carlo simulation
- Special topics
  - Verification, validation, and accreditation
  - Distributed simulation

Intentionally too long; will be covered as time permits.

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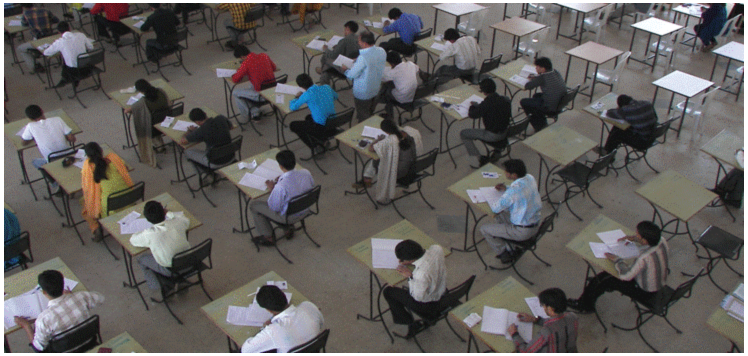
The emergence of M&S as a distinct discipline

"Science used to be composed of two endeavors, theory and experiment. Now it has a third component: computer simulation, which links the other two."
[Colwell, 1999] [Colwell, 2000]

Dr. Rita Colwell
Director, National Science Foundation
April 29 1999

CMSP certification background

- Professional certification, in general
  - Indicator of individual expertise and competence
  - Milestone in maturation of professional discipline
  - Exists for law, medicine, project mgt, finance, …
- Professional certification, for M&S professionals
  - CMSP “version 1” 2001, “version 2” 2010
  - Approximately 400 people designated as CMSPs



CMSP organizing principles

- Overseen by M&SPCC
- Quality
  - Traceability to requirements set by M&SPCC
  - Exam questions based on credible sources, periodically updated and improved
- Transparency
  - Open process, clear values
  - Publicly available program data
  - Evidence of compliance with requirements
- Confidence; CMSPs are knowledgeable
- Ethics; ethical use of M&S part of certification

Benefits of CMSP certification for individuals

- CMSP as credential
  - Peers: community-recognized certification of M&S expertise
  - Customers: qualifications discriminator for competitive proposals
  - Employer: professional certification for career advancement
- CMSP as learning experience
  - Preparation for and completion of CMSP exam enhances M&S knowledge
  - Recertification requirements motivate continuous M&S learning

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Certification types: User/Manager

1. Employ and explain key terms, definitions, and concepts in modeling and simulation.
2. Apply important principles of modeling and simulation practice, including simulation ethics, business considerations, and related communities of practice.
3. Understand and work effectively within typical and important uses of modeling and simulation, including application areas and domains of use.
4. Identify, assess, and select relevant simulation technologies, including modeling paradigms and implementation architectures, for a specific application.
5. Determine whether the use of simulation is, or is not, appropriate for a specific application.
6. Plan, initialize, and execute simulation runs or trials to satisfy project requirements.
7. Analyze, interpret, and apply the results of simulation runs in the context of an application.
8. Manage aspects of projects involving the use or development of simulation models and systems.

Certification types: Developer/Technical

1. Employ and explain key terms, definitions, and concepts in modeling and simulation.
2. Apply important principles of modeling and simulation practice, including simulation ethics, business considerations, and related communities of practice.
3. Understand and work effectively within typical and important uses of modeling and simulation, including application areas and domains of use.
4. Design and develop simulation models of various types, including mathematical, logical, structural, and conceptual.
5. Identify the underlying mathematical issues associated with many simulation models, including numerical evaluation algorithms, digital discretization, and numerical precision.
6. Implement simulation models as executable software and verify those implementations.
7. Validate simulation models using suitable methods and assess the suitability of a model for a specific application.
8. Design and implement technical infrastructures needed to support simulation systems.

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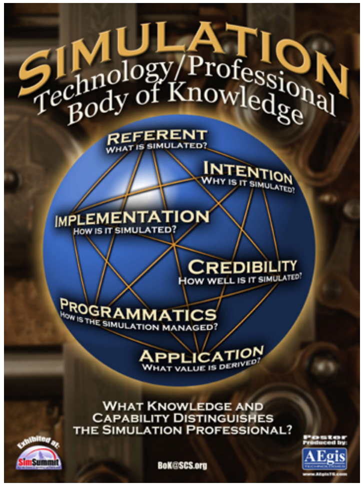
Exam topics and subtopics

- Intent: coverage of M&S body of knowledge
- Structure: 8 topics, 54 subtopics
- Content
  - Initially based on SimSummit M&S BoK Index
  - Revised per expert recommendations
  - Revised per source availability and topic testability

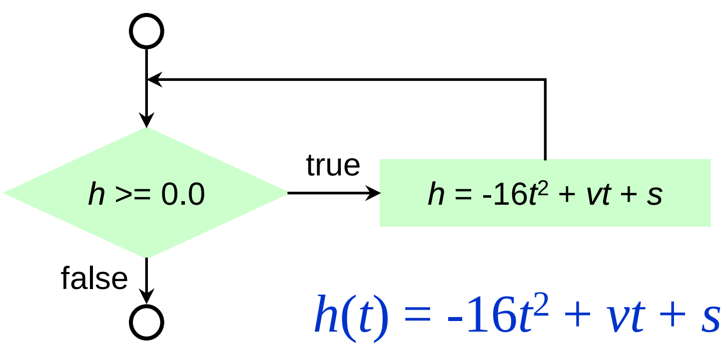


http://www.sim-summit.org/

Topic 1: Concepts and context

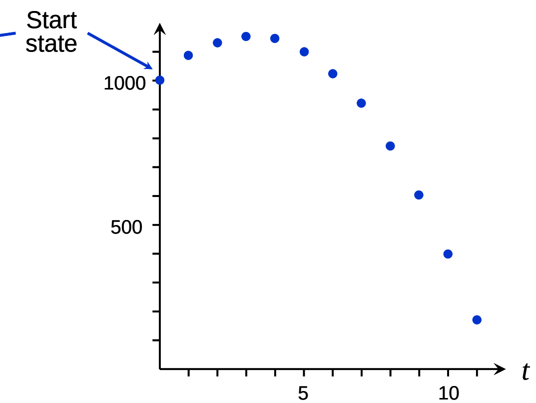
Essential terminology, foundational concepts, community consensus categorizations, and overarching modeling paradigms; history of the development and use of M&S.

1. Concepts and context
   - 1.1 Fundamental terms and concepts
   - 1.2 Categories and paradigms
   - 1.3 History of M&S



$$h(t) = -16t^2 + vt + s$$

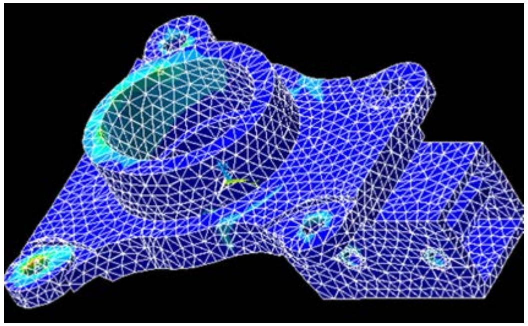
t	$h(t)$
0	1000
1	1084
2	1136
3	1156
4	1144
5	1100
6	1024
7	916
8	776
9	604
10	400
11	164



Topic 2: Applications of M&S

Important and cross-cutting M&S application types; modeling methods and organizing principles for each.

2. Applications of M&S
    - 2.1 Training
    - 2.2 Analysis
    - 2.3 Experimentation
    - 2.4 Acquisition
    - 2.5 Engineering
    - 2.6 Test and evaluation



Topic 3: Domains of use of M&S

Domains in which M&S has found wide use;
key modeling methods and applications for each.

3. Domains of use of M&S
   - 3.1 Combat and military
   - 3.2 Aerospace
   - 3.3 Medicine and health care
   - 3.4 Manufacturing and material handling
   - 3.5 Logistics and supply chain
   - 3.6 Transportation
   - 3.7 Computer and communications systems
   - 3.8 Environment and ecology
   - 3.9 Business
   - 3.10 Social science
   - 3.11 Energy
   - 3.12 Other domains of use

Topic 4: Modeling methods

Technical aspects of widely used modeling methods; characteristics and suitable applications for each.

4. Modeling methods
    - 4.1 Stochastic modeling
    - 4.2 Physics-based modeling
    - 4.3 Structural modeling
    - 4.4 Finite element modeling and computational fluid dynamics
    - 4.5 Monte Carlo simulation
    - 4.6 Discrete event simulation
    - 4.7 Continuous simulation
    - 4.8 Human behavior modeling
    - 4.9 Multi-resolution simulation
    - 4.10 Other modeling methods

Topic 5: Simulation implementation

Engineering principles and practices for developing and validating M&S systems; M&S standards; special models.

5. Simulation implementation
   - 5.1 Modeling and simulation life-cycle
   - 5.2 Modeling and simulation standards
   - 5.3 Development processes
   - 5.4 Conceptual modeling
   - 5.5 Specialized languages
   - 5.6 Verification, validation, and accreditation
   - 5.7 Distributed simulation and interoperability
   - 5.7 Virtual environments and virtual reality
   - 5.8 Human-computer interaction
   - 5.9 Semi-automated forces
   - 5.10 Stimulation

Topic 6: Supporting tools, techniques, and resources

Technical infrastructures, M&S resources, and organizations supporting the development and use of M&S.

6. Supporting tools, techniques, and resources
   - 6.1 Major simulation infrastructures
   - 6.2 M&S resource repositories
   - 6.3 M&S organizations

Topic 7: Business and management of M&S

Business of M&S and M&S as a business; professional conduct for M&S practitioners; M&S workforce.

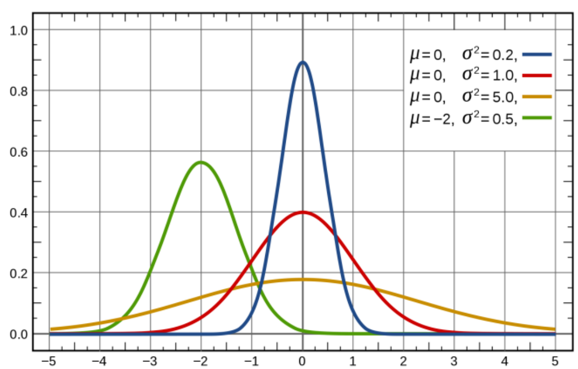
7. Business and management of M&S
   - 7.1 Ethics and principles for M&S practitioners
   - 7.2 Management of M&S projects and processes
   - 7.3 M&S workforce development *
   - 7.4 M&S business practice and economics *
   - 7.5 M&S industrial development *

* Sources sought for these subtopics.

Topic 8: Related communities of practice and disciplines

Non-M&S topics with which M&S professionals should have some familiarity.

8. Related communities of practice and disciplines
    - 8.1 Statistics and probability
    - 8.2 Mathematics
    - 8.3 Software engineering and development
    - 8.4 Systems science and engineering



$$R = 2.59 \times \sqrt[4]{\sigma \times \left(\frac{\log^{-1}\left(\frac{ERP_t}{10}\right)\log^{-1}\left(\frac{G_r}{10}\right)\log^{-1}\left(\frac{MDS_r}{10}\right)}{\log^{-1}\left(\frac{FEL_r}{10}\right)F_t^2} \right)}$$

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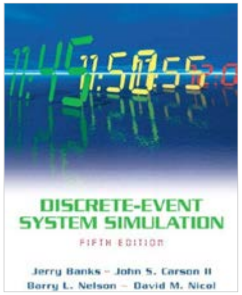
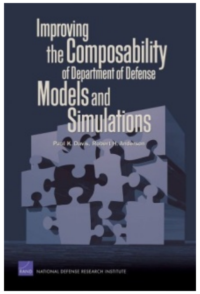
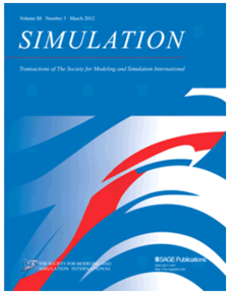
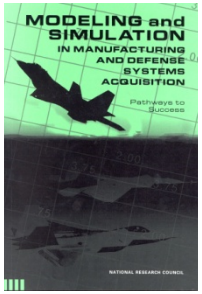
Question counts and sources

- Counts
  - Total: ~2000 new questions
  - Per subtopic: min ≥ 20, mean ~40, max > 100
- Sources
  - Each question directly based on specific source
  - Sources: published, peer-reviewed, publicly available
  - Yes: journal papers, conference papers, books
  - No: briefings, unpublished reports, Wikipedia
  - > 175 different sources
  - Source list available









Question format and metadata

- Format
  - ~75% multiple choice (one correct, three incorrect)
  - ~25% True–False
  - Diagrams, images, mathematical formulas used
- Question metadata
  - Question and answers
  - Unique question number
  - Source citation, including page number
  - Author
  - Subtopic
  - Certification type (User/Mgr, Dev/Tech, Core)
  - Difficulty (1–5)

Example question, with metadata

Question number	8.545
Question	Which of the following is *not* a use of simulation?
Correct answer	Justify decisions already made based other criteria
Incorrect answer	Describe and analyze the behavior of a system
Incorrect answer	Ask and answer “what if” questions about a system
Incorrect answer	Help in designing new systems
Type	Core
Difficulty	2 (Easy)
Topic	1.1 Fundamental terms and concepts
Source	J. Banks, “Principles of Simulation”, in J. Banks (Editor), *Handbook of Simulation: Principles, Methodology, Advances, Applications, and Practice*, John Wiley & Sons, New York NY, 1998, pp. 3-30.
Page number	3
Question author	M. Petty

Example question, with metadata

Question number	6.20
Question	In simulating a physical system governed by partial differential equations, __________ can be used to facilitate estimation of derivatives.
Correct answer	Fourier analysis
Incorrect answer	The Graham-Schmidt process
Incorrect answer	The downhill-simplex method
Incorrect answer	Gauss-Jordan elimination
Type	Developer/Technical
Difficulty	5 (Very difficult)
Topic	4.2 Physics-based modeling
Source	W. Kaplan, *Advanced Calculus, Fourth Edition*, Addison-Wesley, Redwood City CA, 1991
Page number	530
Question author	W. Colley

Example question, with metadata

Question number	9.78
Question	Which of the following terms best describes use of models and simulation by the military, for the purposes of obtaining insight into the cost and performance of military equipment?
Correct answer	Requirements and acquisition
Incorrect answer	Exploration of advanced technologies and concepts
Incorrect answer	Training
Incorrect answer	Geo-navigation
Type	User/Manager
Difficulty	3 (Moderate)
Topic	3.1 Combat and military
Source	R. D. Smith, *Military Simulations & Serious Games*, Modelbenders Press, Orlando FL, 2009.
Page number	38
Question author	S. Barbosa

Example question, with metadata

Question number	8.546
Question	True or False: Only systems that actually exist, as opposed to those that have been planned or designed but not implemented, can be simulated.
Correct answer	False
Incorrect answer	True
Type	Core
Difficulty	2 (Easy)
Topic	1.1 Fundamental terms and concepts
Source	J. Banks, “Principles of Simulation”, in J. Banks (Editor), *Handbook of Simulation: Principles, Methodology, Advances, Applications, and Practice*, John Wiley & Sons, New York NY, 1998, pp. 3-30.
Page number	4
Question author	M. Petty

Example question, with metadata

Question number	9.65
Question	Which of the following terms best describes the purpose of sensor footprint exaggeration in military simulations?
Correct answer	It ensures that detection calculations are carried out on all detectable objects between two time steps
Incorrect answer	It is used for marketing brochures
Incorrect answer	It compensates for hindrances to line-of-sight
Incorrect answer	It normalizes sensor footprints
Type	Developer/Technical
Difficulty	4 (Difficult)
Topic	3.1 Combat and military
Source	R. D. Smith, *Military Simulations & Serious Games*, Modelbenders Press, Orlando FL, 2009.
Page number	357
Question author	S. Barbosa

Example question, with metadata

Question number	8.10
Question	Which of the following terms is best defined as “the process of determining whether an implemented model is consistent with its specification”?
Correct answer	Verification
Incorrect answer	Validation
Incorrect answer	Accreditation
Incorrect answer	Calibration
Type	Core
Difficulty	2 (Easy)
Topic	5.6 Verification, validation, and accreditation
Source	M. D. Petty, “Verification, Validation, and Accreditation”, in J. A. Sokolowski and C. A. Banks, *Modeling and Simulation Fundamentals: Theoretical Underpinnings and Practical Domains*, John Wiley and Sons, Hoboken NJ, 2010, pp. 325-372.
Page number	330
Question author	M. Petty

Examination instances

- Examination instance generation
  - Unique instance generated for each candidate
  - Candidate selects certification type
  - Candidate selects excluded subtopics
  - Questions selected randomly within selections
- Examination instance
  - 100 questions
  - From selected certification type (U/M, D/T) or Core
  - At least 10 questions per topic
  - No questions from excluded subtopics
  - Mean difficulty minimum 2.5, maximum 3.5

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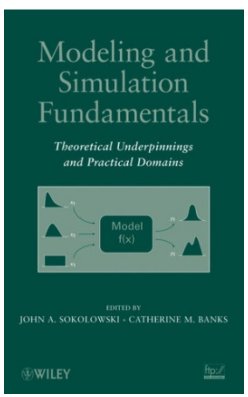
Certification requirements

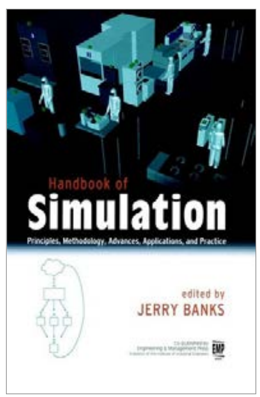
- Education, work experience, and examination
- Letters of recommendation (3)
- Signed ethics statement

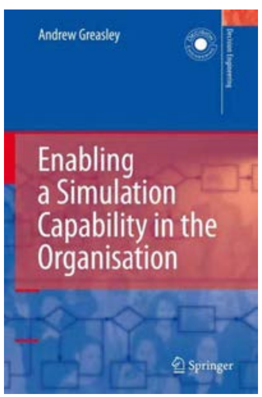
Education	Related work experience	CMSP exam
A.S. degree	8 years	Passing grade
B.S. degree	6 years	Passing grade
M.S. degree	5 years	Passing grade
Ph.D. degree	3 years	Passing grade

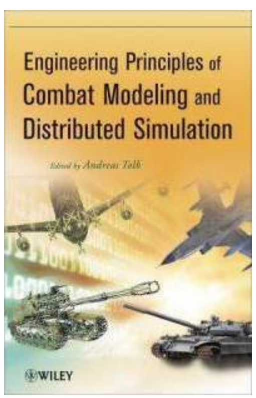
Preparing for the CMSP exam

- CMSP exam intentionally not “crammable”
  - Questions from a large number of sources
  - Passing requires broad knowledge and experience
- Preparing for the exam
  - Attend CMSP prep course: UCF, AEgis, UAH
  - Secure access to sources for “take home” period
  - Read sources



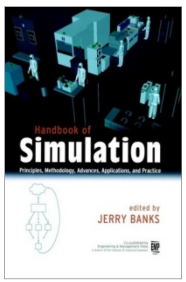






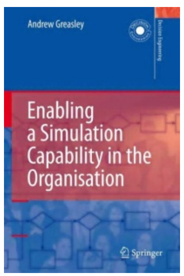
Key sources

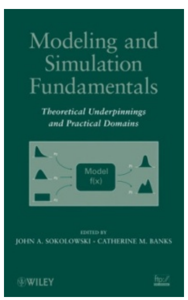
- More than 175 different sources for questions …
- … but four “key” sources should be available before attempting the exam



[BanksJ, 1998] J. Banks (Editor), *Handbook of Simulation: Principles, Methodology, Advances, Applications, and Practice*, John Wiley & Sons, New York NY, 1998.

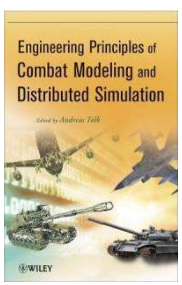
[Greasley, 1998] A. Greasley, *Enabling a Simulation Capability in the Organization*, Springer-Verlag, London UK, 1998.





[Sokolowski, 2010] J. A. Sokolowski and C. M. Banks (Editors), *Modeling and Simulation Fundamentals: Theoretical Underpinnings and Practical Domains*, John Wiley and Sons, Hoboken NJ, 2010.

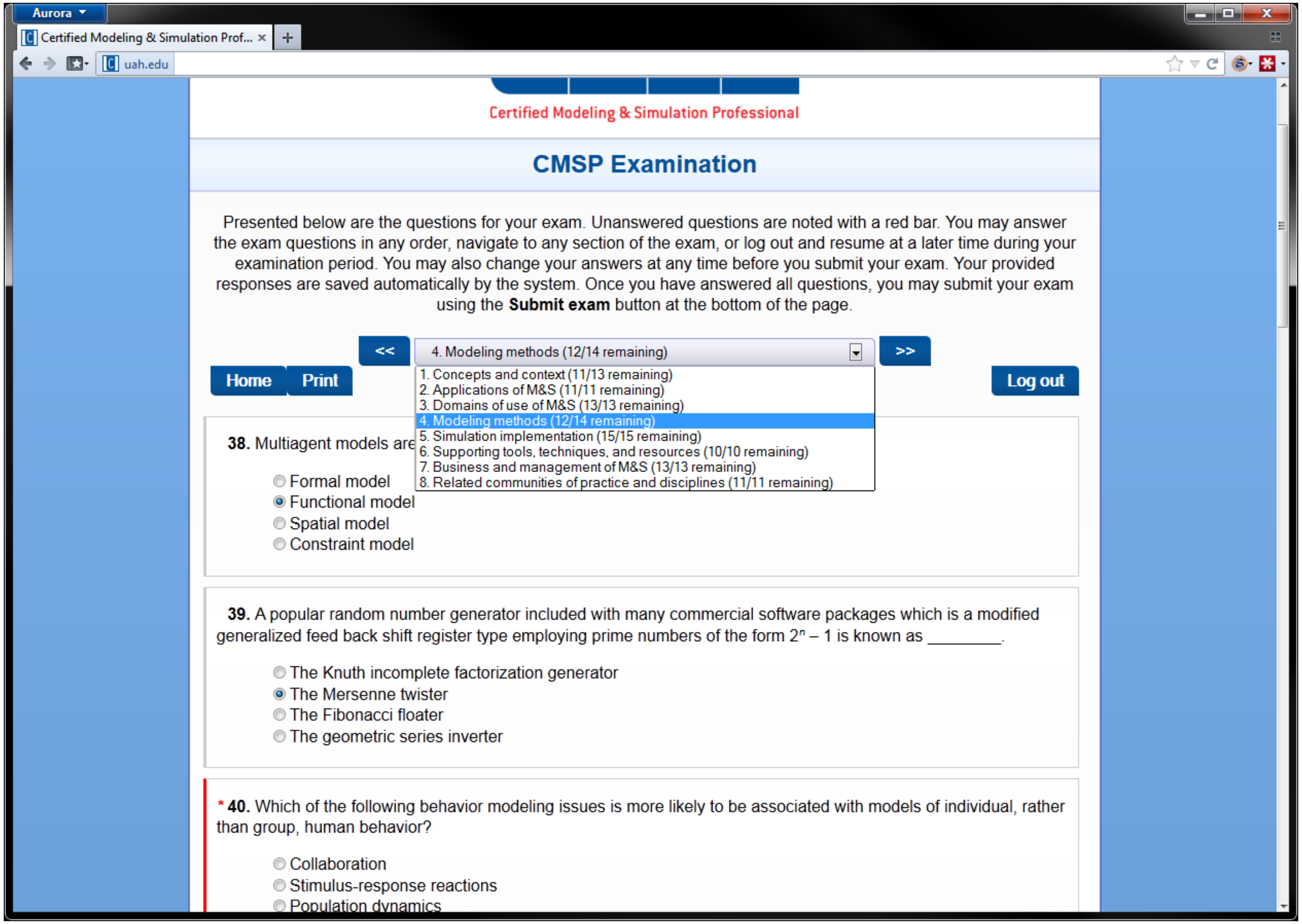
[Tolk, 2012] A. Tolk (Editor), *Engineering Principles of Combat Modeling and Distributed Simulation*, John Wiley & Sons, Hoboken NJ, 2012.



Examination delivery process

- Candidate applies and pays fee ($250)
- Administrator creates account for candidate
- Candidate selects certification type, exclusions
- System generates examination instance
- System give candidate web access to instance
- Candidate answers 100 questions over 14 days
- Candidate submits completed examination
- System scores examination
- Administrator notifies candidate of result

Examination web site



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CMSP recertification

- CMSP designees must recertify every 4 years
  - Recertification application and fee
  - Formal resubscription to Simulationist Code of Ethics
  - Minimum 275 recertification units
- Recertification units
  - Employment
  - Publications
  - Professional society participation
  - Education
  - Conference participation
  - Continuing education units

Part 2: Content survey

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- Modeling methods
  - Survey of modeling methods
  - Discrete event simulation
  - Monte Carlo simulation
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Concepts of model and simulation

- Model: representation of something else
- Simulation: executing a model over time

$$R = 2.59 \times \sqrt[4]{\sigma \times \left(\frac{\log^{-1}\left(\frac{ERP_t}{10}\right) \log^{-1}\left(\frac{G_r}{10}\right) \log^{-1}\left(\frac{MDS_r}{10}\right)}{\log^{-1}\left(\frac{FEL_r}{10}\right) F_t^2} \right)}$$

Model

Simulation

Both

Definition: Model

Model. A physical, mathematical, or otherwise logical representation of a system, entity, phenomenon, or process. [DOD, 2011]

To an observer B, an object A^* is a model of an object A to the extent that B can use A^* to answer questions that interest him about A. [Minsky, 1965]

- Representation of something else, often a “real-world” system
- Some aspects of the modeled system are represented in the model, others not

Example: Model

Equation describing vertical height
of an object moving under gravity.

$h(t) = -4.9t^2 + vt + s$

h = height (meters)
t = time in motion (seconds)
v = initial velocity (meters per second, + is up)
s = initial height (meters)

Note that at $t = 0$, $h = s$, as expected.

Definition: Simulation

Simulation. [Executing] a model over time. [DOD, 2011]

The imitation of the operation of a real-world process or system over time. [BanksJ, 1998]

A technique for testing, analysis, or training in which real world systems are used, or where a model reproduces real world and conceptual systems. [DOD, 1996]

Alternative uses of the term

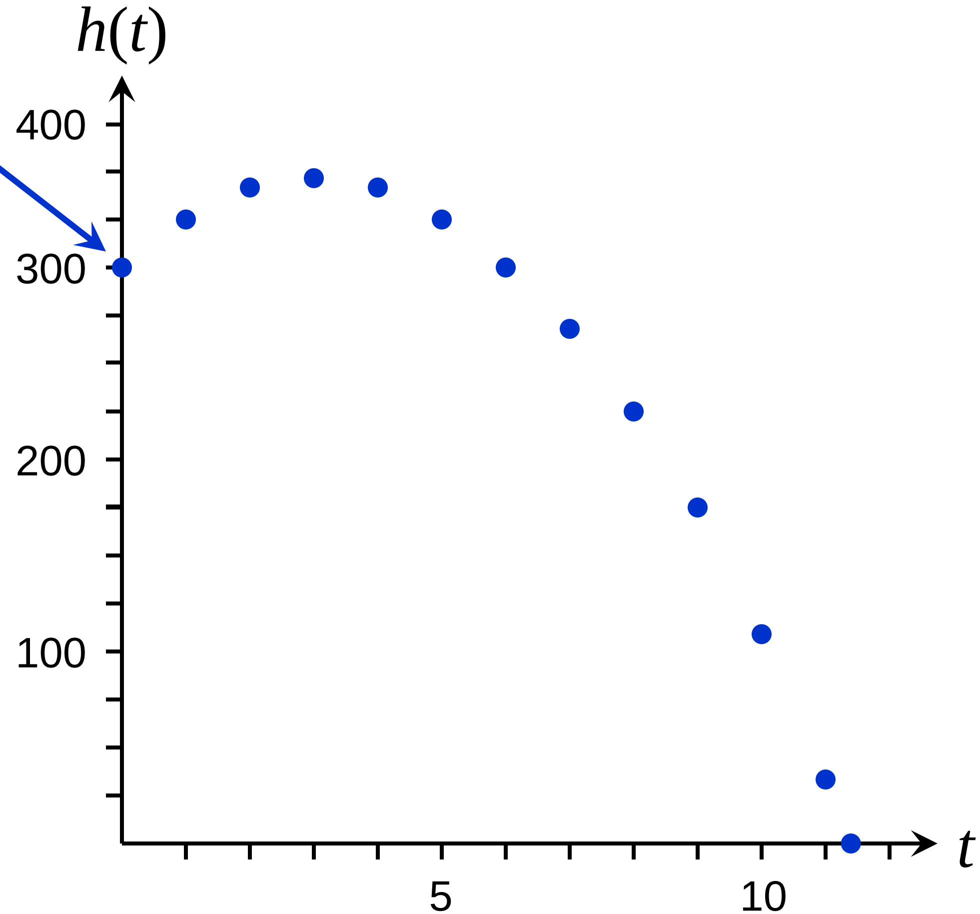
- A large composite model (avoid)
- Software implementation of a model (avoid)
- Application of a model to solve a problem [Velten, 2009]
- An experiment performed on a model [Fritzson, 2004]
- Several others [Ören, 2009] [BanksC, 2010]

Example: Simulation

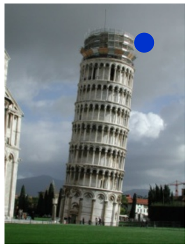
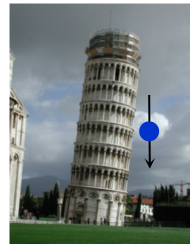
Model: $h(t) = -4.9t^2 + vt + s$ Data: $v = 30$, $s = 300$

t	$h(t)$
0	300.0
1	325.1
2	340.4
3	345.9
4	341.6
5	327.5
6	303.6
7	269.9
8	226.4
9	173.1
10	110.0
11	37.1
11.46	0

Start state



Simulation vs reality


Real-world system in start state

Time

Physics

Real-world system in end state

Modeling

Initialization

Interpretation

Validation

Model in start state

Simulation

Computation

Model in end state

$$h(t) = -4.9t^2 + vt + s$$
$$300 = -4.9(0)^2 + 30(0) + 300$$

$$h(t) = -4.9t^2 + vt + s$$
$$0 = -4.9(11.46)^2 + 30(11.46) + 300$$

Definitions: Simuland and referent

Simuland. The subject of a model or simulation.

- A real-world (or notional) system of interest
- Object, phenomenon, or process to be simulated

Referent. The body of knowledge available to a modeler regarding a simuland.

- Quantitative and formal,
  e.g. physics equations for aircraft flight dynamics
- Qualitative and informal,
  e.g., pilot’s expectation of buffet before stall

Definition: Intended use

Intended use. The purpose for or function of a model; what the model will be used for; the problem to be addressed by the model. [DOD, 2012]

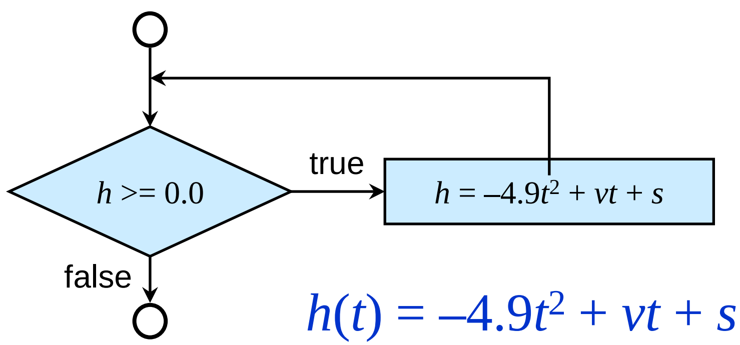
Characteristics [Piersall, 2014]

- "Not a capability, solution, or implementation"
- Expressed from the perspective of the user
- Should be formally specified

> "Any attempt to suppress the role of the intentions of the investigator, *B*, leads to circular definitions or to ambiguities about essential features ..." [Minsky, 1965]

> "Modeling and simulation is always goal-driven, … , we should know the purpose of our potential model before we sit down to create it." [Cellier, 1991]

Definitions: Conceptual and executable models



$$h(t) = -4.9t^2 + vt + s$$

Conceptual model [BanksC, 2010]

- Simuland components, structure
- Aspects of simuland to model
- Implementation specifications
- Use cases
- Assumptions
- Initial model parameter values

```
/* Height of an object moving in gravity.  */
/* Initial velocity v and height s constants. */
main()
{
  float h, v = 30.0, s = 300.0;
  int t;
  for (t = 0, h = s; h >= 0.0; t++)
  {
    h = (-4.9 * t * t) + (v * t) + s;
    printf("Height at time %d = %f\n", t, h);
  }
}
```

Executable model

- Computer software
- Implemented conceptual model [DOD, 2011]
- AKA computational model [Waltz, 2010] [DOD, 2011]

Definition: Abstraction

Abstraction. Intentional omission of aspects of the simuland considered negligible or irrelevant.

Abstraction may be motivated by …

- Cost; reduce implementation and testing resources by omitting simuland aspects not need for application
- Execution speed; don’t compute details or effects that are negligible
- Understanding; omit aspects of simuland not understood well enough to model accurately

“Modeling and simulation aims at simplification,
rather than at a useless production of complex copies of a complex reality. …
The best model is the simplest one that still serves its purpose.” [Velten, 2009]

Examples: Abstraction

Simuland
P-51D Mustang

Models

Physical model
Represents:
Appearance
Abstracts:
Size

Physical model
Represents:
Aerodynamics
Omits:
Ailerons

[Bollay, 1951]

Physical model
Represents:
Flight
Omits:
Appearance

Models

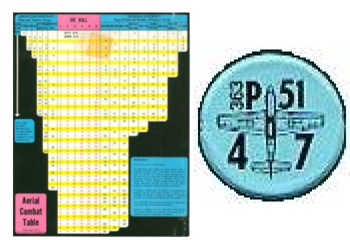
Visual model
Represents:
Appearance
Omits:
Flight

Functional model
Represents:
Aerodynamics
Omits:
Appearance

$$\iiint_{\Omega} \mathbf{P}\frac{\partial \mathbf{W}}{\partial t}\,dV + \iint_{\partial\Omega} \overline{\overline{\mathbf{H}}} \bullet \mathbf{n}\,dS = \iint_{\partial\Omega} \overline{\overline{\mathbf{H}_v}} \bullet \mathbf{n}\,dS$$

[Han, 2012]

Aggregate model
Represents:
Combat
Abstracts:
Pilot skill



Definition: Validity

Validity. Accuracy of model's representation or simulation's results. AKA fidelity.

"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..."
[Gross, 1999]

Validity is relative to …

- Simuland: How closely do the simulation results match the simuland's behavior?
- Intended use: How much validity is needed for the model's intended use?

Definition: Resolution

Resolution. The degree of detail with which the real-world is simulated. More detail is higher resolution. AKA granularity.

Examples (low to high resolution)

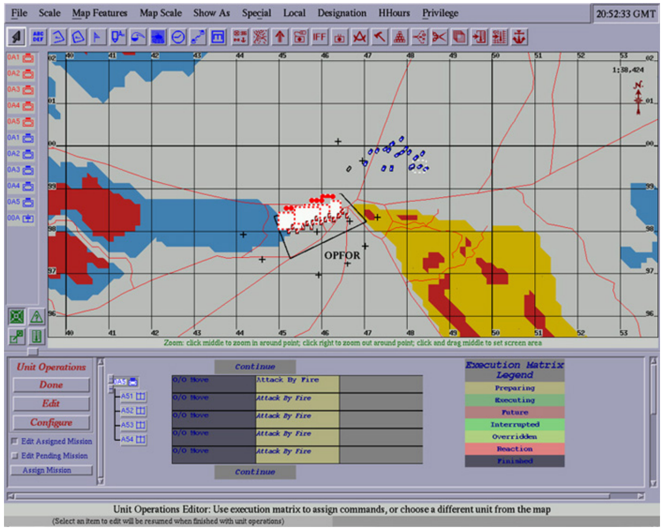
- Simulate fighter squadron as a whole
  - Squadron capabilities, strength represented abstractly
- Simulate individual aircraft
  - Separate model(s) for each individual aircraft
  - Aircraft capabilities represented abstractly
- Simulate sensor and weapons systems
  - Separate model(s) for each system on each aircraft

Definition: Scale

Scale. Size of the overall scenario or event the simulation represents. AKA level.

Typical scales for military simulations

- Engineering, Component
  - System or subsystem of a single entity
- Engagement, Platform
  - 1-v-1 to many-v-many
- Mission, Battle
  - 10s to 1000s of entities
- Theater, Campaign
  - 10000s of entities



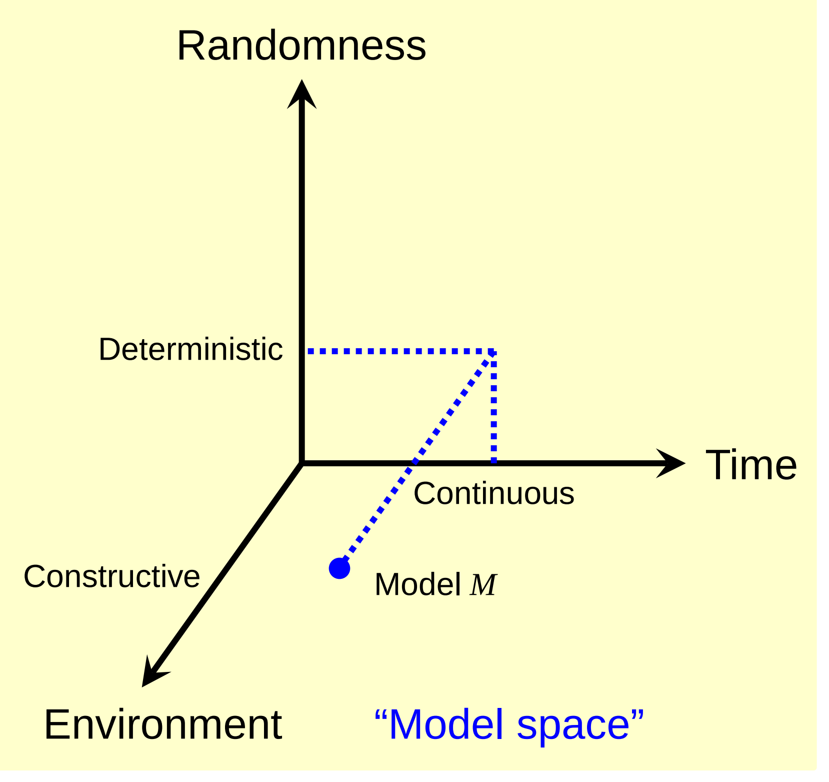
OneSAF Testbed

Part 2: Content survey

- Definitions and concepts
  - M&S terms and attributes
  - M&S categories
- Modeling methods
  - Survey of modeling methods
  - Discrete event simulation
  - Monte Carlo simulation
- Special topics
  - Verification, validation, and accreditation
  - Distributed simulation

Different M&S categories

- Application type
  - Training, Analysis, Experimentation, Engineering, Acquisition, Entertainment
- Randomness
  - Deterministic, Stochastic
- Time
  - Discrete, Continuous
- Environment
  - Live, Virtual, Constructive
- Modeling method
  - Many; surveyed later



Definition: Training

Training. M&S used to produce learning in a user or participant.

- Realistic enough to produce useful skills or knowledge
- Safer, more forgiving of mistakes
- Encounter unusual and/or dangerous situations

P-8 Poseidon flight simulator [Spenser, 2010]

Definition: Analysis

Analysis. M&S used to predict, test, or evaluate a real or notional system or idea.

- Used to answer questions
- Repeatability often desirable
  - Avoid confounding variability
- Careful experimental design
  - Trials planned in advance to cover cases
  - Multiple trials for statistical significance

JCATS, Wurtsmith AFB

Definition: Experimentation

Experimentation. M&S used to explore design or solution spaces, or to gain insight into an incompletely understood situation. [Ceranowicz, 1999]

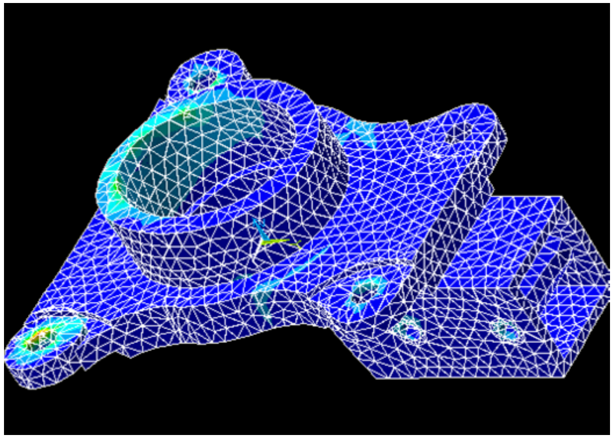
[An] iterative process of collecting, developing and exploring concepts to identify and recommend the best value-added solutions for changes in the doctrine, organization, training, material, leadership and people required to achieve significant advances in future joint operational capabilities. [Helfinstine, 2001]

- Simulation used to "explore" possibilities
- Less "controlled" than analysis
  - Later trials may be determined by earlier
  - Statistical significance may not be important

Definition: Engineering

Engineering. M&S used to develop, analyze, or test an engineering design.

- Model artificial systems and components
- Models physics-based, no “behavior”
- No virtual environment or simulators
- User not expected to benefit from experience of execution
- Primary goal: informative result



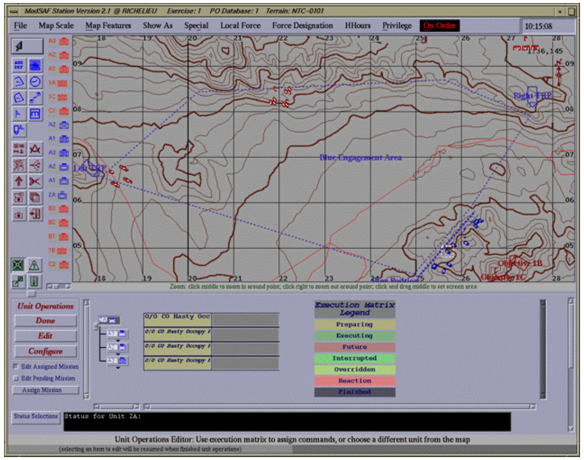
FEM of a bracket

Definition: Acquisition

Acquisition. M&S used to specify, design, develop, and acquire new systems.

- Simulation used to acquire systems
  - Effectiveness and selection: "Build the right thing"
  - Engineering and production: "Build the thing right"
- Goal: save lives, money, time

AAAV



ModSAF

Definition: Entertainment

Entertainment. M&S used to entertain or amuse a user or participant.

- Engaging gameplay and/or goals
- Place user in situation, place, or activity he/she may not have access to in reality
- Realism secondary to user enjoyment

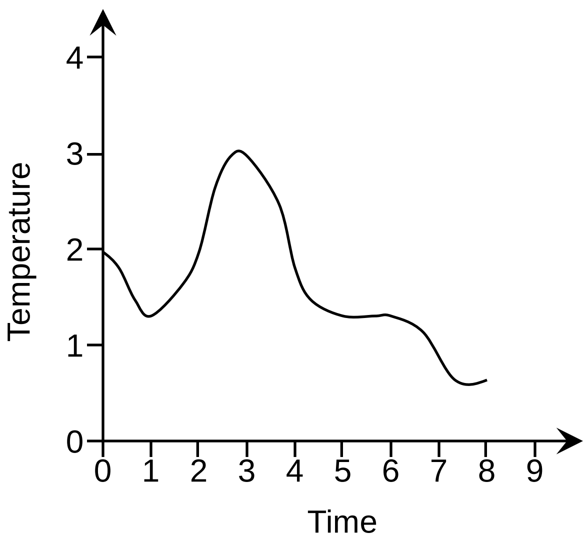
Combat Flight Simulator 3

World of Warcraft

Definition: Continuous

Continuous model. Model where state variables can change (pseudo-)continuously over time. Typically time advances in small fixed time steps. AKA “time-stepped”. [BanksJ, 2010]

Continuous simulation. Simulation using continuous models.



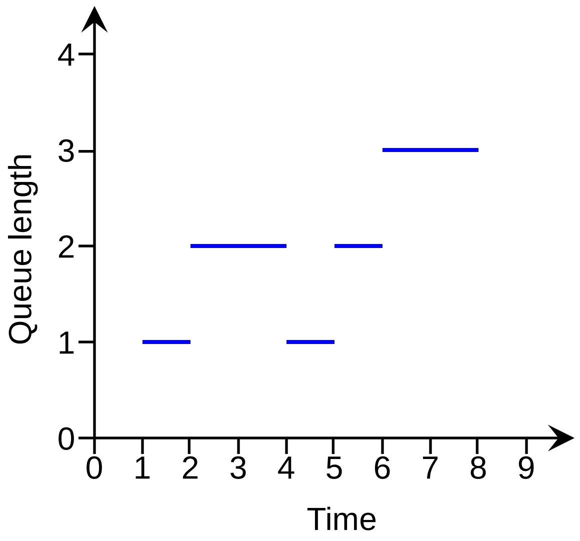
[BanksJ, 2010]

```
t = start_time
while t < end_time
   t = t + Δt
   calculate simulation state at t
endwhile
```

Definition: Discrete

Discrete model. Model where model state variables change only at a discrete set of points in time (“events”). AKA “event-driven”. [BanksJ, 2010]

Discrete event simulation. Simulation using discrete models and event handling.



[BanksJ, 2010]

```
t = 0
while t < end_time
   t = time of next event e
   process event e
   possibly schedule future events
endwhile
```

Definition: Live

Live. Simulation involving real people operating real systems. [DOD, 2011]

- Real systems
- Systems operated by participants
- Participant experience close to reality
- Instrumentation substitutes for simuland aspects
  - e.g., weapon firings or impacts
  - e.g., spacecraft launch
- Primary goal: useful experience
- Typical application: training

Example: Hazmat exercise

- Live training for local emergency responders
- Practice hazardous material response, cleanup
- Simulation
  - Harmless or noxious hazmat surrogate
  - Roleplayers act as victims
  - Real equipment used

Triage

Decontamination

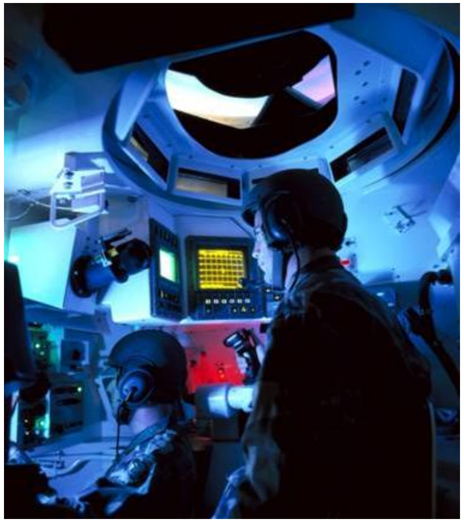
Definition: Virtual

Virtual. Simulation involving real people operating simulated systems. [DOD, 2011]

- Simulators and virtual environment
- Simulators operated by participants
- Participant experience usefully realistic
- Important simuland aspects modeled
- Participants exercise motor control skills, decision skills, or communication skills [DOD, 2011]
- Primary goal: useful experience
- Typical application: training

Example: Close Combat Tactical Trainer

- Virtual simulators
  - Trainees in vehicle simulators
  - Computer generated battlefield
- Combat training
  - Trains team tactics
  - Platoon to battalion units



M1 simulator, interior

M1 simulator, exterior

Virtual battlefield

Definition: Constructive

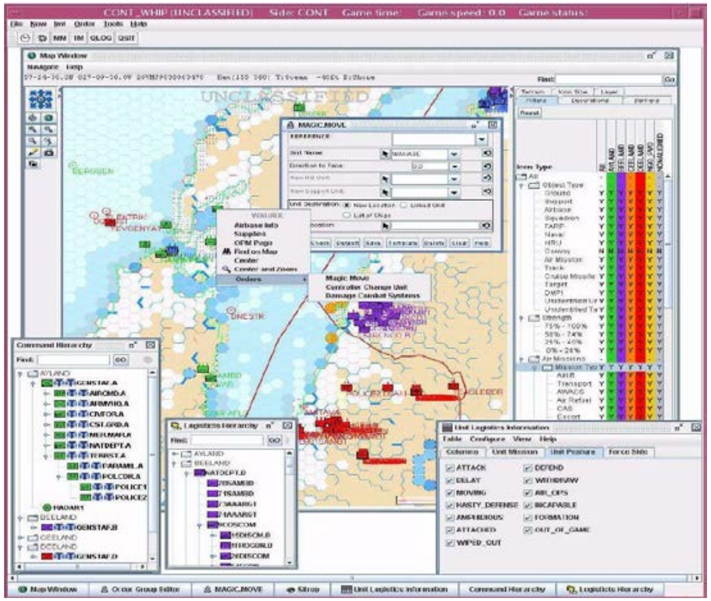
Constructive. Simulation involving simulated people operating simulated systems. Real people make inputs to such simulations, but are not involved in determining the outcomes. [DOD, 2011]

- No real systems, virtual environment, or simulators
- Important simuland aspects modeled
- Operator and model control simuland behavior
- Operator not expected to benefit from use
- Primary goal: useful result
- Typical applications: analysis, experimentation

Example: Joint Theater Level Simulation

[Kang, 1998] [JFCOM, 2007]

- "Wargame" style constructive simulation
- JTLS models
  - Hexagonal terrain
  - Military units (air, ground, naval)
  - Movement, sensing, logistics: abstract mathematical models
  - Combat: Lanchester equations
- Applications
  - Training (exercise driver)
  - Analysis



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Definition: Physical model

Physical model. A physical object which models physical aspects of the simuland. [Haefner, 2005]

AKA surrogate.

Physical models are

- Typically used in live simulation
- Usually not a perfect replica, but "close enough"
- Often motivated by
  - Safety; use of simuland dangerous
  - Cost; use of simuland costly
  - Non-availability; simuland not available for use

Example: Harvard glass flowers



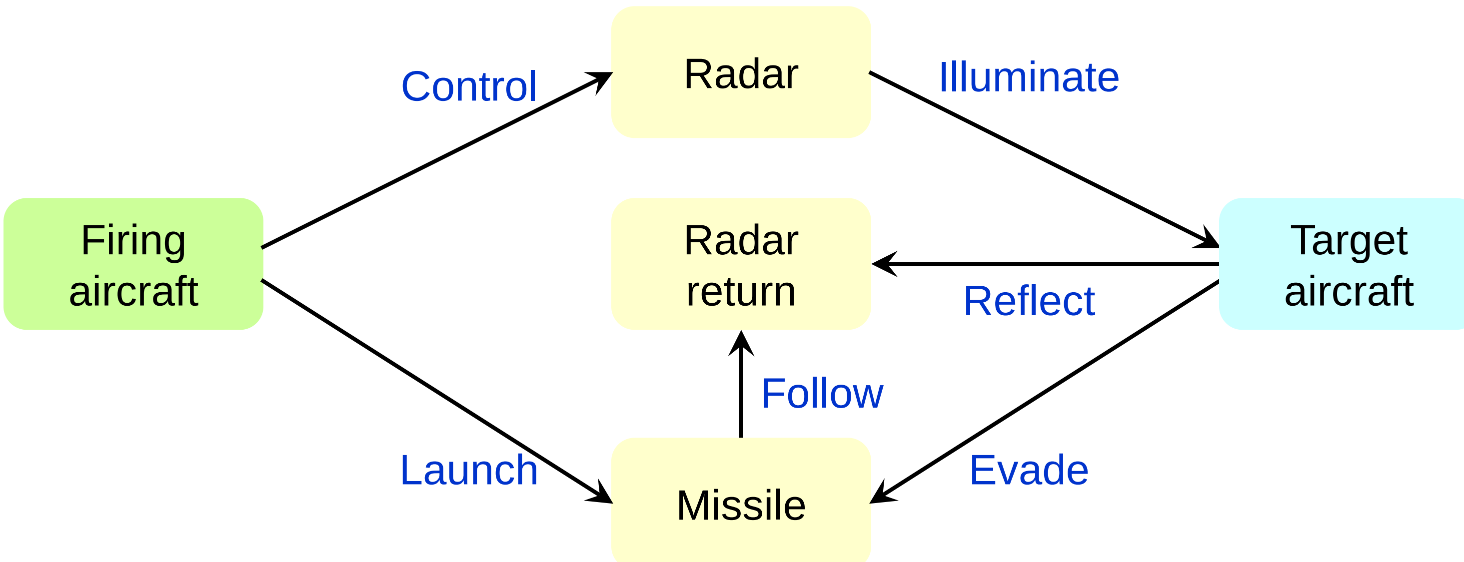
- Glass models of plants
- Made 1887–1936 by Leopold and Rudolf Blaschka
- 3000 models, 847 species
- Used in botany instruction
- Always available, regardless of season

Definition: Conceptual model

Conceptual model. Representation, in any of a variety of narrative or graphical means, of the elements, relationships, and causal relationships of a simuland and its context. Adapted from [Waltz, 2010]

- Possible forms: Text, photographs, sketches, equations, concept maps, tables, algorithms, data, UML diagrams
- Uses
  - Communicate among SMEs, modelers, users, managers, and customers
  - Define what will be represented and omitted in implemented executable model [Petty, 2010]
  - Document model assumptions
  - Support comparison of implemented model capabilities to stated requirements [Petty, 2010]

Example: Concept map



- Semi-active radar homing air-to-air missile
- Boxes = objects, arrows = interactions
- Additional components, interactions may be added

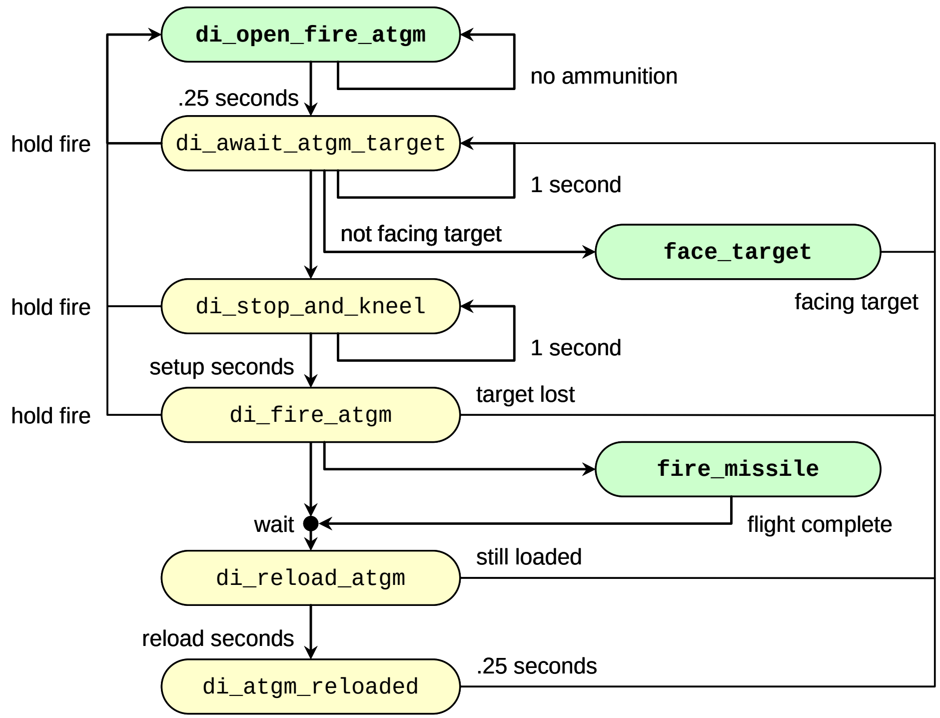
Definition: Declarative models

- Description [Fishwick, 1995]
  - Model represents qualitatively distinct simuland states
  - Simulation traces sequence of states over time
  - State transitions conditional (inputs or events), or stochastic (probability distributions)
  - Processes, phenomena often modeled stochastically
- Forms
  - Finite state automata
  - Markov chains
  - Queueing models, e.g., discrete event simulation
  - Formal models

Example: Finite state machine

- Description
  - Structured as directed graph;
    vertices are states, edges are transitions
  - Uniform or continuing activities are states
  - Changes from one activity or another are transitions
  - Transitions triggered by conditions (input, event, time)
  - Concept adapted from theoretical computer science
  - AKA finite state automata (FSA)
- Modes of use
  - FSM is complete model
  - FSM is organizing framework for other models

Example: Dismounted infantry ATGM FSM



[Petty, 2009a]

- Example of FSM used to organize other models
- Each state’s action implemented as source code

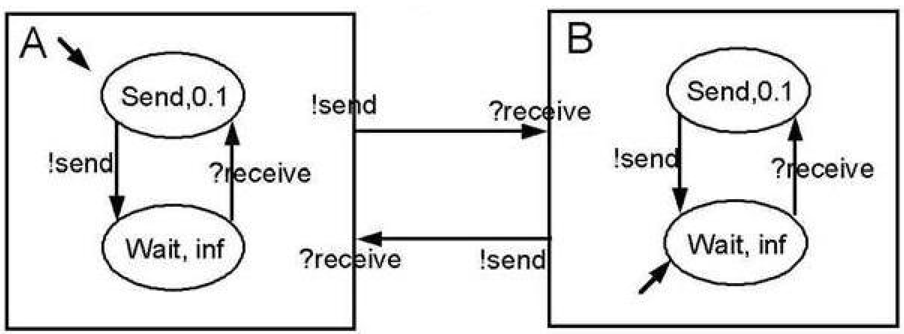
Definition: Formal models

- Description
  - Modeling notation or language defined mathematically
  - Precise, unambiguous syntax and semantics
  - Allows proofs of desirable model properties,
    e.g., syntactic interoperability, state reachability
  - Potentially amenable to automated analyses
  - Theoretically equivalent to programming language
- Modes of use
  - Use formal model as design specification
    for subsequent implementation as software
  - Execute formal model directly using interpreter

Example: Discrete Event System Specification

[Zeigler, 2000]

- DEVS: Well known formal modeling notation
- Research literature of example applications



The atomic DEVS model for player A of Fig. 1 is given Player= $<X,Y,S,s_0,ta,\delta_{ext},\delta_{int},\lambda>$ such that

$X = \{?receive\}$

$Y = \{!send\}$

$S = \{(d,\sigma)|d \in \{Wait, Send\}, \sigma \in \mathbb{T}^\infty\}$ and $s_0 = (Send, 0.1)$

$ta(s) = \sigma$ for all $s \in S$

$\delta_{ext}(((Wait,\sigma),t_e),?receive) = (Send, 0.1)$

$\delta_{ext}(((Send,\sigma),t_e),?receive) = (Send, \sigma - t_e)$

$\delta_{int}(Send,\sigma) = (Wait,\infty), \delta_{int}(Wait,\sigma) = (Send, 0.1)$

$\lambda(Send,\sigma) = !send, \lambda(Wait,\sigma) = \phi$

Both Player A and Player B are deterministic DEVS models.

DEVS model of ping-pong rally
[Wikipedia, 2011]

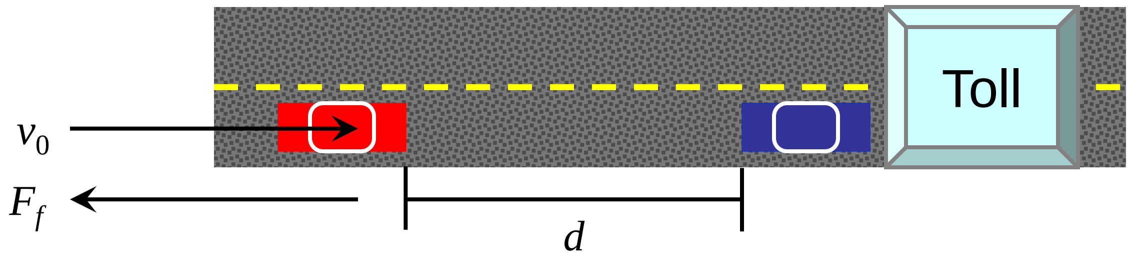
Definition: Functional models

- Description
  - Model represents dynamic physical processes and phenomena of simuland and context
  - Often consists of directionally-connected equations
  - Equations based on physics, hence functional models AKA physics-based
  - Often differential equations, or discretized versions
  - May be directly solvable (AKA “analytic”) or may require numerical approximation (AKA “numeric”)
  - Methods for latter exist, e.g., Runge-Kutta [Colley, 2010]
- Forms
  - Direct implementation as source code
  - Block diagrams in modeling environment

Example: Deceleration

Auto deceleration at toll booth

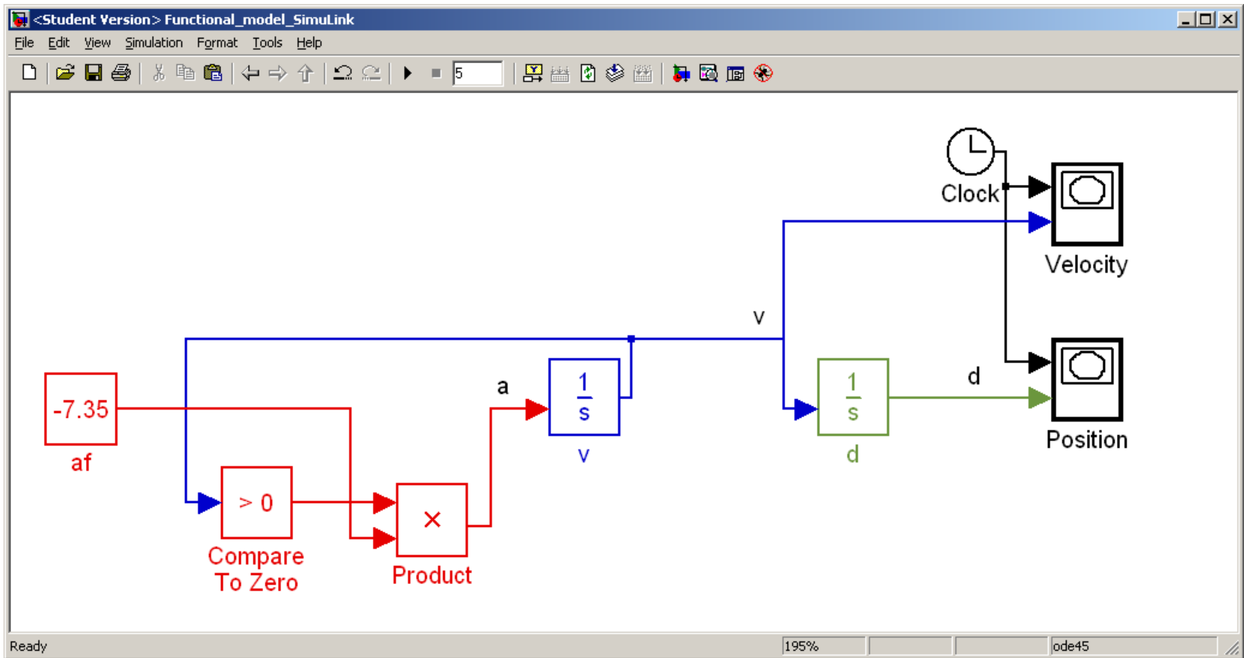
- Is there sufficient stopping distance in toll booth ramp?
- Model with physics equations, modeling environment



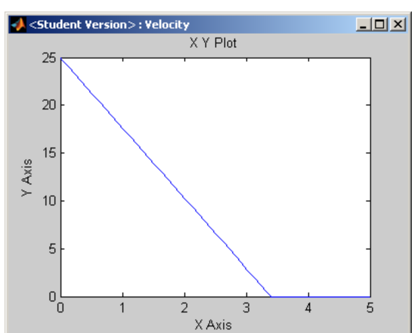
[McKenzie, 2010]

$F = ma$	Newton's second law	$a = dv/dt$	Acceleration
$F_f = ma_f$	f denotes friction	$v = dx/dt$	Velocity
$F_f = m\mu g$	$a_f = m\mu g$ [McKenzie, 2010]		
$ma_f = \mu mg$	Algebra		
$a_f = \mu g$	Algebra		

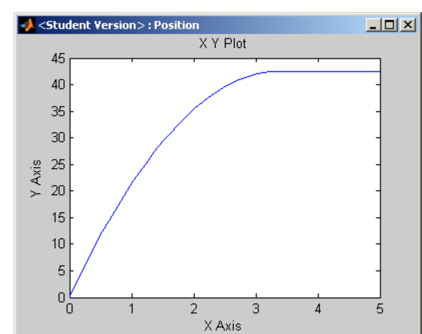
Example: Deceleration implementation



Matlab model



X Axis: Time
Y Axis: Velocity



X Axis: Time
Y Axis: Distance

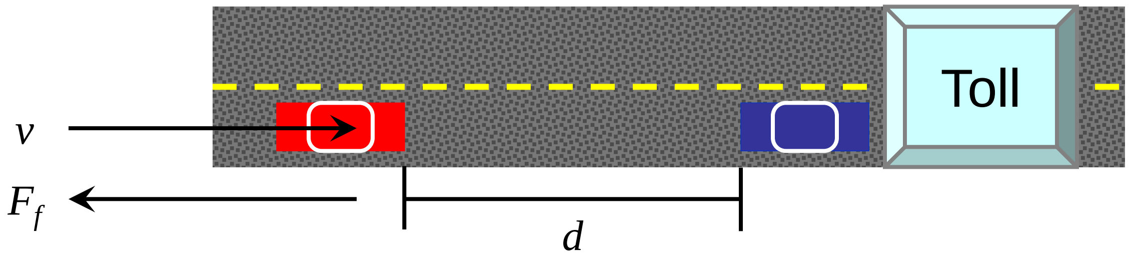
Adapted from [McKenzie, 2010]

Definition: Constraint models

- Description
  - Similar to functional models
  - No explicit directionality of connections, rather balancing of quantities or relationships
  - Often physics-based equations or components
- Forms
  - Direct implementation as source code
  - Block diagrams in modeling environment

Example: Stopping distance

- How much distance is required to stop for given speed?



[McKenzie, 2010]

$F_f = m\mu g$	Friction force
$\frac{1}{2}mv^2$	Car kinetic energy
$\frac{1}{2}mv^2 = F_f d$	To stop, kinetic energy equals friction over distance
$\frac{1}{2}mv^2 - \mu mgd = 0$	Algebra
$d = \frac{1}{2}v^2/\mu g$	Solve for distance; constraint model

Velocity mph	Velocity m/s	Stopping distance
20	8.9408	5.438
30	13.4112	12.235
40	17.8816	21.752
50	22.3520	33.987
55	24.5872	41.125
60	26.8224	48.942
70	31.2928	66.615

Stopping distance, given speed

Stopping distance	Velocity m/s	Velocity mph
10	12.124	27.121
20	17.146	38.355
30	21.000	46.976
40	24.249	54.243
50	27.111	60.645
60	29.698	66.434
70	32.078	71.757

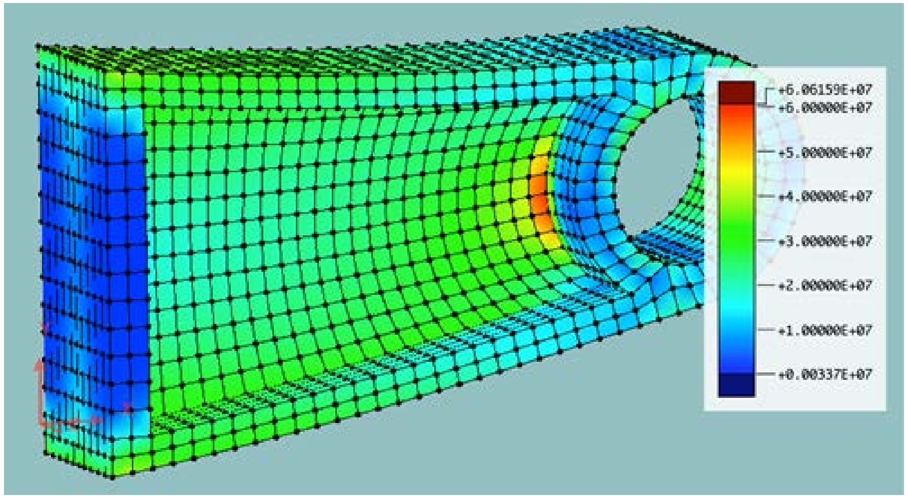
Speed, given stopping distance

Definition: Spatial models

- Description
  - Simuland, or space occupied by simuland, partitioned into a large number of spatial elements
  - Model state of simuland at each element, or model entities located within the elements
  - Entities/elements treated in “regularized manner”, i.e., update rules for each element often identical
  - State or activity of each entity/element often depends on neighboring entities/elements
- Forms
  - Direct implementation as source code
  - Dedicated spatial modeling tools

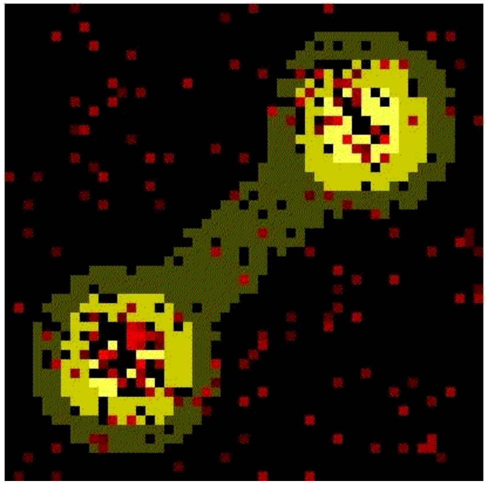
Example: Finite element modeling

- Simuland represented by "mesh" of nodes (elements) and connecting edges (neighboring elements)
- Nodes' states modeled with physics equations
- State computations iterated over successive time steps
- Each time step, each node's state calculated based on
  - Length of time step
  - Neighbors' states

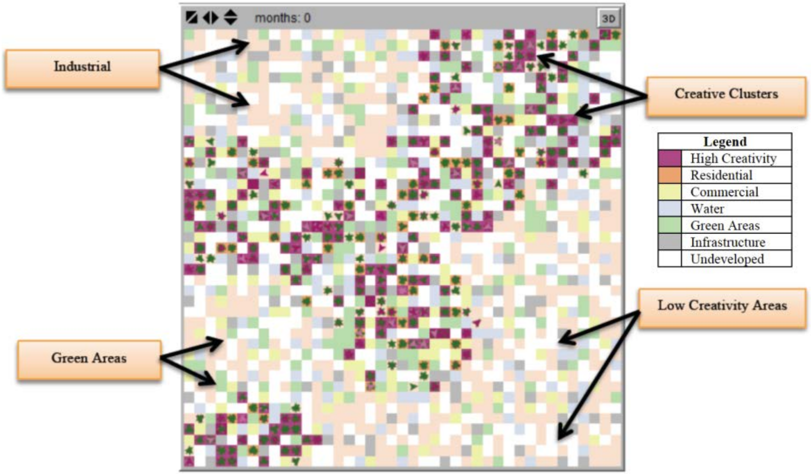


Example: Agent based models

- Individual entities ("agents") focus of model
- Agents may occupy, move between elements
- Agents interact with each other and environment according to behavior rules and parameters
- Complex behavior emerges from interaction
- Widely varying in details, sophistication



Sugarscape [Epstein, 1996]



Creative City [Malik, 2015]

Definition: Visual models

Visual model. A model of the appearance of an object, perhaps in different variations.

Visual models
- Often based on polygons (shape) and textures (colors applied to polygons)
- May or may not be specific to a particular image generator
- Realism of image not related to validity of underlying physics or behavior

Example: Aircraft visual models

Personal computer flight simulation game

Microsoft® *CFS 3*, 1920x1200 pixels

P-38J
Note polygonalization in model

P-38L
Same polygons, different textures

Definition: Data-based models

Data-based model. A model based on data (rather than equations, blocks, or logic) that describe the represented aspects of the simuland.

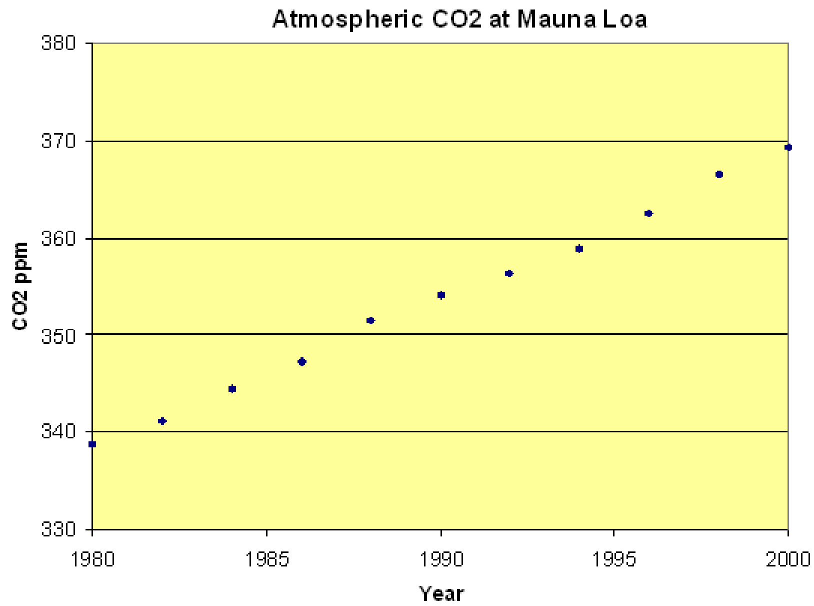
AKA empirical [Waltz, 2010], phenomenological [Velten, 2009], data-driven [Velten, 2009], statistical [Velten, 2009]

- Model not directly based on physics equations
- Data collected (or generated) in advance
- Examples: probability distribution models, linear regression models

Example: Atmospheric CO_2

Model based on observational data

Year	CO2 ppm
1980	338.7
1982	341.1
1984	344.4
1986	347.2
1988	351.5
1990	354.2
1992	356.4
1994	358.9
1996	362.6
1998	366.6
2000	369.4
2002	372.9



$\sum x = 23{,}892$

$\sum y = 4{,}263.9$

$\sum x^2 = 47{,}569{,}544$

$\sum y^2 = 1{,}516{,}451.25$

$\sum xy = 8{,}490{,}312.6$

$\bar{x} = 1991$

$\bar{y} = 355.33$

$$\text{Slope} \quad m = \frac{n\sum xy - (\sum x)(\sum y)}{n\sum x^2 - (\sum x)^2} = \frac{12 \cdot 8{,}490{,}312.6 - 23{,}892 \cdot 4{,}363.9}{12 \cdot 47{,}569{,}544 - 23{,}892^2} \approx 1.5519$$

$$\text{Intercept} \quad b = \bar{y} - m\bar{x} = 255.33 - 1.5519 \cdot 1991 = -2{,}734.55$$

$$\text{Model} \quad C = 1.5519t - 2734.55$$

[Stewart, 2008]
[Brase, 2009]

Definition: Aggregate models

Aggregate model. A model that represents a large number of small objects and actions in a combined, or aggregate, way.

Aggregate models

- Often used in constructive simulation
- Generally not directly physics-based
  - Abstraction of many physics-based interactions

Example: Lanchester equations

Differential equations for attacker and defender force attrition with respect to time; widely used for military operations research. [Lanchester, 1956] [Davis, 1995]

$$\frac{dA}{dt} = -K_d A^r D^s \qquad \frac{dD}{dt} = -K_a D^t A^u$$

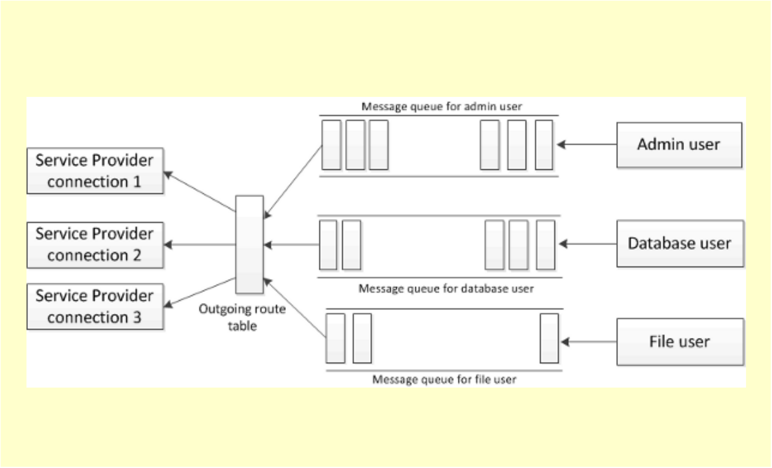
Lanchester

A	Attacker strength (abstract, aggregate value)
D	Defender strength (abstract, aggregate value)
K_a, K_d	Lethality (K_a attacker, K_d defender)
r, s, t, u	Free parameters, time independent

Part 2: Content survey

- Definitions and concepts
  - M&S terms and attributes
  - M&S categories
- Modeling methods
  - Survey of modeling methods
  - Discrete event simulation
  - Monte Carlo simulation
- Special topics
  - Verification, validation, and accreditation
  - Distributed simulation

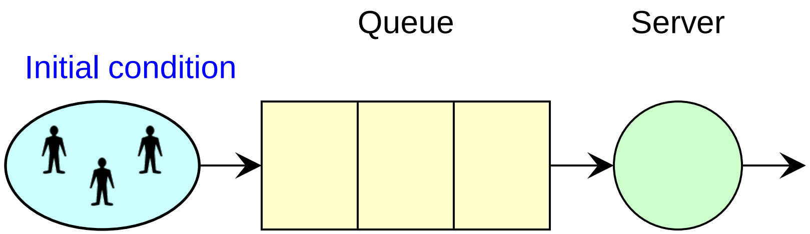
DES: Customers, queues, servers, and events



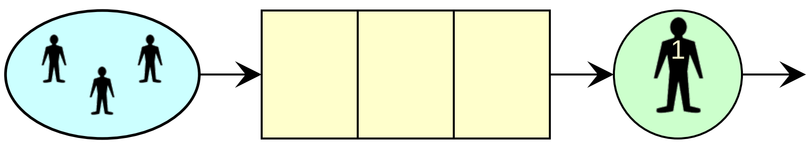
Example: Simple queueing system simulation

Event-driven, discrete, probability-based

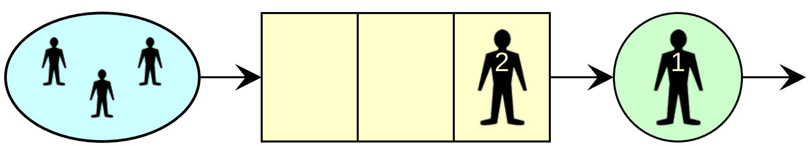
Initial condition



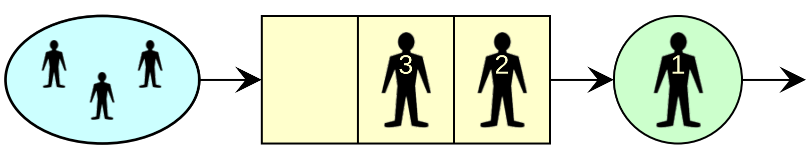
t = 0, Customer 1 arrives, begins service



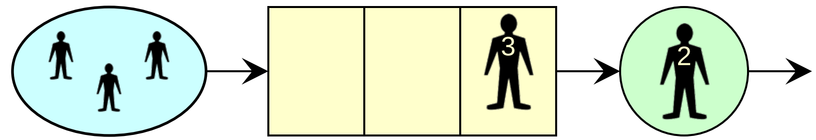
t = 3, Customer 2 arrives, enters queue



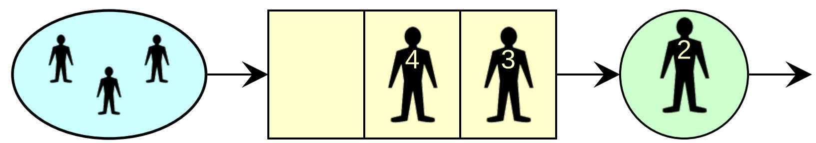
t = 4, Customer 3 arrives, enters queue



t = 7, Customer 1 departs, Customer 2 begins service



t = 9, Customer 4 arrives, enters queue



. . .

- What was the maximum queue length?
- What was the average queue length?
- What the average customer wait for service?
- What was the average customer service time?

Scope of DES

- Simulands representable as a queuing system
- Queueing system
  - Characterized by customers, queues, and servers
  - State changes discretely at events
  - Customer attributes may affect events or service times

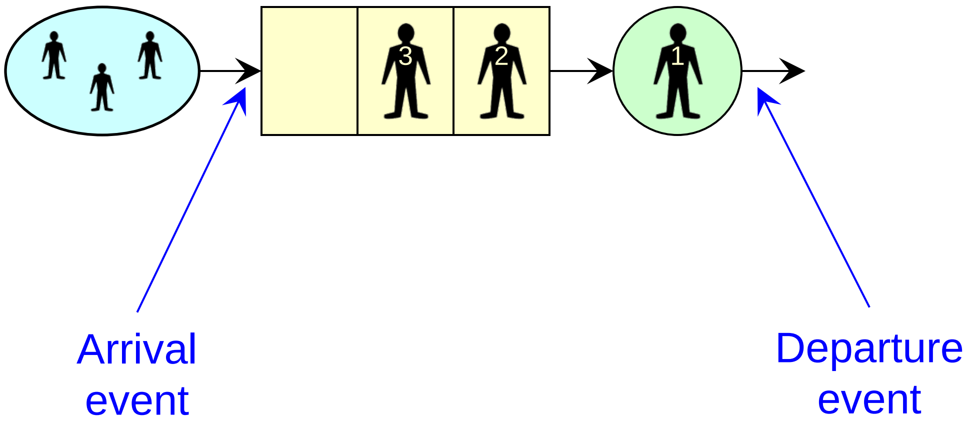
Simuland	Customers	Attributes	Servers	Events
Bank lobby	Customers	Account balance	Teller ATM	Arrival Departure
Subway	Riders	Origin Destination	Subway car	Arrival at station Arrival at destination
Assembly line	Assemblies	Speed Breakdown rate	Welding robot Installation worker	Breakdown
Comm network	Messages	Length Destination	Router Switch	Arrival at destination
Field hospital	Wounded	Wound type Blood pressure	Surgeon Operating room	Arrival at hospital Begin treatment

Basic logic of DES

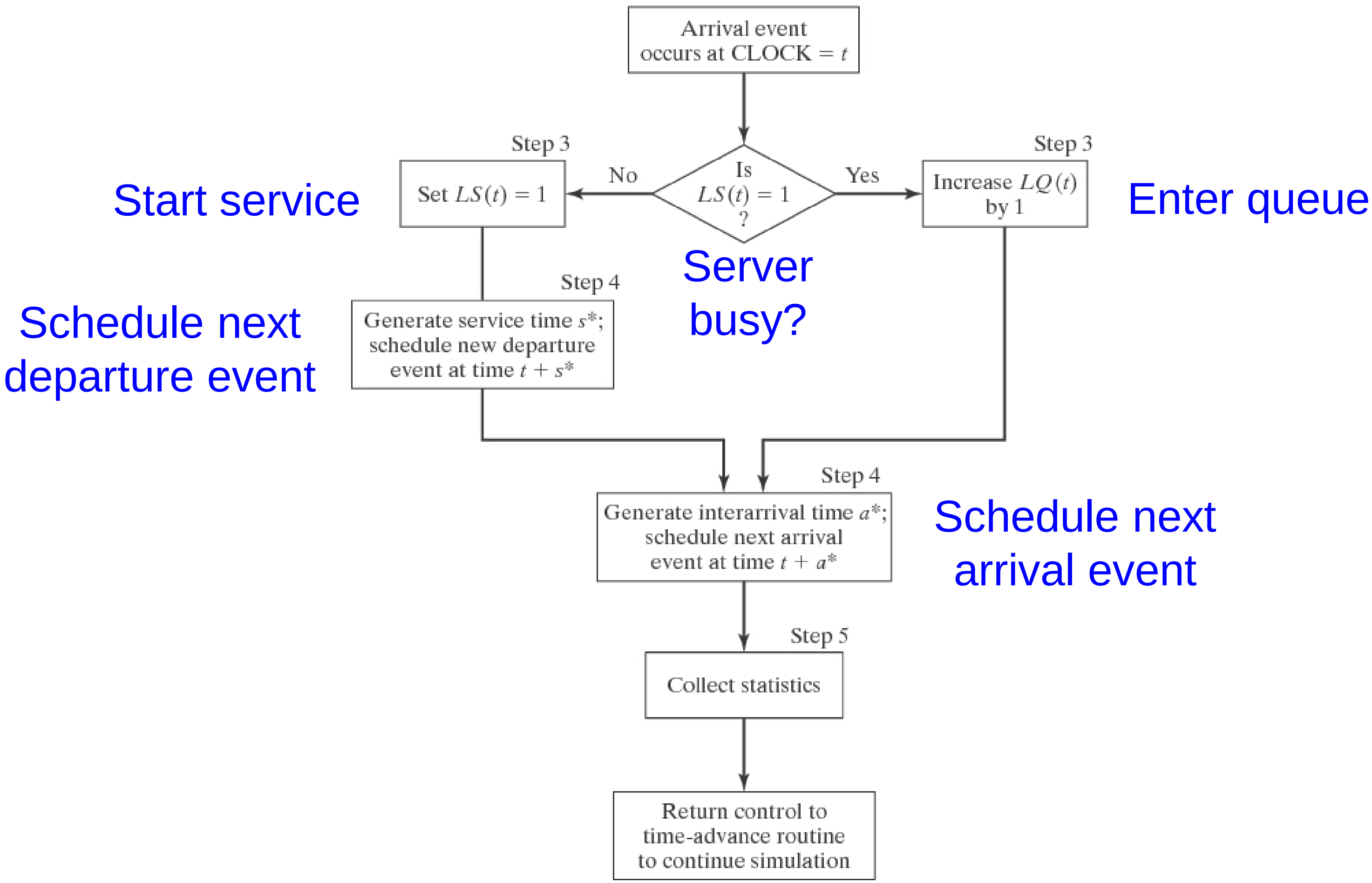
- Model status
  - Current simulation time $\mathrm{CLOCK} = t_0$
  - Future Event List (FEL), with next event (e_1, t_1)
- Event-driven time advance algorithm
  - Remove next event (e_1, t_1) from FEL
  - Advance (set) CLOCK to t_1
  - Process event e_1 per rules for event type: update system state and possibly schedule future events by inserting events into FEL
  - Repeat

Time advances from event time t_i to next event time t_j without simulating time in between the events.

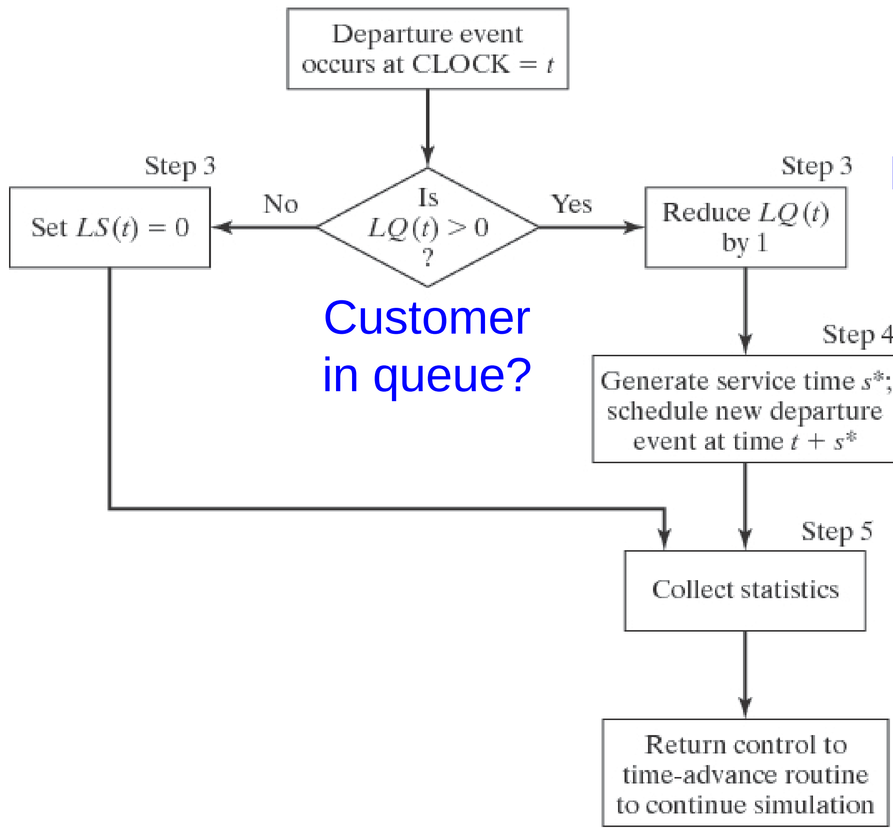
Events in a single queue, single server system



Event logic: Arrival



Event logic: Departure



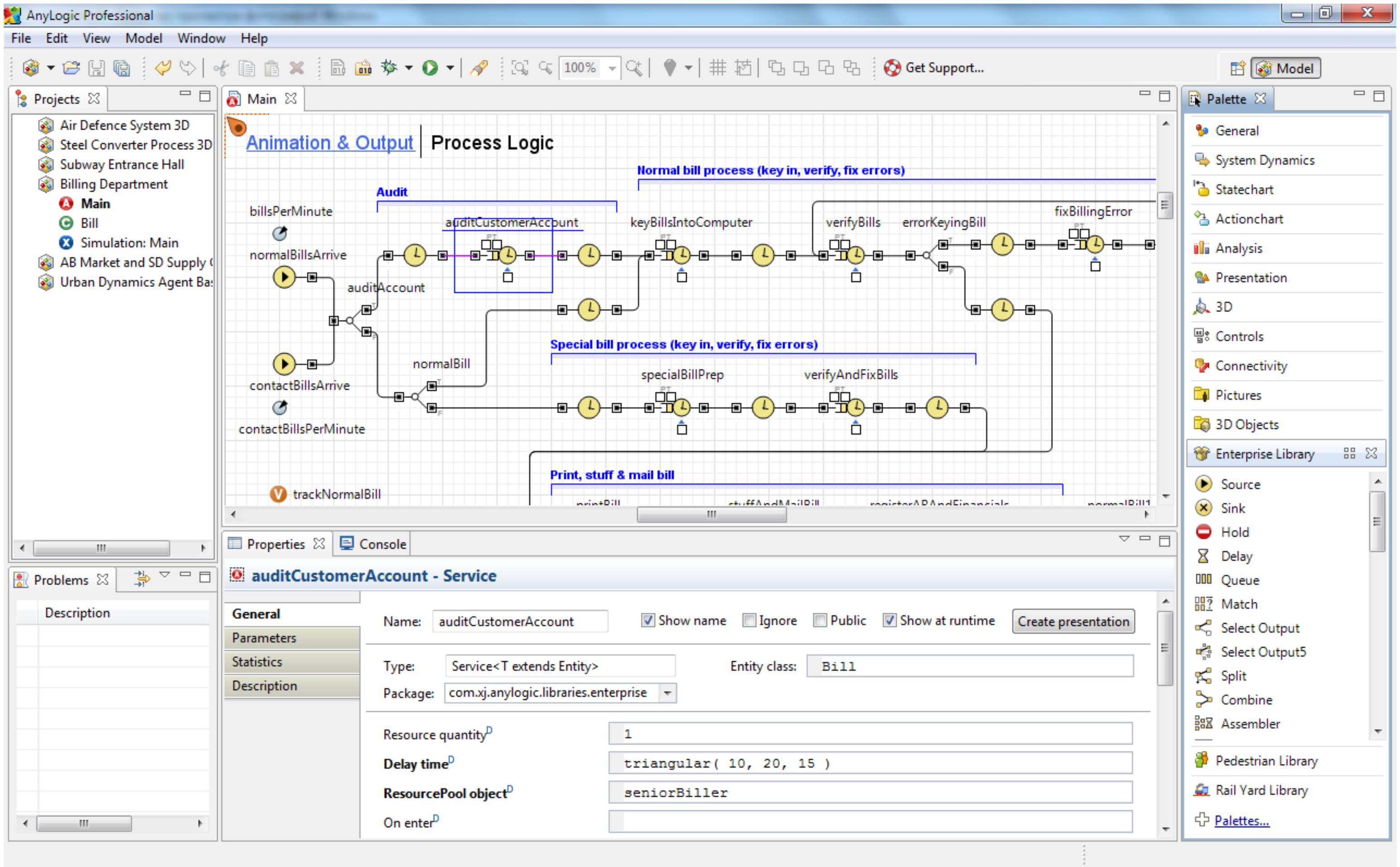
Server idle

Customer
in queue?

Remove customer
from queue
Start service

Schedule next
departure event

Modeling multistep processes

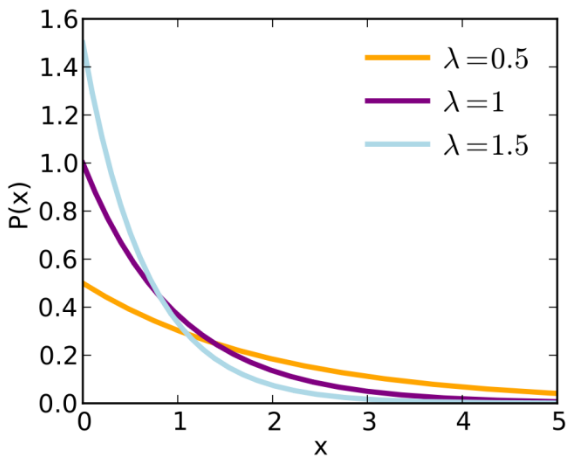


Randomness and random variates

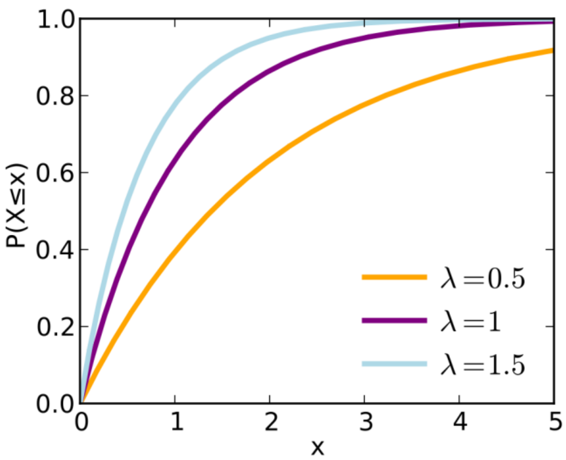
- Randomness in discrete event simulation
  - Randomness used extensively in DES
  - DES randomness imitates uncertainty in real life
  - Represents system aspects not otherwise modeled, individually unpredictable but follow a pattern
  - e.g., system events (interarrival times)
  - e.g., system activities (service times)
- Random variates
  - Random values for quantities of interest
  - Generated per probability distributions that model phenomenon or process

Exponential distribution

Probability density function (pdf)



Cumulative distribution function (cdf)



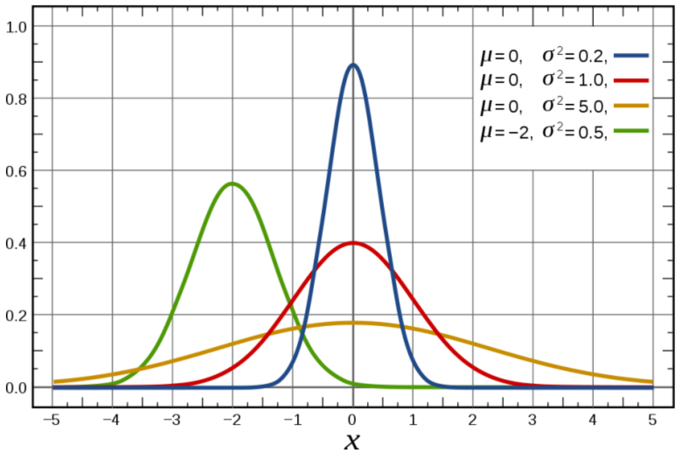
$$\text{pdf} \quad f(x) = \begin{cases} \lambda e^{-\lambda x} & x \geq 0 \\ 0 & otherwise \end{cases}$$

$$\text{cdf} \quad F(x) = \begin{cases} 0 & x < 0 \\ \int_0^x \lambda e^{-\lambda t} dt = 1 - e^{-\lambda x} & x \geq 0 \end{cases}$$

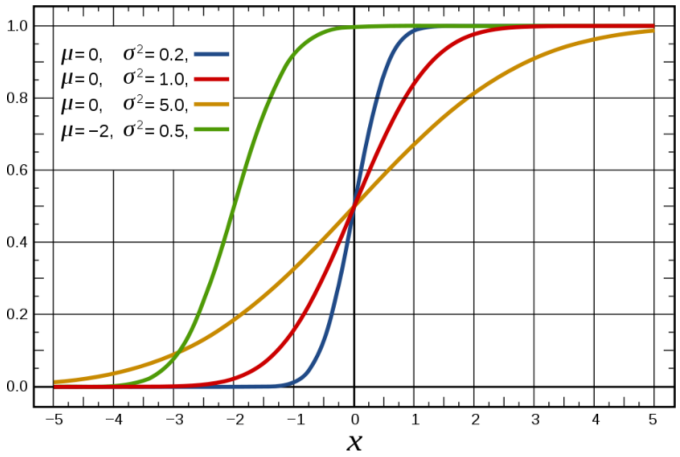
- Larger values increasingly less probable
- Parameter λ is rate (events per time unit), $1/\lambda$ is mean interevent time

Normal distribution

Probability density function



Cumulative distribution function



$$\text{pdf} \quad f(x) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left[-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2\right]$$

$$\text{cdf} \quad F(x) = \int_{-\infty}^{x} \frac{1}{\sigma\sqrt{2\pi}} \exp\left[-\frac{1}{2}\left(\frac{t-\mu}{\sigma}\right)^2\right] dt$$

- Values clustered symmetrically around mean
- Parameters mean μ is center, variance σ^2 is measure of dispersion

Commonly used probability distributions

Type of simuland	Phenomenon or process	Distribution
General queueing systems	Interarrival times	Exponential
	Service times	Normal
Inventory and supply chain	Demand	Poisson
	Time between demands	Poisson
	Lead time	Gamma
Reliability and maintainability	Time to failure	Weibull
Limited data	Varies	Triangular
Varies	No suitable theoretical	Empirical

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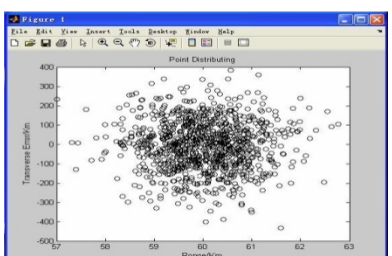
Two definitions of Monte Carlo Simulation

Definition 1

Stochastically varying initial conditions	→	Deterministic simulation	→	Stochastically varying results
Probability distributions used to model variability in initial conditions		Often time-stepped physics-based model; time represented explicitly		Multiple runs with run-to-run variability in results; analyzed statistically

Definition 2

Fixed initial conditions	→	Stochastic simulation	→	Stochastically varying results
Specific known or given initial conditions		Probability distributions used to model variability in simuland processes; often no explicit representation of time		Multiple runs with run-to-run variability in results; analyzed statistically



1

2

Monte Carlo 1 procedure

Defining a Monte Carlo model

1. Identify a set of random variables that specify the initial condition.
2. Select probability distribution and parameters for each.
3. Develop deterministic model to calculate results from a set of inputs.

Executing a Monte Carlo simulation

1. Repeat for each of n trials:
   - 1.1 Randomly generate random variate for each input.
   - 1.2 Calculate trial outcome with deterministic model.
   - 1.3 Record trial outcome.
2. Statistically analyze the results.

Monte Carlo 2 procedure

Defining a Monte Carlo model

1. Identify a set of input variables that specify the initial condition.
2. Select specific values for each.
3. Develop stochastic model based on probability distributions to calculate results from a set of inputs.

Executing a Monte Carlo simulation

1. Repeat for each of n trials:
   - 1.1 Initialize model with selected input values.
   - 1.2 Calculate trial outcome with stochastic model.
   - 1.3 Record trial outcome.
2. Statistically analyze the results.

Example (MC1): Missile impacts [Zhang, 2008]

- Application
  - Deterministic 6DOF model of missile trajectory
  - Used to calculate impact point given initial conditions
  - Measure x and y error w.r.t. aiming point
  - Compare model and live test x and y error variances
  - Two ranges: 60 Km and 100 Km
  - 6 live tests, 800 Monte Carlo model trials each range
- Monte Carlo analysis
  - For each trial, generate initial conditions from probability distributions
  - Calculate impact point using model
  - Repeat for 800 trials
  - Compare variances

Missile trajectory initial conditions [Zhang, 2008]

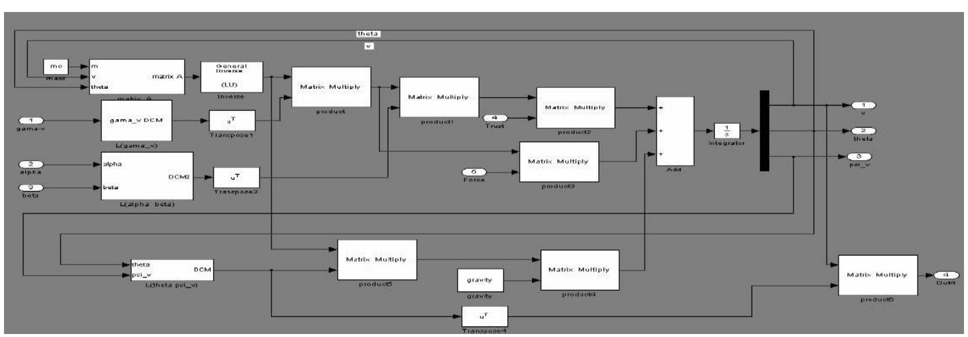
- Source does not identify initial conditions
- Conjectured initial condition variables
  - Launch elevation
  - Launch azimuth
  - Engine thrust while burning
  - Engine burn time
- Setting initial condition variables
  - Appropriate probability distribution selected for each
  - Random variate for each variable for each trial

Missile trajectory model

- Physics based
- Organized into modules: velocity, rotation, atmospheric conditions, aerodynamics, thrust
- Implemented in MATLAB Simulink

$$m\frac{dV}{dt} = P\cos\alpha\cos\beta - X - mg\sin\theta$$
$$mV\frac{d\theta}{dt} = p(\sin\alpha\cos\gamma_V + \cos\alpha\sin\beta\sin\gamma_V) + Y\cos\gamma_V - Z\sin\gamma_V - mg\cos\theta$$
$$-mV\cos\theta\frac{d\varphi_V}{dt} = P(\sin\alpha\sin\gamma_V - \cos\alpha\sin\beta\sin\gamma_V) + Y\sin\gamma_V + Z\cos\gamma_V$$

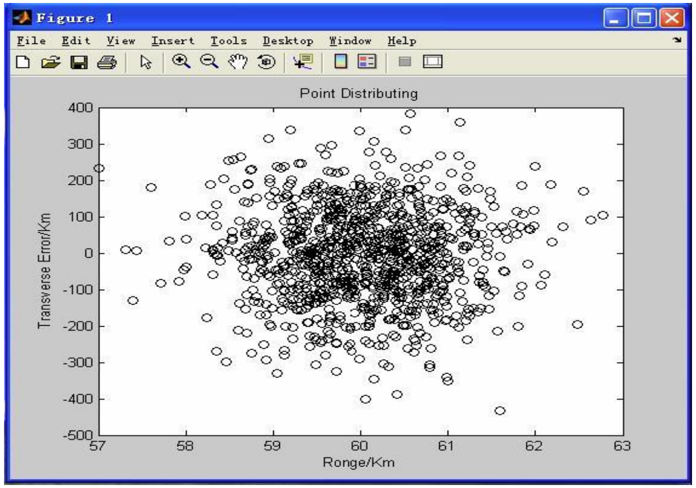
Velocity module equations



Velocity module block diagram

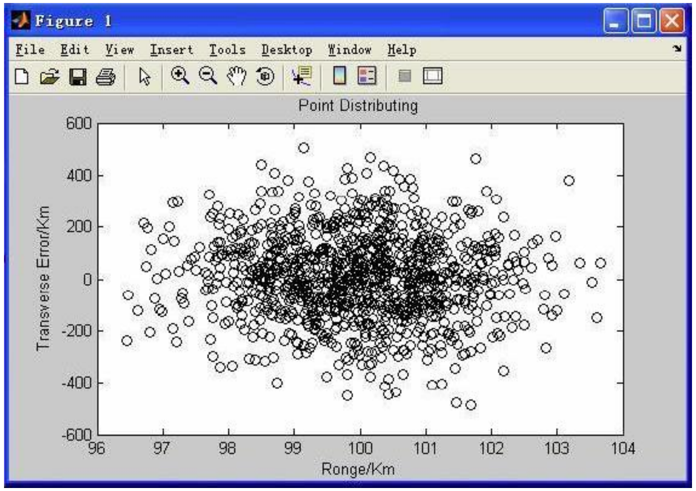
Impact data

60 Km



Trial	x error s	y error s	n
Model	526.62	85.91	800
Simuland	566.66	89.77	6

100 Km



Trial	x error s	y error s	n
Model	921.39	111.25	800
Simuland	980.52	120.68	6

Example (MC2): Attrition combat [Strickland, 2011]

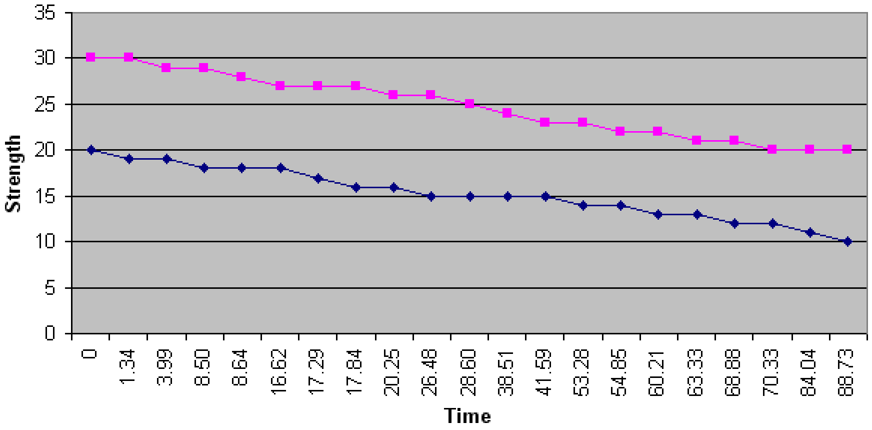
- Application
  - Force-on-force attrition
  - Direct fire only
  - No maneuver
- Modeling
  - Markov chain Lanchester attrition model
  - Fixed initial conditions, stochastic model → MC2
- Notation
  - Blue strength B, Red strength R
  - Blue lethality (vs Red) K_B, Red lethality (vs Blue) K_R
  - Blue force attrition rate $A_B(B, R) = K_R \cdot \min(B, R)$
  - Red force attrition rate $A_R(B, R) = K_B \cdot \min(B, R)$

Model details

- Model assumptions
  - No more than one shooter may engage a target at a time
  - Time between Blue casualties exponentially distributed with rate $\lambda_B = A_B(B, R) = K_R \cdot \min(B, R)$
  - Time between Red casualties exponentially distributed with rate $\lambda_A = A_R(B, R) = K_B \cdot \min(B, R)$
  - Battle ends when either side reaches break strength
- Simulation
  - Stochastically generate times of first Blue, Red casualties
  - Identify earlier casualty time and decrement side's strength
  - Compare decremented side's strength to break strength
  - Generate time of next casualty for decremented side
  - Repeat

Results, single trial

	Initial strength	Break strength	Lethality			
Blue	20	10	0.010			
Red	30	15	0.006			
Step	Time	Blue strength	Red strength	Next Blue casualty	Next Red casualty	Result
0	0	20	30	1.34	3.99	Continue
1	1.34	19	30	8.50	3.99	Continue
2	3.99	19	29	8.50	8.64	Continue
3	8.50	18	29	17.29	8.64	Continue
4	8.64	18	28	17.29	16.62	Continue
5	16.62	18	27	17.29	20.25	Continue
6	17.29	17	27	17.84	20.25	Continue
7	17.84	16	27	26.48	20.25	Continue
8	20.25	16	26	26.48	28.60	Continue
9	26.48	15	26	53.28	28.60	Continue
10	28.60	15	25	53.28	38.51	Continue
11	38.51	15	24	53.28	41.59	Continue
12	41.59	15	23	53.28	54.85	Continue
13	53.28	14	23	60.21	54.85	Continue
14	54.85	14	22	60.21	63.33	Continue
15	60.21	13	22	68.88	63.33	Continue
16	63.33	13	21	68.88	70.33	Continue
17	68.88	12	21	84.04	70.33	Continue
18	70.33	12	20	84.04	91.41	Continue
19	84.04	11	20	88.73	91.41	Continue
20	88.73	10	20	98.63	91.41	Red



Results, multiple trials

Initial conditions	Trials	100	100	100
	Blue initial strength	20	20	20
	Red initial strength	30	30	30
	Blue break strength	10	10	10
	Red break strength	15	15	15
	Blue lethality	**0.008**	**0.010**	**0.012**
	Red lethality	0.006	0.006	0.006
Results	Blue wins	34	52	76
	Red wins	66	48	24
	Blue mean losses	8.88	8.08	7.14
	Red mean losses	11.01	12.85	14.06

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Definition

Verification. The process of determining that a model implementation and its associated data accurately represents the developer's conceptual description and specifications. [DOD, 2009]

- Transformational accuracy [Balci, 2002]
  - Transform specifications to code
- Software engineering quality
  - Software engineering methods apply

Definition

Validation. Determining the degree to which a model or simulation and its associated data are an accurate representation of the real world from the perspective of the intended uses of the model.
[DOD, 2009]

Comparing model results with experimental data.
[Velten, 2009]

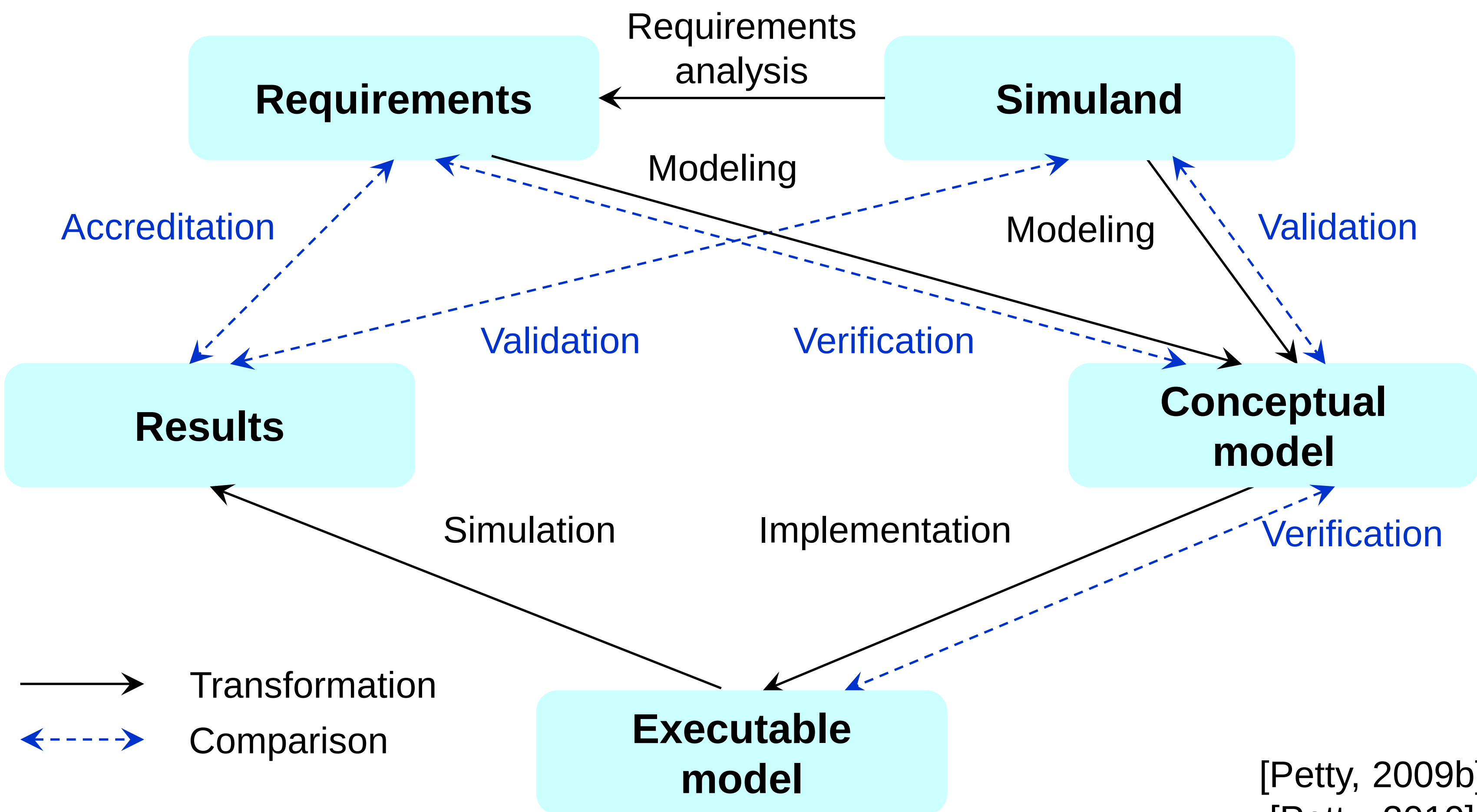
- Representational accuracy [Balci, 2002]
  - Recreate simuland with results
- Modeling quality
  - Special validation methods needed

Definition

Accreditation. Official certification [by a responsible authority] that a model or simulation is acceptable for use for a specific purpose. [DOD, 2009]

- Official usability for specific purpose or function
  - Management decision, not technical process
  - Not a blanket or general-purpose approval
- Accrediting (or accreditation) authority
  - Agency or person responsible for use of model
  - Normally not model developer

VV&A comparisons



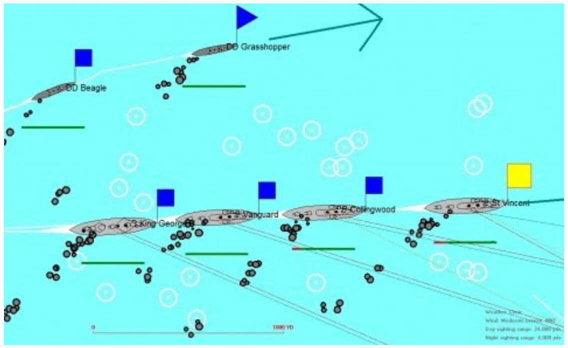
[Petty, 2009b]
[Petty, 2010]

VV&A errors and risks [Balci, 1981] [Balci, 1985] [Balci, 1998]

	Model valid	Model not valid	Model not relevant
Model used	Correct	**Type II error** Use of invalid model; Incorrect V&V; Model user's risk; **More** serious error	**Type III error** Use of irrelevant model; Accreditation mistake; Accreditor's risk; **More** serious error
Model not used	**Type I error** Non-use of valid model; Insufficient V&V; Model builder's risk; **Less** serious error	Correct	Correct

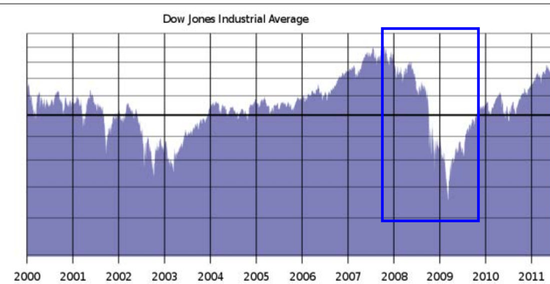
VV&A error examples

Model | Reality | Error

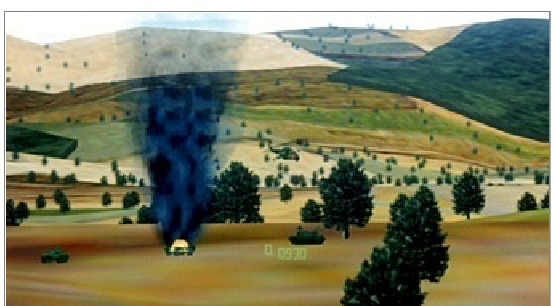


Type I
Japanese wargames and the Battle of Midway
[Fuchida, 1955]
[Barker, 1971]

$$\Pr\left[T_A < 1, T_B < 1\right] = \phi_2(\phi^{-1}(F_A(1)), \phi^{-1}(F_B(1)), \gamma)$$



Type II
Gaussian copula and the 2008 Financial Crisis
[Salmon, 2009]



Type III
SIMNET, *Primetime Live*, and the 1991 Gulf War

V&V methods

- Many V&V methods available, ~85 in 1998 [Balci, 1998], more developed since [Balci, 2002] [Petty, 2010]
- Different purposes, advantages, suitable models

Informal	Static	Dynamic	Formal
-Audit -Desk checking -Documentation Checking -Face validation -Inspections -Reviews -Turing test -Walkthroughs	-Cause-Effect Graphing -Control Analysis -Data Analysis -Fault/Failure Analysis -Interface Analysis -Semantic Analysis -Structural Analysis -Symbolic Evaluation -Syntax Analysis ...	-Acceptance Testing -Alpha Testing -Assertion Checking -Beta Testing -Bottom-up Testing -Comparison Testing -Statistical Techniques -Structural Testing -Submodel/Module Testing ...	-Induction -Inductive Assertions -Inference -Logical Deduction -Lambda Calculus -Predicate Calculus -Predicate Transformation -Proof of Correctness

[Balci, 1998]

Informal V&V methods

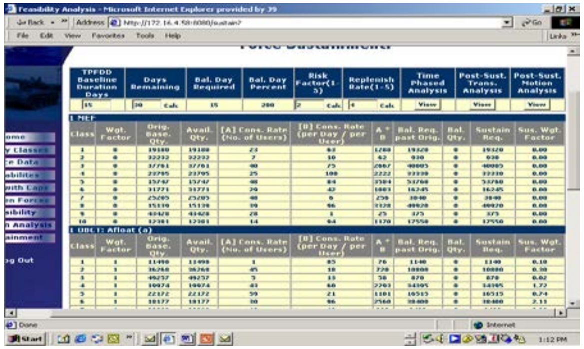
- Characteristics
  - Methods that rely heavily on Subject Matter Expert (SME) expertise and evaluation
  - More often qualitative and subjective
  - More often performed by SMEs
  - Effectiveness depends on SME qualifications [Balci, 2002]
  - Useful when modeling notional system [Balci, 2002]
- Example informal V&V methods
  - Inspection
  - Face validation
  - Turing test

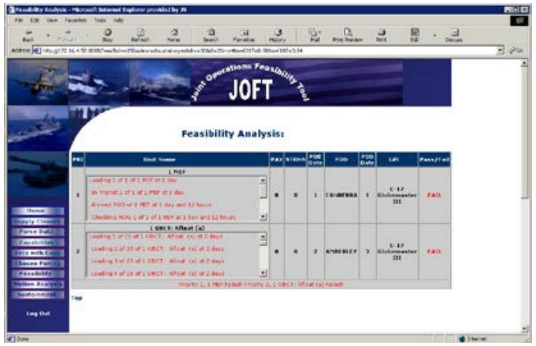
Face validation (validation)

- SMEs, modelers, and users observe model execution and/or examine results
- Compare results to simuland behavior, as understood by SMEs
- Assessment
  - Model validity evaluated subjectively
  - Based on expertise, estimates, and intuition
- Comments
  - Frequently used because of simplicity
  - Often used when user interaction important
  - Clearly better than no validation

Face validation example: JOFT

- Joint Operations Feasibility Tool [Belfore, 2004]
  - Assess deployment transportation feasibility
  - Assess logistical sustainment feasibility
- Validation process
  - Special scenarios exercise full range of capabilities
  - 20 SMEs with extensive experience evaluated model
  - Assessments elicited via written questionnaires
- Process structure addressed face validation limits



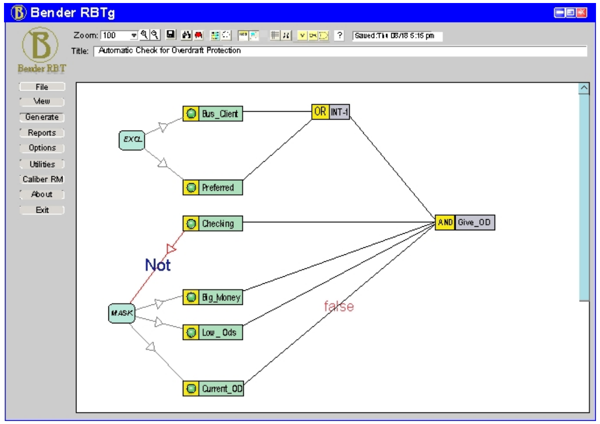


Static V&V methods

- Characteristics
  - Methods based on artifact characteristics that can be determined without running a simulation
  - Often involve analysis of executable model code
  - May be supported by automated tools or manual notations or diagrams
  - More often performed by technical experts
- Example static V&V methods
  - Data analysis
  - Cause-effect graphing

Cause-effect graphing (validation)

- Compare causes and effects in simuland to those in conceptual model
  - Cause: event or condition
  - Effect: state change triggered by cause
- Compare simuland to conceptual model
- Identify missing, extraneous, and inconsistent cause-effect relationships



Cause-effect graph

Dynamic V&V methods

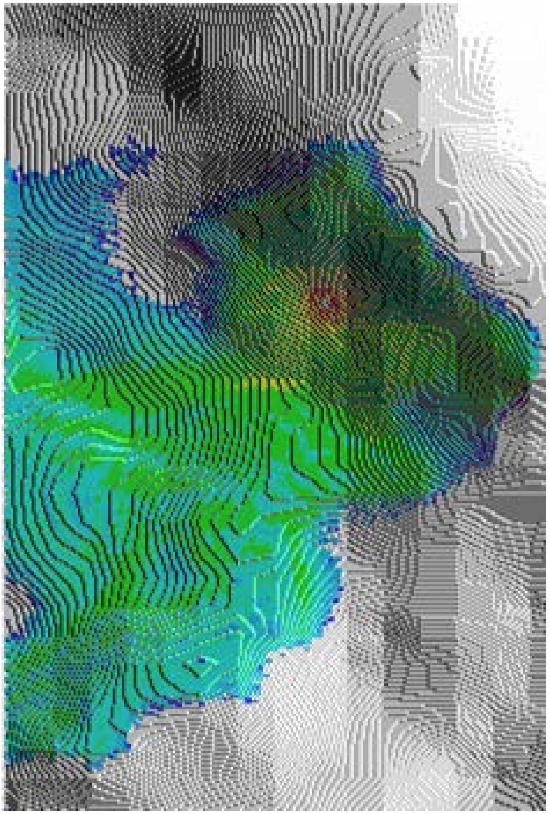
- Characteristics
  - Methods that involve running the executable model and assessing the results
  - May compare results with simuland or other models
  - More often quantitative and objective
  - More often performed by technical experts
- Example dynamic V&V methods
  - Execution tracing
  - Sensitivity analysis
  - Predictive validation
  - Comparison testing
  - Statistical methods

Comparison testing (verification or validation)

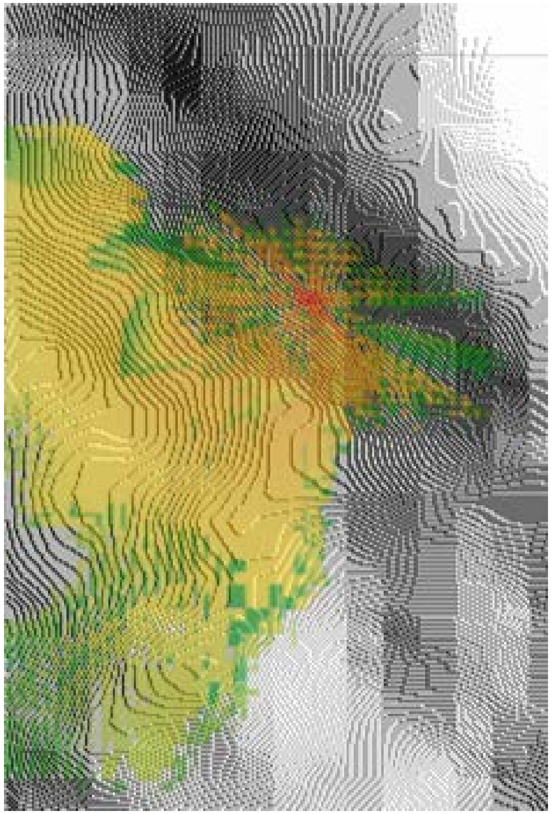
- Run simulations of simuland (and scenario) using two different models, compare results
- Compare results to results
- Differences between results signal problems
- Comments
  - If differences, which model has problems?
  - If one model assumed valid, validation method
  - If neither model assumed valid, verification method

Comparison testing example: Radio propagation model [Filiposka, 2011]

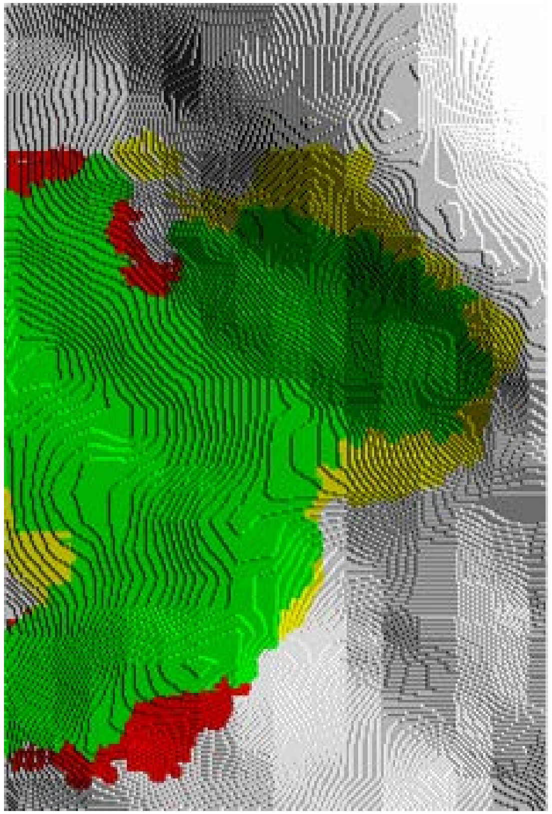
- Durkin’s radio propagation model
  - Estimates radio coverage area of a transmitter
  - Models attenuation caused by diffraction
  - Considers shadowing caused by terrain
  - Predicts transmission loss using path geometry
- Validated using comparison testing
  - Durkin’s model compared to freely available Longley-Rice Irregular Terrain Model
  - Estimated radio coverage areas compared



Longley-Rice



Durkin's



Coverage comparison
Green = Both
Yellow = Longley-Rice only
Red = Durkin's only

[Filiposka, 2011]

Statistical methods (validation)

- Compare model results to simuland observations using statistical methods
  - Various statistical methods: regression analysis, analysis of variance, confidence intervals, hypothesis tests, others [Balci, 1998] [Petty, 2010]
  - May be used in combination with other methods
- Compare results to simuland
- Comments
  - Each statistical method defines statistic or metric of "closeness" or similarity; measure of validity
  - Generally underutilized
  - Selecting method requires knowledge of assumptions

Example applications of statistical methods

Model(s)	Statistical method	Reason for selection
Spacecraft propulsion system sizing	Linear regression	Paired data, simuland–model
Medical clinic waiting Seaport loading/unloading Historical tank battle	Confidence intervals	Single simuland observation, multiple model runs
Bombing accuracy	Confidence intervals with error tolerance	Single simuland observation, multiple model runs, error tolerance available
Waiting line Ground combat	Hypothesis test for equivalence of means	Multiple simuland observations, multiple model runs
Commander decision making	Hypothesis test for equivalence of means	Multiple simuland observations, multiple model runs, equality not assumed
Missile impact accuracy	Hypothesis test for equivalence of variances	Multiple simuland observations, multiple model runs
Wastewater treatment facility	Hypothesis test for equivalence of variances	Multiple simuland observations, multiple model runs
	Confidence interval for difference of two means	Multiple simuland observations, multiple model runs, variances not equal
Sewage collection site	Hypothesis test for equivalence of variances	Multiple simuland observations, multiple model runs
	Hypothesis test for equivalence of means	Multiple simuland observations, multiple model runs, variances equal

Formal V&V methods

- Characteristics
  - Methods based on formal mathematical proofs of program correctness
  - Quantitative (or logical) and objective
  - Performed by technical experts
  - Difficult to apply in practice [Balci, 1998]
- Example formal V&V methods
  - Inductive assertions
  - Predicate calculus

Predicate calculus (validation)

- Logically analyze conceptual model
  - Predicate calculus is a formal logic system
  - Create, manipulate, and prove statements
  - Simuland, conceptual model described in pred calc
  - Prove properties of both to show logical consistence
- Compare conceptual model to simuland
- Quite difficult to apply to non-trivial problems

$$(\forall x)[D(x) \rightarrow (\forall y)(R(y) \rightarrow C(x, y))]$$
$$(\exists x)[D(x) \wedge (\forall y)(R(y) \rightarrow C(x, y))]$$
$$(\forall y)[R(y) \rightarrow (\forall x)(C(x, y) \rightarrow D(x))]$$
$$(\forall x)(\forall y)[R(y) \wedge C(x, y) \rightarrow D(x)]$$

Last two: “Only dogs chase rabbits.” [Gersting, 2003]

Part 2: Content survey

- Definitions and concepts
  - M&S terms and attributes
  - M&S categories
- Modeling methods
  - Survey of modeling methods
  - Discrete event simulation
  - Monte Carlo simulation
- Special topics
  - Verification, validation, and accreditation
  - Distributed simulation

Example distributed simulation: America's Army

- Recruiting and familiarization tool for U. S. Army
- Multiplayer online game, linked via Internet
- First person shooter
- 13M registered users (2014)

Definition

Distributed simulation. Multiple collaborating simulations distributed across locations, computers, and/or processes.

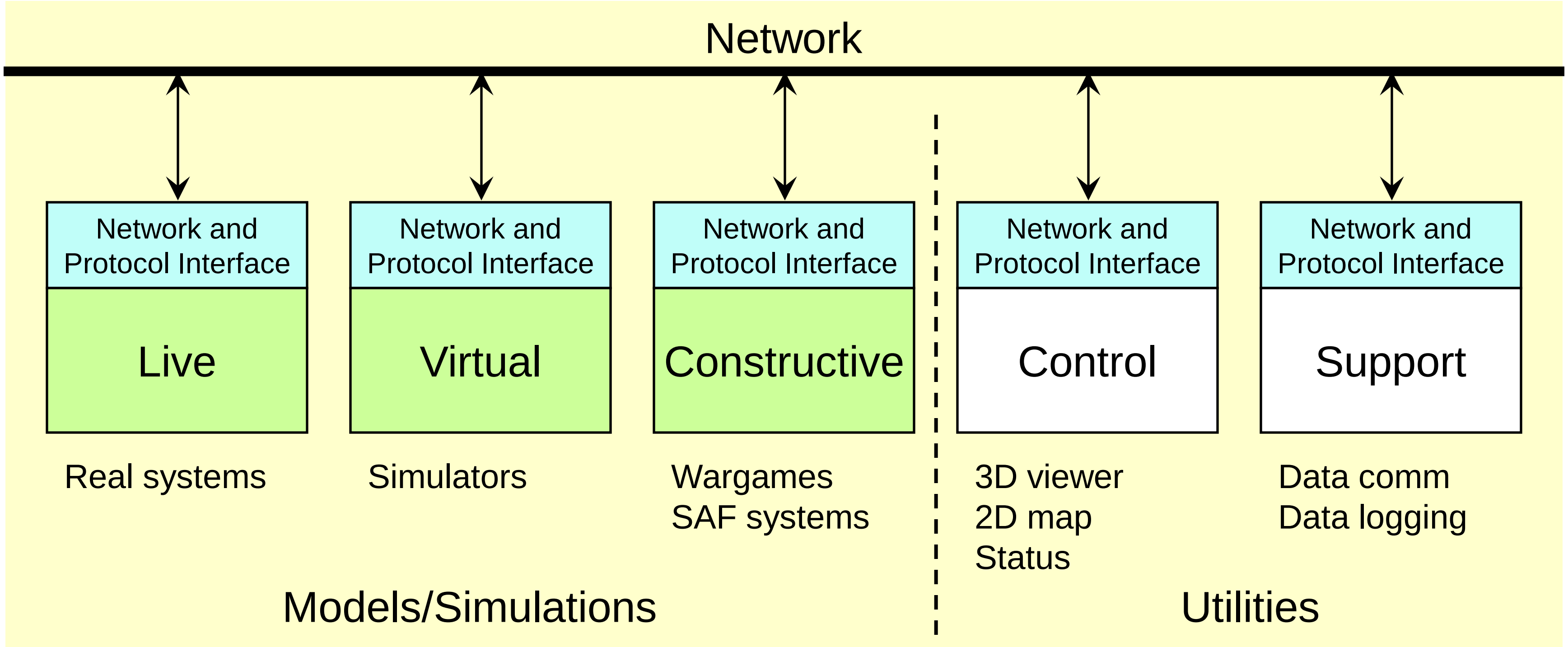
Distributed simulations typically
- Cooperatively simulate simuland
- Each simulates some portion of simuland
- Exchange data about simuland via network messages

Definitions

- Interoperability; the ability of models to meaningfully communicate in a distributed simulation
- Composability; the ability to combine and recombine models and model components into different complex simulations

Distributed simulation system components

- Models/Simulations (simulation nodes)
- Utilities (non-simulation support nodes)
- Network and protocol



Definition

Distributed simulation protocol. Network protocol designed to support a category of distributed simulation systems.

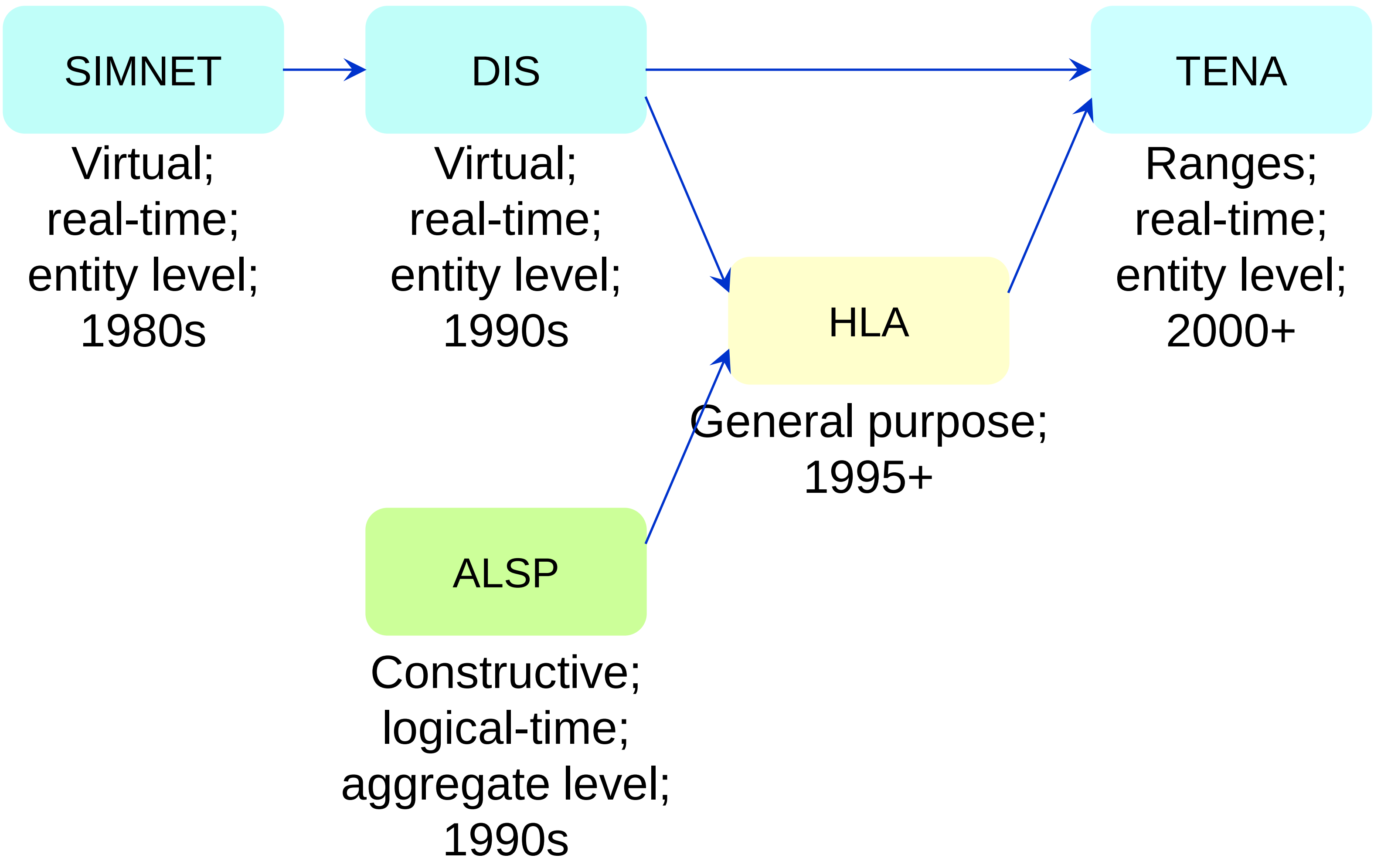
General protocol characteristics

- Definitions of
  - Data items
  - Message formats
  - Interaction sequences
- Standardized to support interoperability

Distributed simulation interoperability protocols

- Simulator Networking SIMNET
  - First functional distributed simulation protocol
  - Homogenous, entity-level, mostly virtual
- Distributed Interactive Simulation DIS
  - Expanded capabilities w.r.t. SIMNET
  - Heterogeneous, entity-level, mostly virtual
- Aggregate Level Simulation Protocol ALSP
  - Heterogeneous logical time constructive
- High Level Architecture HLA
  - General purpose, subsumes previous protocols
- Test and Training Enabling Architecture TENA
  - Designed with test range applications in mind

Distributed simulation protocol development



Distributed simulation protocol: Distributed Interactive Simulation (DIS) [IEEE, 1995]

- Development history
  - Developed from SIMNET, beginning early 1990s
  - Exploited lessons learned from SIMNET
- Characteristics
  - Mounted combat (primarily)
  - Distributed, virtual, entity level, real-time
  - Heterogeneous, non-proprietary
  - Open protocol standard development process
- Used for multiple simulation systems

Basic concepts of DIS

- Simulation nodes
  - Multiple distributed simulators, simulations, utilities
  - Exchange messages via a network (LAN)
- Network messages
  - Conform to predefined standard protocol
  - Called Protocol Data Units (PDUs)
  - Transmitted broadcast (UDP/IP, TCP/IP)
- Message purposes
  - Report entity state (movement, status)
  - Mediate interactions between entities
  - Manage or control simulation execution

Main parts of DIS protocol [Loper, 1995]

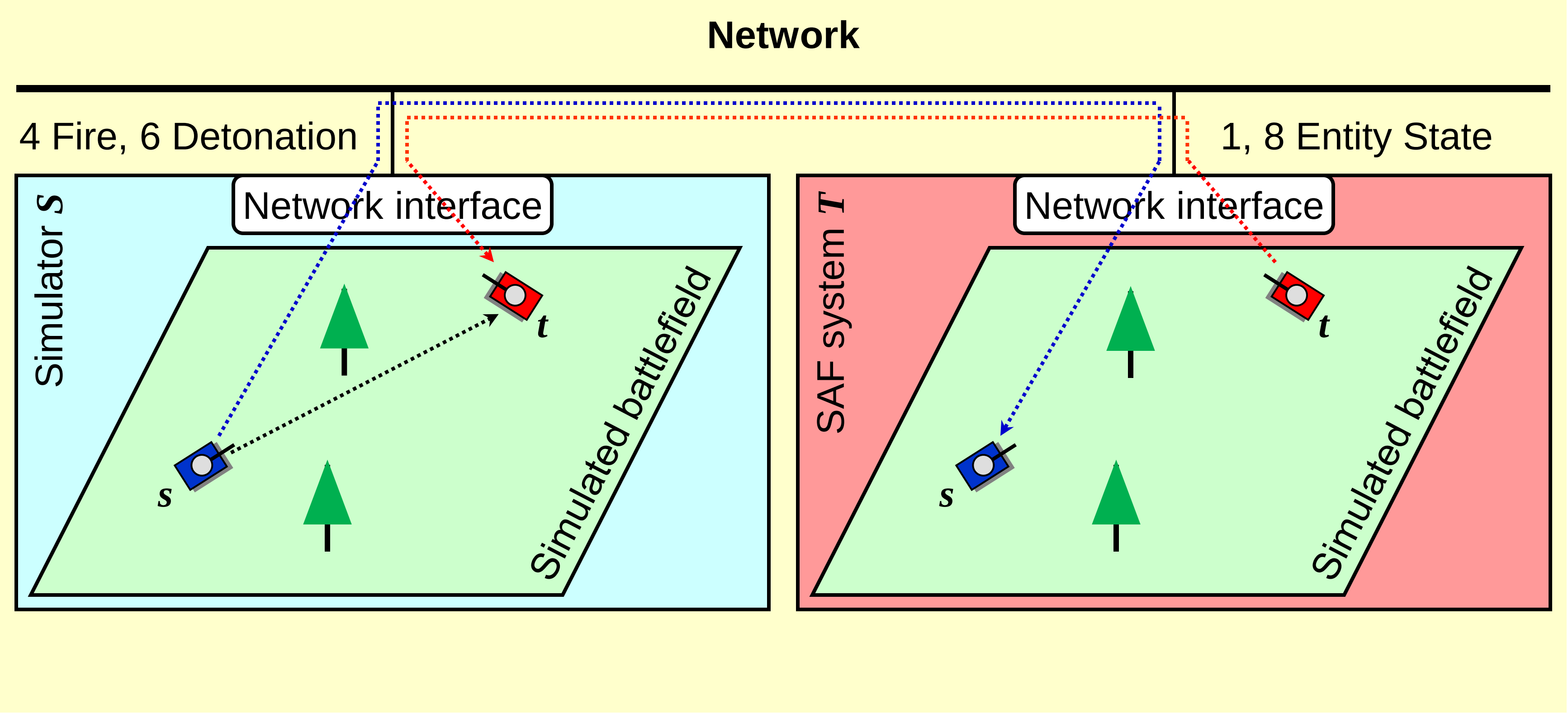
- Data items to be passed
- Format of data items
  - e.g., int vs. float, value enumerations
- Grouping of data items into messages (PDUs)
- Conditions for sending PDUs
  - Specific to PDU type
- Processing to perform upon receiving PDUs
  - Specific to PDU type
- Key algorithms to be shared among nodes
  - e.g., dead reckoning

Most common DIS PDU types

- Entity State
  - Announce entity existence, location, movement, and appearance
- Fire
  - Announce that entity has fired a weapon
  - Important for rendering muzzle flashes
- Detonation
  - Announce that round has hit entity or terrain
- Collision
  - Exchanged between colliding entities

Example DIS interaction: direct fire

- Entities interact by exchanging PDUs
- Protocol defines PDU sequence for interaction

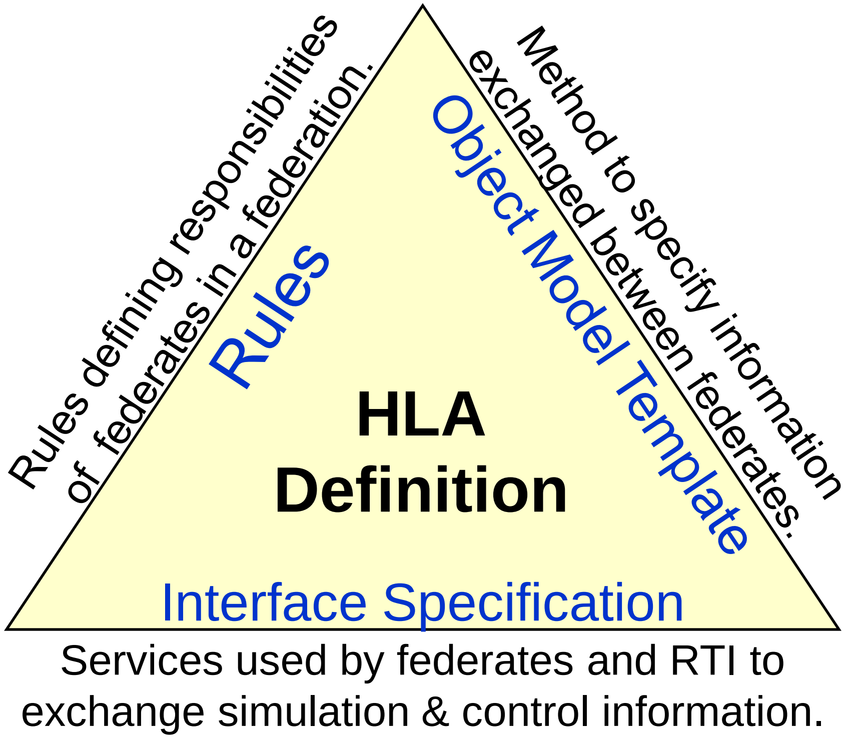


Distributed simulation protocol: High Level Architecture [Dahmann, 1998b] [Möller, 2012]

- Architecture
  - Distributed simulation systems assembled by connecting nodes via network and protocol
- Flexibility
  - No fixed protocol can serve all users' needs, nor can all future applications be anticipated
  - Protocol must allow customization
  - Intended to be general purpose protocol [Dahmann, 1998a]
- Separation of functionality
  - Application-specific (i.e., data definition)
  - General infrastructure (i.e., data transport)

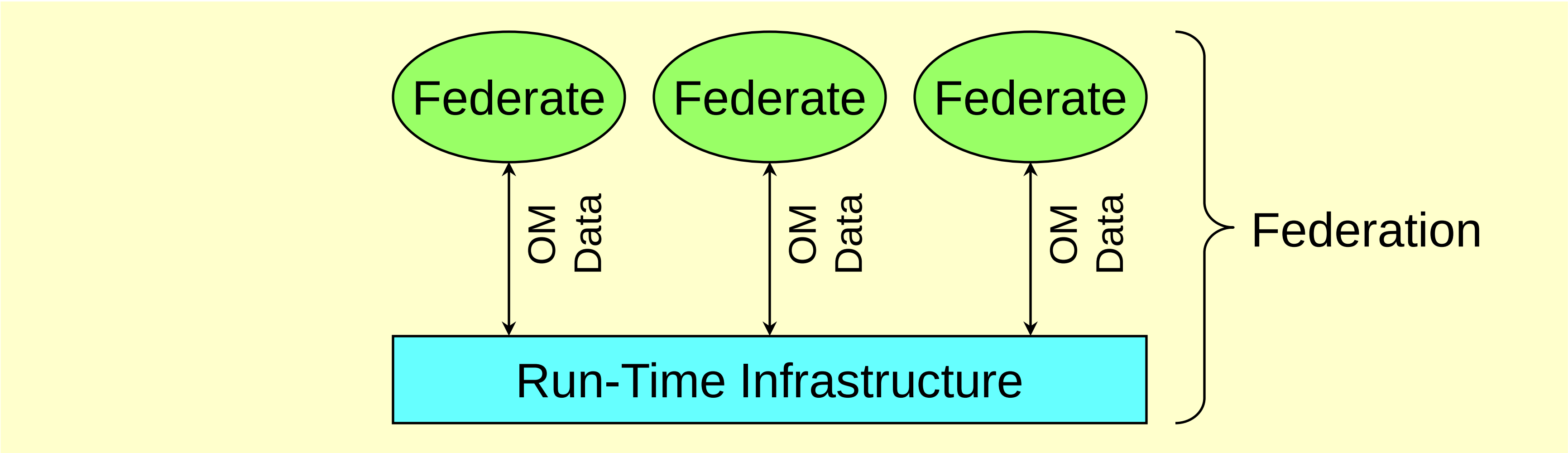
HLA specifications

- Rules [IEEE, 2010a]
- Object Model Template [IEEE, 2010c]
- Interface Specification [IEEE, 2010b]

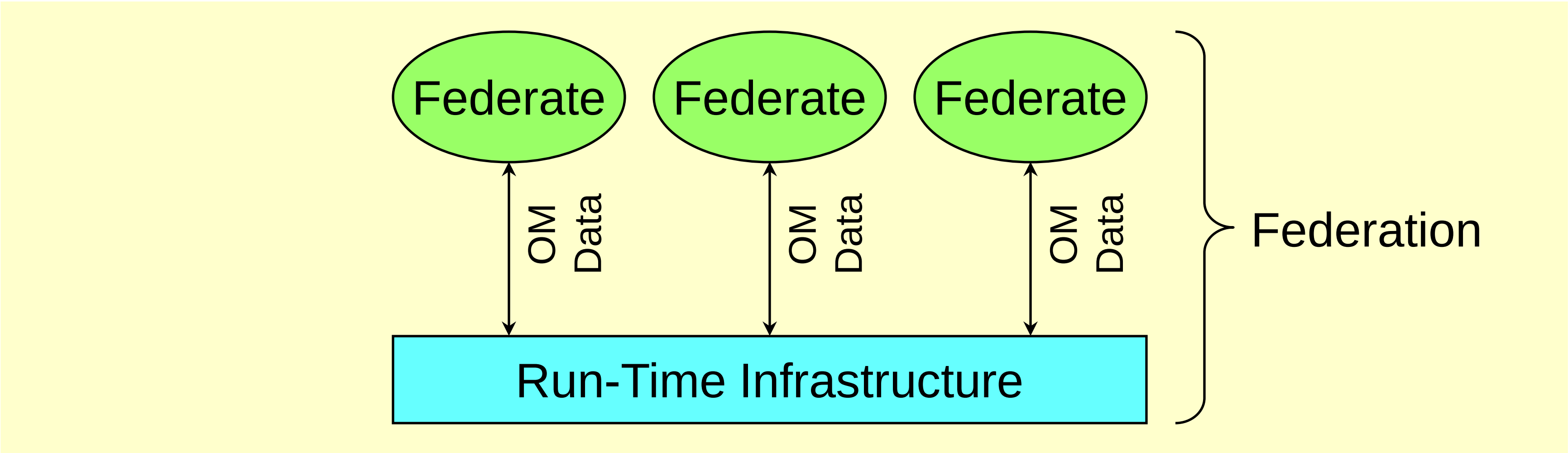


HLA terms

- Federate; individual node in distributed simulation system (simulation or utility)
- Federation; set of interoperating nodes



- Object Model; specification of data to be exchanged by a federation
- Run-Time Infrastructure (RTI); software that supports exchange of data in federation
- RTI service; specific capability provided by RTI



HLA Rules

- Define responsibilities and restrictions
- 10 rules total
- 5 rules each for federates and federations

HLA object models

- Define data to be sent and received in federation
- Object classes and attributes
  - Persistent objects
  - Hierarchy, single inheritance
- Interaction classes and parameters
  - Non-persistent interactions between objects
  - Hierarchy, single inheritance
- Documented per Object Model Template
- Similar, not same, as “object-oriented”
- Special object models
  - Federation Object Model (FOM); OM for federation
  - Simulation Object Model (SOM); OM for federate

HLA Interface Specification

- Purpose
  - Formal definition of operations ("services") used to exchange simulation and control information in a federation execution
  - Formal specification of interface between RTI and federates, defined as a set of functions with API
- Interface Specification and the RTI
  - Interface Spec; defines services and software interface to use them
  - RTI; implements and executes the services

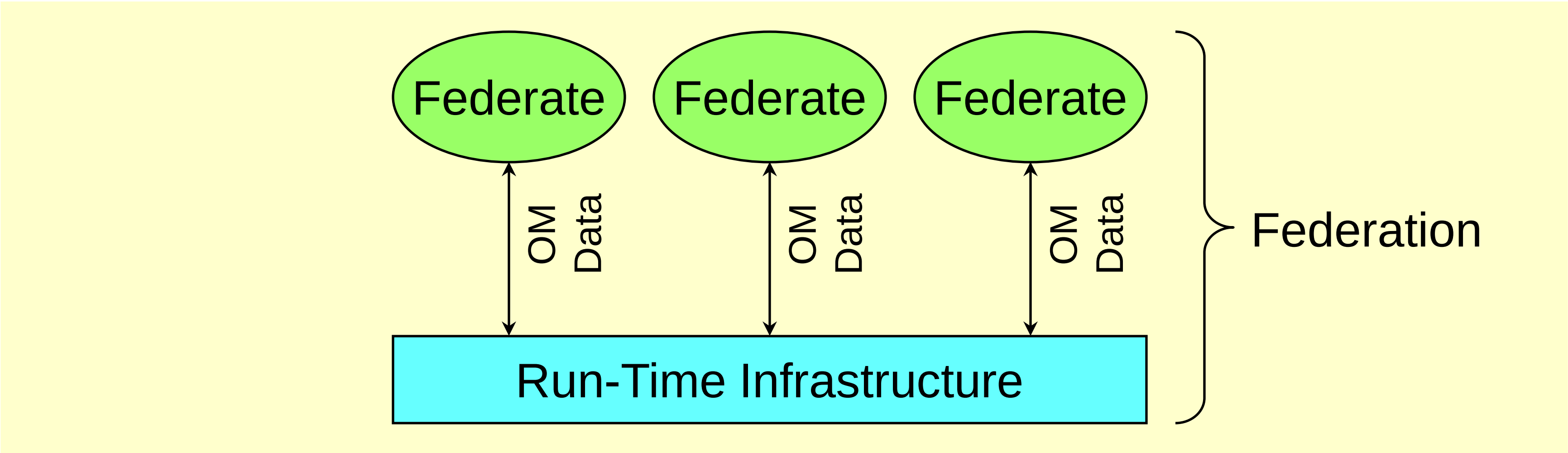
Service Category	Functionality	Services 1516-2010
Federation Management	Create, control, destroy federation executions Join and resign federation executions Pause, resume, checkpoint, restart	31
Declaration Management	Announce intent to send or receive object and interaction information	12
Object Management	Create and delete objects Send and receive object attribute updates Send and receive interactions	29
Ownership Management	Transfer ownership of object attributes between federates	18
Time Management	Control and synchronize simulation time	23
Data Distribution Management	Filter data sent between federates	12
Support	Provide infrastructure status information to federates	43

Run-Time Infrastructure (RTI)

- Not a part of the definition of HLA
- Software realization of the HLA definition
- Provides run-time support to federation
  - Transports data between federates
  - Controls federation execution
  - Manages simulation time

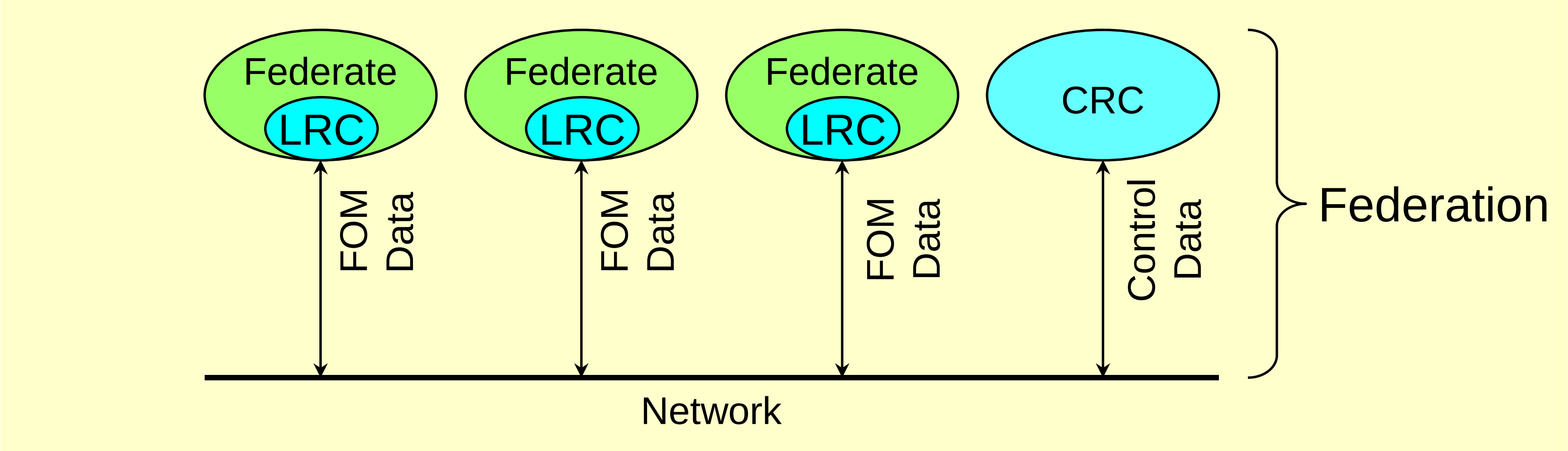
Logical view of a federation

- Federates send data to and receive data from RTI, via services
- RTI is intermediary between federates



Technical view of a federation

- LRC integrated into each federate
- Federate passes data to/from LRC via services; LRCs exchange data via network
- CRC handles special services



LRC = Local RTI Component CRC = Central RTI Component

HLA standards

- DoD 1.3
  - Original HLA standard
  - Initial RTI and HLA software implemented in DoD 1.3
  - DoD 1.3 software no longer supported
  - No longer in use?
- IEEE 1516-2000
  - Developed from DoD 1.3
  - Many improvements [DMSO, 2004] [Morse, 2004]
  - Widely used
  - Federates, federations, tools, products available
- HLA 1516-2010
  - Developed from IEEE 1516
  - Standardized 2010 [IEEE, 2010a] [IEEE, 2010b] [IEEE, 2010c]

Conclusion

Summary

- CMSP: professional certification for M&S
- Renewed exam
  - Topical coverage of M&S Body of Knowledge
  - Questions traceable to authoritative sources
- Examination delivered via custom web system
- Content comprehensive of M&S

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End notes

- Additional information regarding exam structure
  M. D. Petty, G. S. Reed, and W. V. Tucker, "Topics, Structure, and Delivery of the New Certified Modeling and Simulation Professional Examination", *Proceedings of the Spring 2012 Simulation Interoperability Workshop*, Orlando FL, March 26-30 2012, pp. 188-195.
- Additional information regarding exam content
  - Online UAH PCS courses: http://www.uah.edu/pcs/professional-development/engineering?target=index&categoryId=10416
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