CS 582
Modeling and Simulation II

Distributed Simulation
Concepts and Protocols

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Center for Modeling, Simulation, and Analysis

Instructor biography

- Mikel D. Petty, Ph.D.
- Current position
  - Director; Center for Modeling, Simulation, and Analysis
  - Associate Professor, Computer Science
- Education
  - Ph.D. Computer Science, UCF 1997
  - M.S. Computer Science, UCF 1988
  - B.S. Computer Science, CSUS 1980
- Research
  - Modeling and simulation
  - > 175 research papers published
  - ~ $15 million total research funding awarded

Instructor Distributed Simulation experience

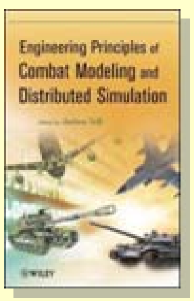
- Selected Dist Sim research projects
  - 1992: Multi-resolution modeling
  - 1992: I/ITSEC DIS interoperability demo
  - 1996: HLA Platform Proto-Federation
  - 1997: DIS–HLA protocol translator
  - 1997: HLA Data Distribution Management services
  - 1998: HLA medical federation
  - 2000: IEEE 1516-2000 HLA standard
  - 2003: Crowd model in HLA
  - 2010: IEEE 1516-2010 HLA standard
  - 2013: IEEE 1730-2013 DMAO standard
- ~90 Dist Sim publications 1995-2012

Overall conceptual outline

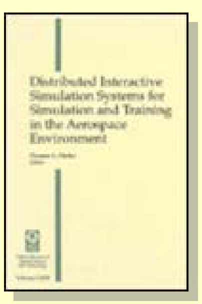
- Concepts and Protocols
  - What is Dist Sim?
  - Why is Dist Sim useful?
  - How does Dist Sim work, in concept?
  - What Dist Sim protocols have been developed?
- HLA Development
  - How can a Dist Sim be implemented using HLA?
  - What tools and products support HLA development?
- Applications and Case Studies
  - What applications are appropriate for Dist Sim?
  - How has Dist Sim been used successfully?

Primary sources

B. Möller, et al, *The HLA Tutorial: A Practical Guide for Developing Distributed Simulations*, Pitch Technologies, Linkoping Sweden, 2012. [Möller, 2012]



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



T. Clarke (Editor), *Distributed Interactive Simulation Systems for Simulation and Training in the Aerospace Environment*, SPIE Critical Reviews of Optical Science and Technology, Vol. CR58, SPIE Press, Bellingham WA, 1995. [Clarke, 1995]

Many other secondary sources (books, papers, and reports).

Concepts and Protocols outline

- Motivation and introduction
- Background definitions and concepts
- Semi-automated forces
- Distributed simulation definitions and concepts
- Distributed simulation protocol standards
- Close Combat Tactical Trainer
- Introduction to interoperability protocols
- Distributed Interactive Simulation
- High Level Architecture

(continued on next slide)

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- Test and Training Enabling Architecture
- Implementing interoperability
- Terrain issues in distributed simulation
- Summary and references

Motivation and introduction

Motivation and objectives

- Motivation
  - Distributed simulation (Dist Sim) widely used in DoD
  - Many important models use Dist Sim
  - Dist Sim protocols embody key M&S ideas
- Objectives
  - Understanding of Dist Sim definitions and concepts
  - Knowledge of important Dist Sim protocols
  - Exposure to key Dist Sim models and systems

M&S architectures

- Architecture: standalone vs distributed
- Standalone
  - Single program running on single computer
  - More common
  - Less complexity and implementation effort
  - Less validation effort
- Distributed (aka networked, interoperable)
  - Multiple programs running on multiple computers, linked via network and protocol
  - Less common
  - More complexity and implementation effort
  - More validation effort

Example distributed simulation: America's Army

- Recruiting and familiarization tool for U. S. Army
- Multiplayer online game, linked via Internet
- First person shooter
- 9.7M registered users, 42.6M downloads (2010)

Advantages (benefits) of distributed simulation

- Access additional computational power
  - Multiple computers
- Support multiple users or participants
- Combine heterogenous models
  - Developed for different purposes
  - Implemented by different developers
- Exploit existing models and model federations
  - Interoperability protocol allows connection and use
- Support geographic separation of users
- Allow multiple security levels in single simulation
  - Models run at different security levels

Background definitions and concepts

Concepts

- 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: A physical, mathematical, or otherwise logical representation of a system, entity, phenomenon, or process. [DOD, 1996] [DOD, 2009]

- 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.

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

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

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

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

Model does represent

- Height of object (output of model)
- Mass of earth (as the -16 coefficient)
- Initial state, as velocity v and height s

Model does not represent

- Air resistance (not included in model)
- Location (assumed to be near surface of earth)
- Mass of object (not included in model)

Definition

Simulation: Executing a model over time.
Also, 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] [DOD, 2009]

Alternative uses of term (to be avoided)

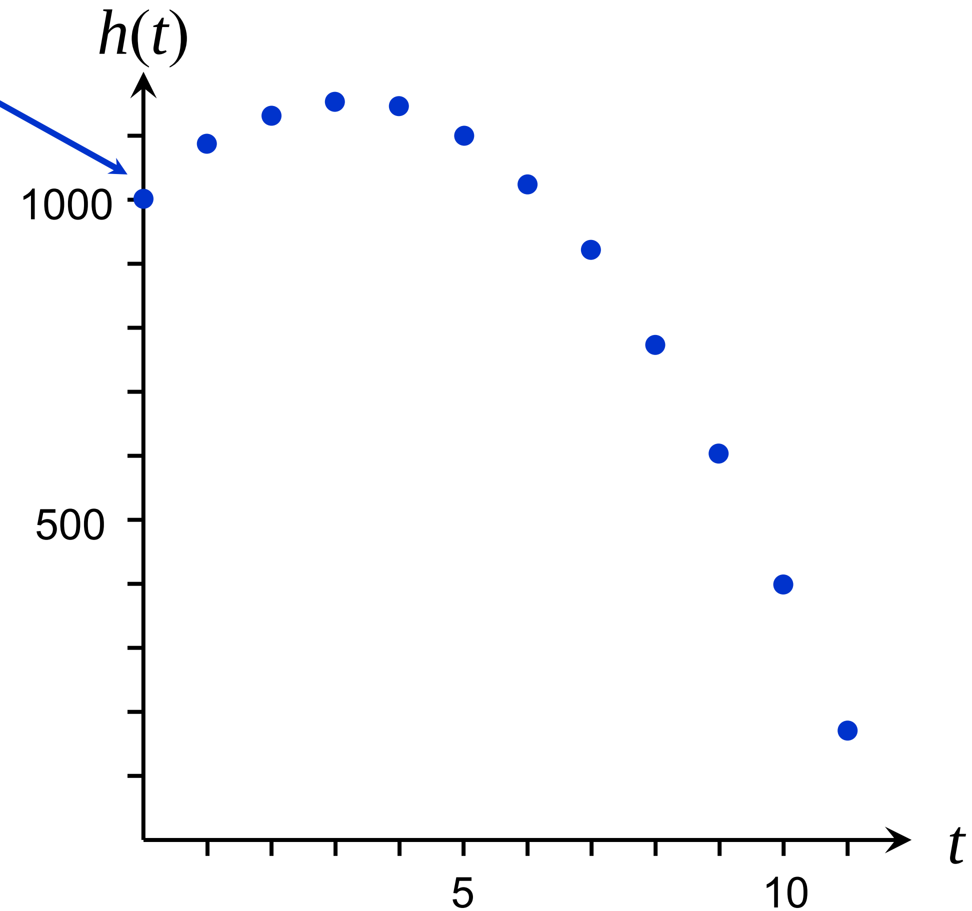
- A large composite model
- Software implementation of a model

Example simulation

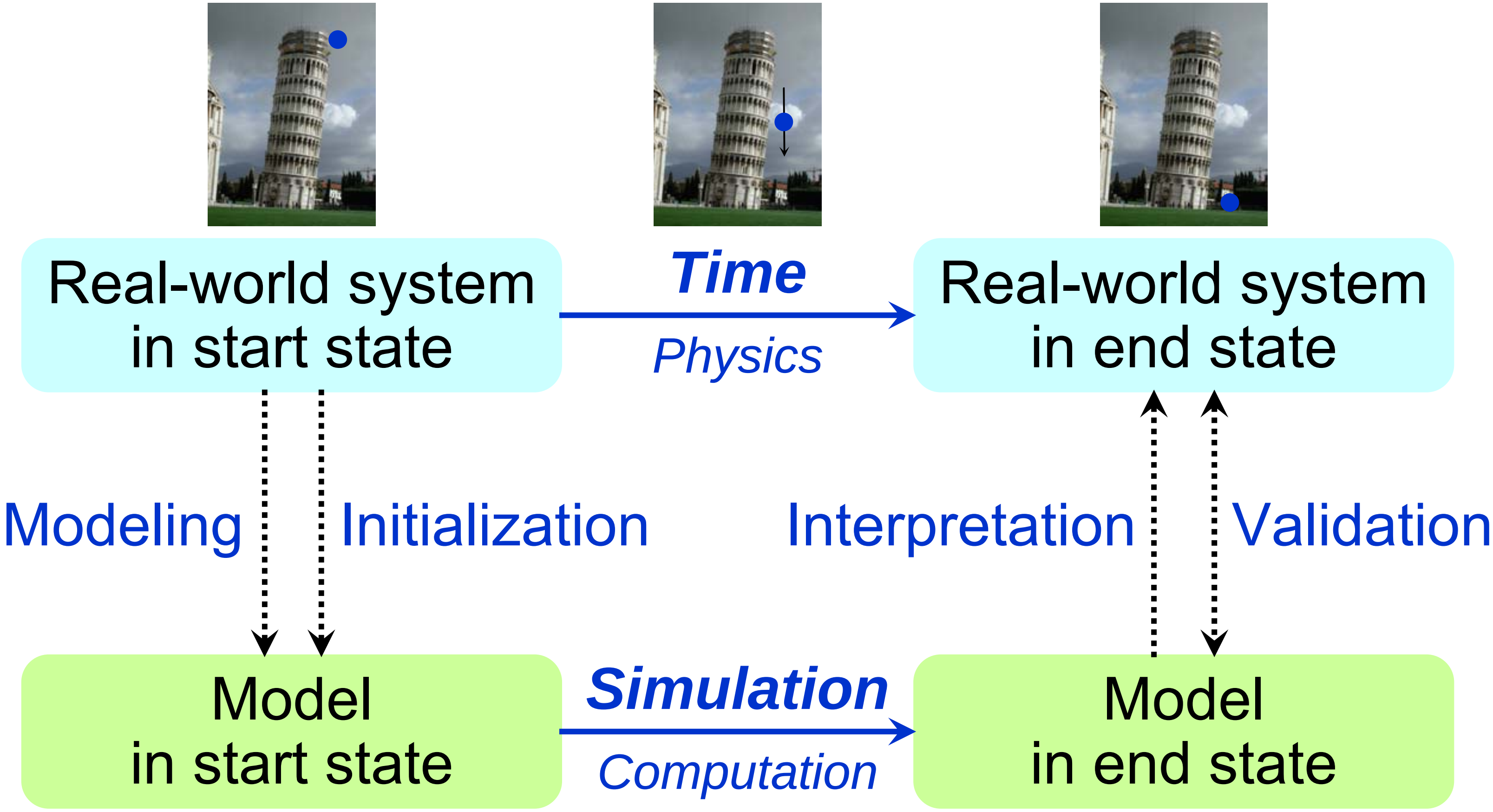
Model: $h(t) = -16t^2 + vt + s$ Data: $v = 100$, $s = 1000$

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

Start state



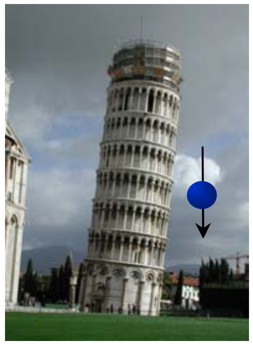
Simulation vs reality



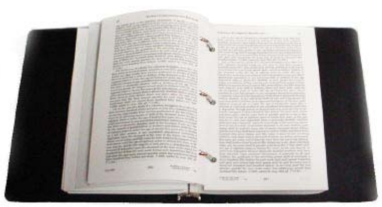
$$h(t) = -16t^2 + vt + s$$
$$1000 = -16(0)^2 + 100(0) + 1000$$

$$h(t) = -16t^2 + vt + s$$
$$0 = -16(11.63)^2 + 100(11.63) + 1000$$

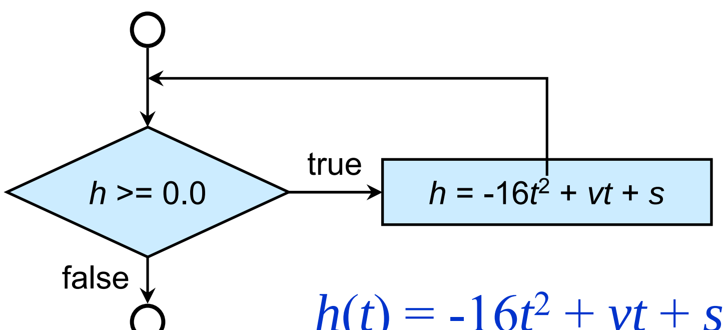
Background definitions, 1 of 2



Simuland
- Real-world system
- Thing to be simulated



Requirements
- Intended uses
- Needed validity, resolution, scale



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

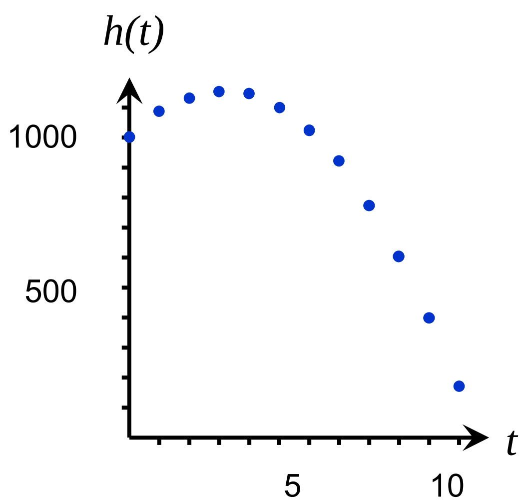
Conceptual model [BanksC, 2010]
- Simuland components, structure
- Aspects of simuland to model
- Implementation specifications
- Use cases
- Assumptions
- Initial model parameter values

Background definitions, 2 of 2

```
/* Height of an object moving in gravity.  */
/* Initial height v and velocity s constants. */
main()
{
  float h, v = 100.0, s = 1000.0;
  int t;
  for (t = 0, h = s; h >= 0.0; t++)
  {
    h = (-16.0 * t * t) + (v * t) + s;
    printf("Height at time %d = %f\n", t, h);
  }
}
```

Executable model

- Computer software
- Implemented conceptual model



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

Results

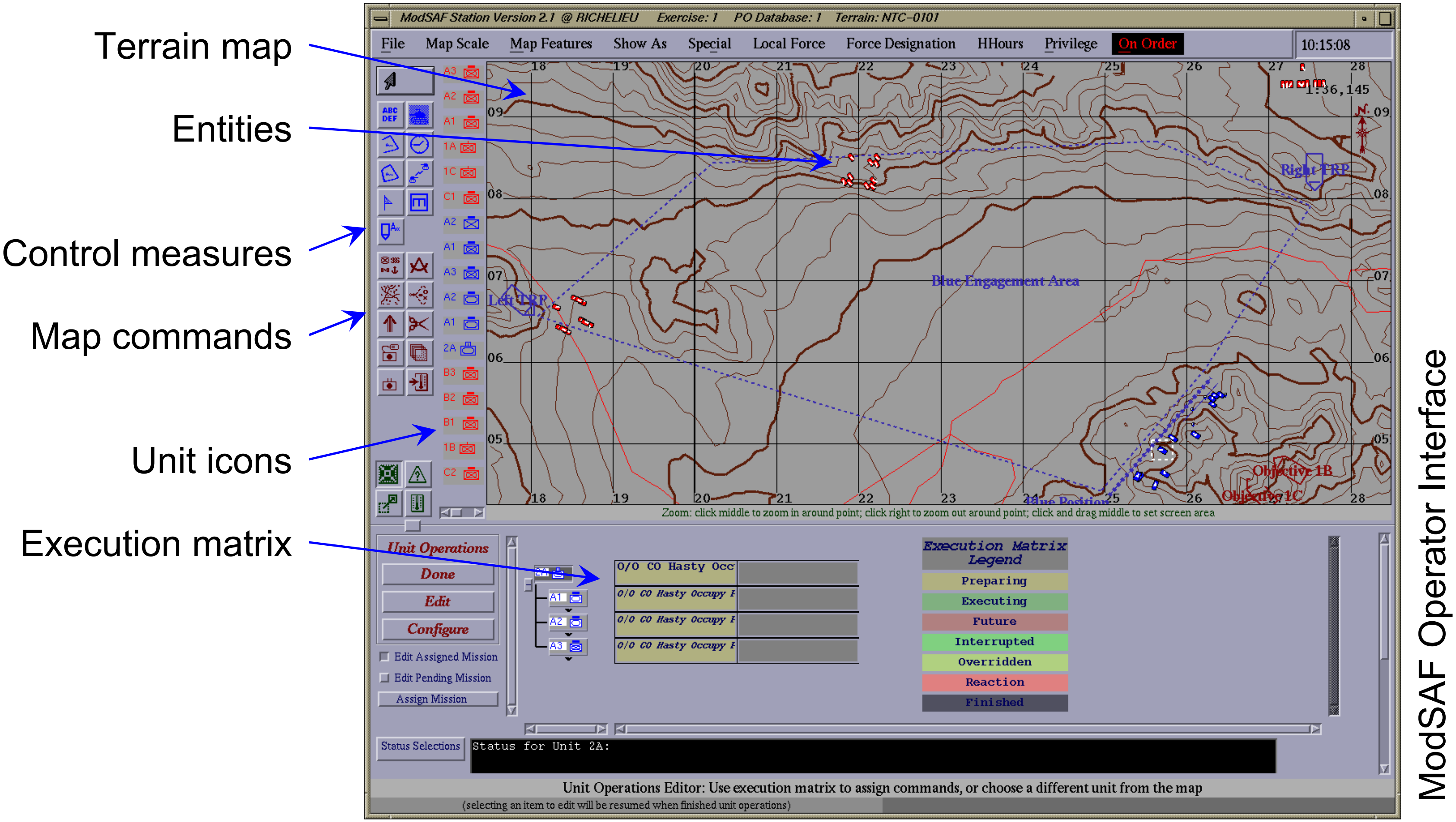
- Output of model
- Produced during simulation

Semi-Automated Forces

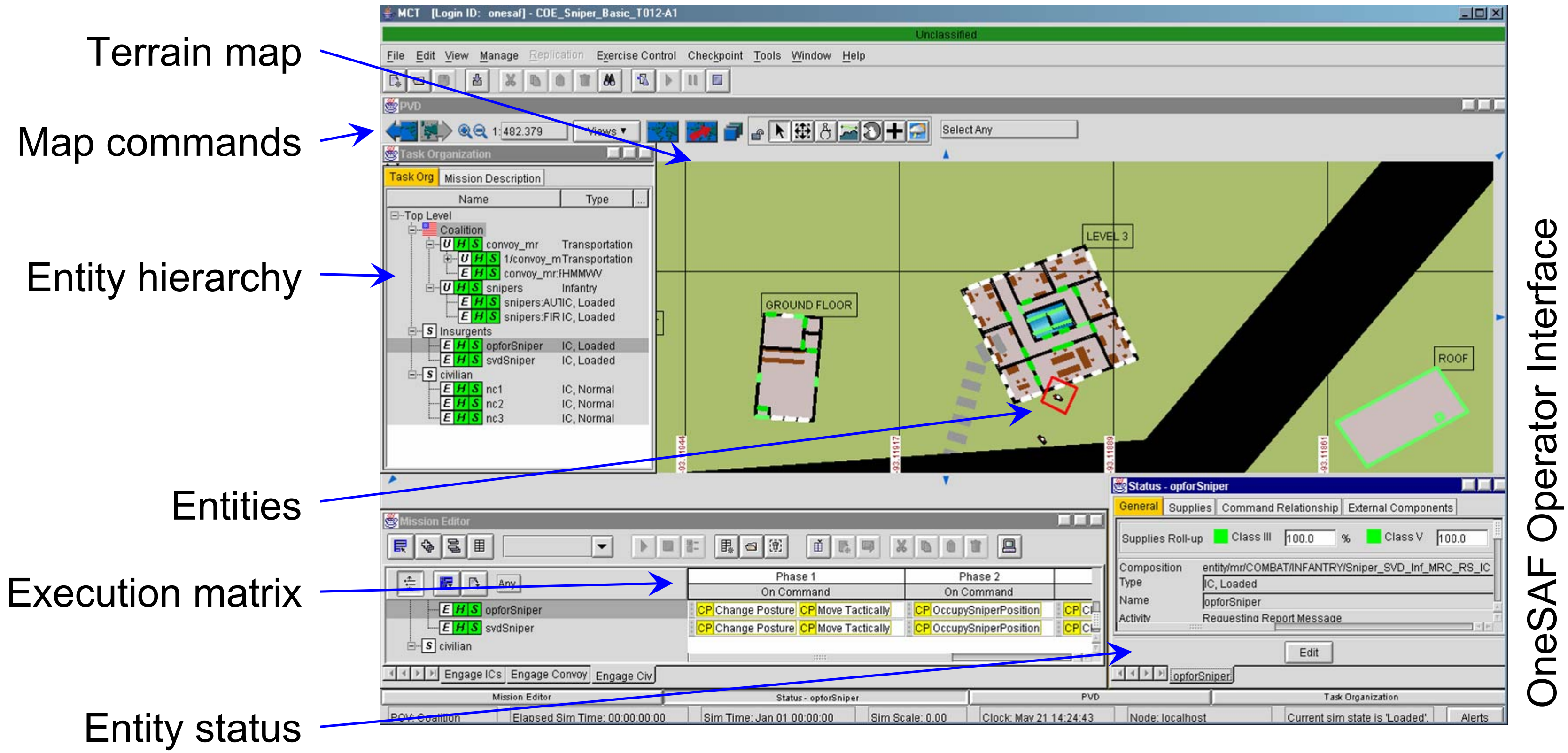
Semi-automated forces (SAF) systems [Petty, 1995]

- Generate and control multiple simulated entities
- Used standalone or with other models
- Autonomous behavior for SAF entities [Petty, 2009]
  - Generated by software in SAF model
  - Controlled by human operator via user interface
  - Military hierarchy represented
- Environment represented (e.g., terrain)
- Example SAF systems
  - ModSAF; once most widely used, now unsupported
  - OneSAF; current U. S. Army standard SAF
  - VT MAK VR-Forces; commercial product
- aka computer generated forces (CGF)

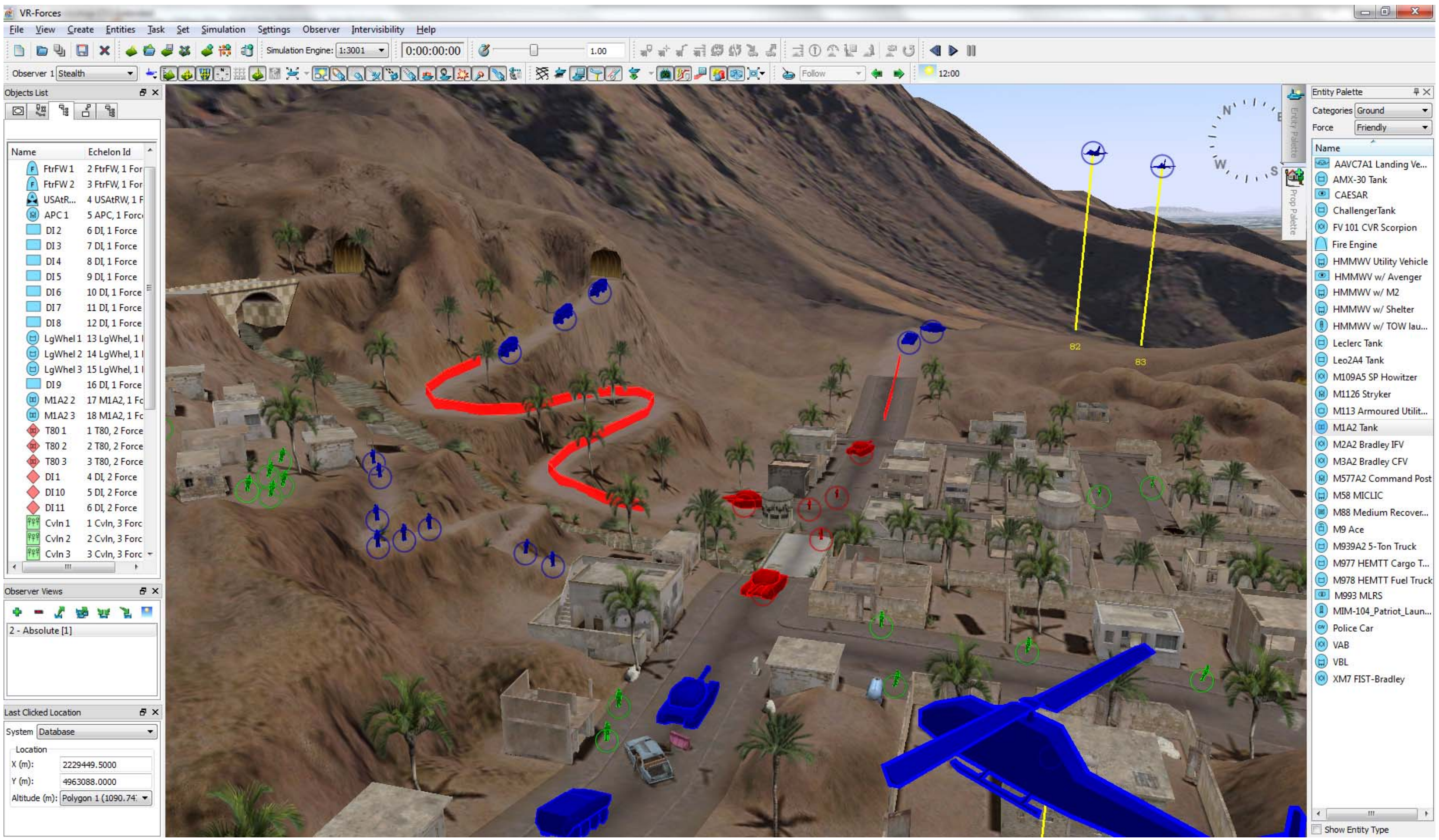
Example SAF: ModSAF



Example SAF: OneSAF

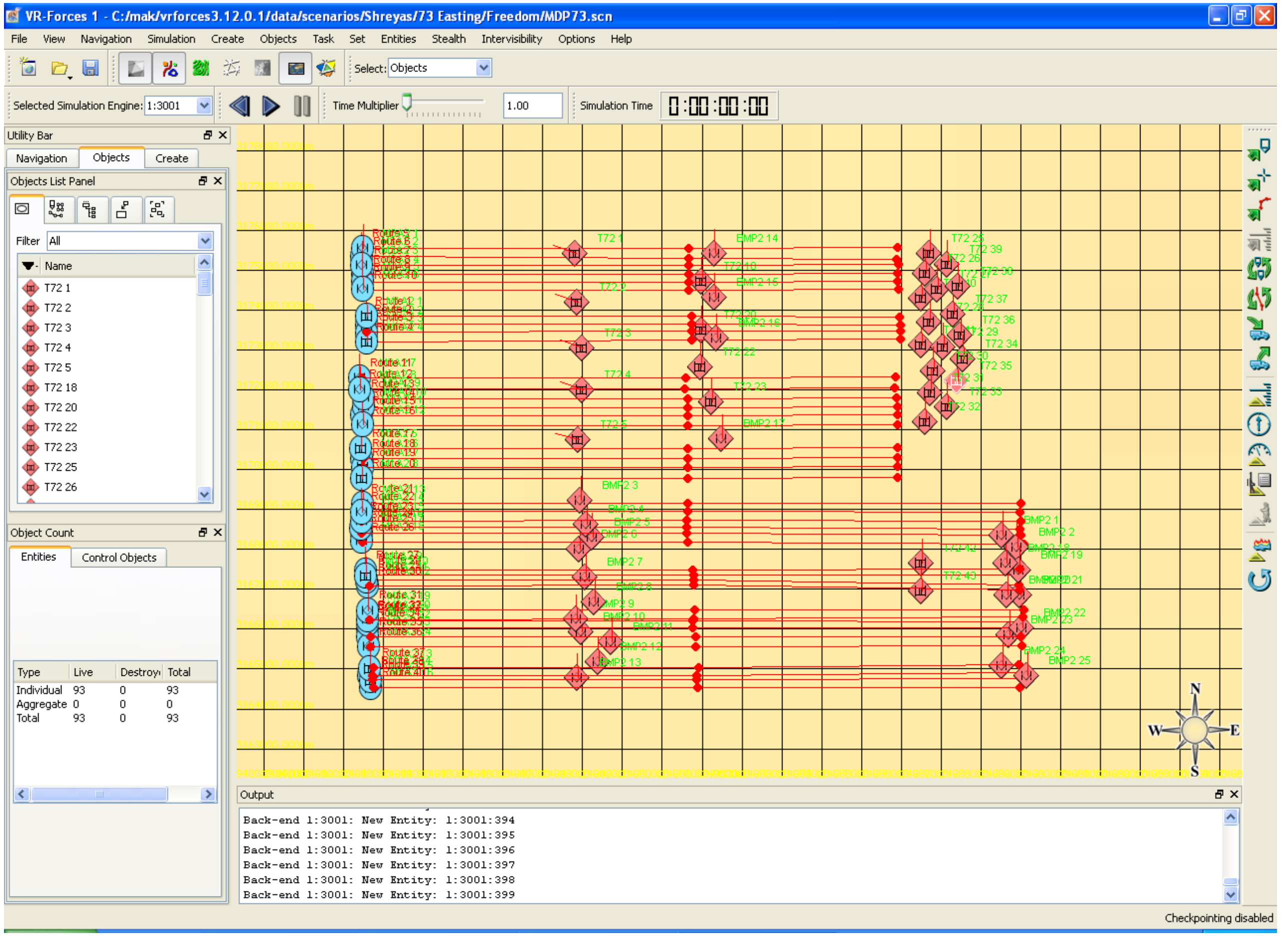


Example SAF: VR-Forces



VR-Forces 3D View

Example SAF: VR-Forces



VR-Forces Operator Interface
Recreation of 1991 Battle of 73 Easting
[Daniels, 2012]

Distributed simulation definitions and concepts

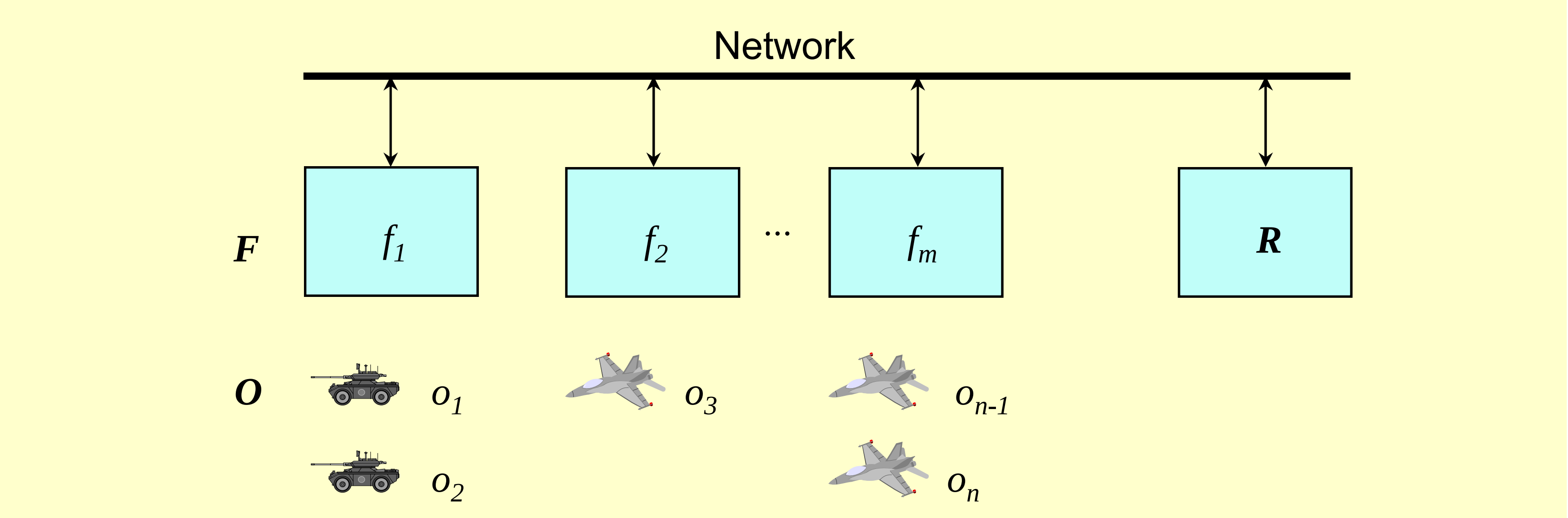
Definition

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

Generic distributed simulation architecture



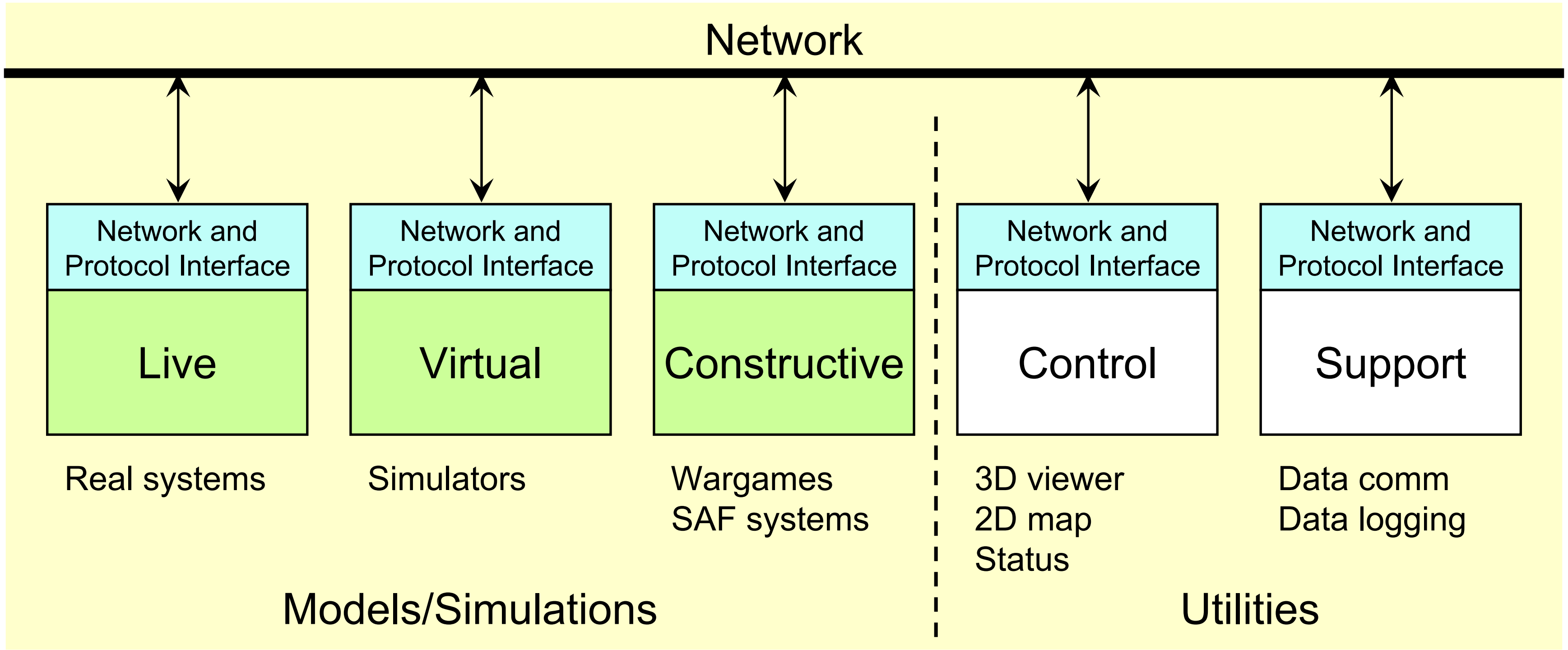
- $F = \{f_1, f_2, \ldots, f_m\}$ simulation nodes
- $O = \{o_1, o_2, \ldots, o_n\}$ simulated entities
- R non-simulation support node
- Network and protocol

Distributed simulation conceptual framework

- Simulation domain
  - What entities are represented?
- Model characteristics
  - How are the entities modeled?
- Software architecture and implementation
  - What implementation techniques are used?
- Simulation infrastructure
  - What network services & protocol are used?
- Computing infrastructure
  - What computing hardware is used?

Distributed simulation system components

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



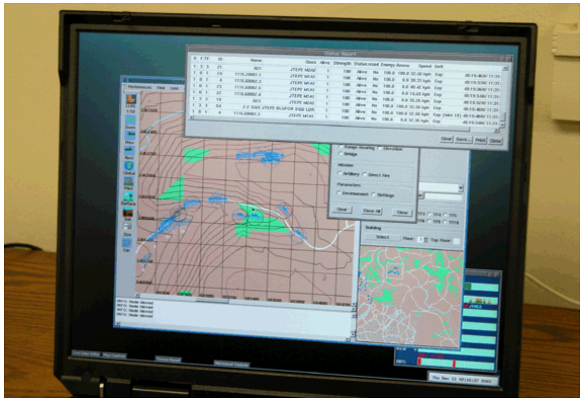
Models/Simulations

Node of a distributed simulation system that is simulating part of the exercise/experiment

- Live; actual systems
- Virtual; simulators
- Constructive; semi-automated forces

Live; instrumented vehicle

Virtual; flight simulator



Constructive; SAF

Utilities

Node of a distributed simulation system that performs a non-simulation support function

- Support data transport
- Log transmitted data "datalogger"
- Provide view into simulation "stealth viewer"
- Monitor and control overall execution "monitor"

Monitor 1992

Stealth, SAF 1998

Informal 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 vs parallel simulation

- Distributed simulation
  - Nodes relatively loosely bound
  - Often (not always) real time
  - Usually implemented on separate computers connected via network and protocol
- Parallel simulation
  - Nodes relatively tightly bound
  - Often (not always) logical time
  - Usually implemented as multiple processes on single multi-processor computer
- Not disjoint

In depth:
Close Combat Tactical Trainer

Example distributed simulation: CCTT

- Close Combat Tactical Trainer
- Virtual simulators
  - Participants (trainees) inside vehicle simulators
  - Computer generated images of battlefield
- Combat training
  - Mounted and dismounted team tactics
  - Platoon to battalion units
- CCTT training sites
  - Fixed: U.S. x6, Germany, South Korea; 10-40 simulators per site
  - Mobile: x8; 1 simulator per trailer

CCTT simulator external views

Simulator bay

M1 simulator

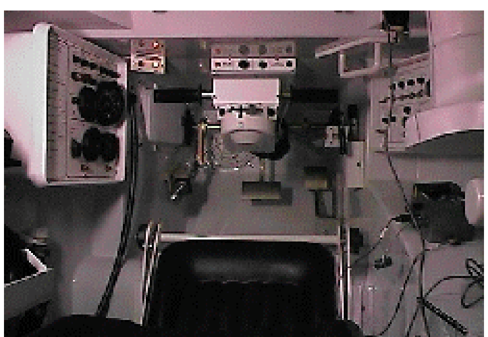
Simulator bay

M1 simulator

CCTT simulator internal views


M1 commander


M1 gunner


M1 driver


M1 loader

CCTT simulator internal views

HMMWV driver

HMMWV observer

Dismounted Infantry

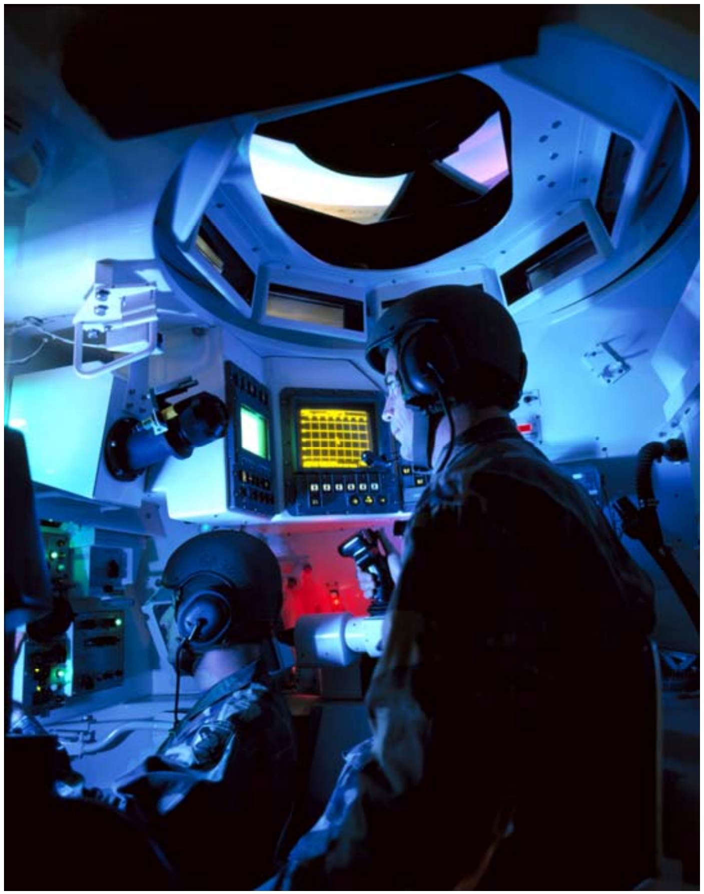
M2 driver

CCTT simulator out-the-window views






Additional CCTT images



Enhanced M1 turret

Battlemaster station

Bridging and burning

Additional CCTT images

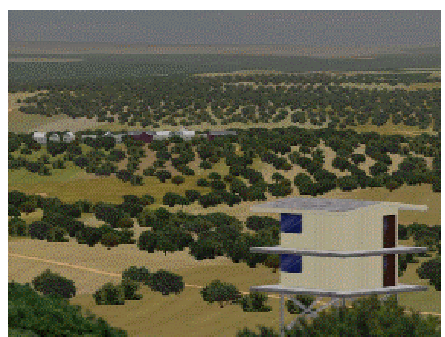

CCTT reconfigurable vehicle trainer


CCTT reconfigurable vehicle trainer

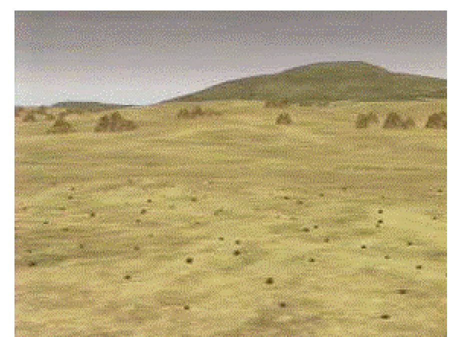
CCTT technical details

- Simulators connected via network
  - Distributed simulation, using DIS protocol
  - Other model types connected, e.g., logger, SAF
- Virtual terrain
  - High-fidelity geospecific or geotypical
  - 9x locations where potential engagements anticipated
  - Central Germany, Kosovo, Korea, Baghdad, NTC, …

Germany

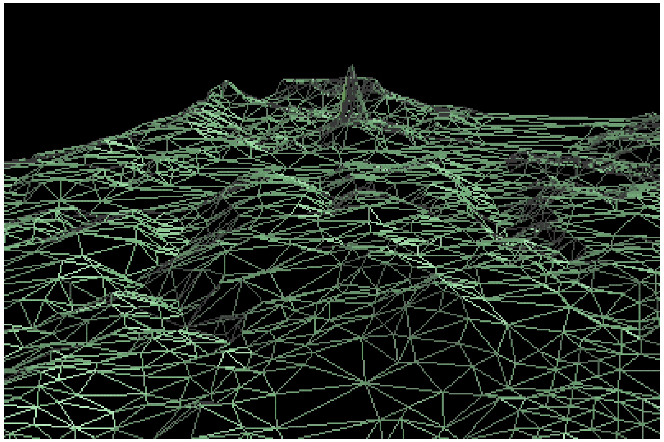


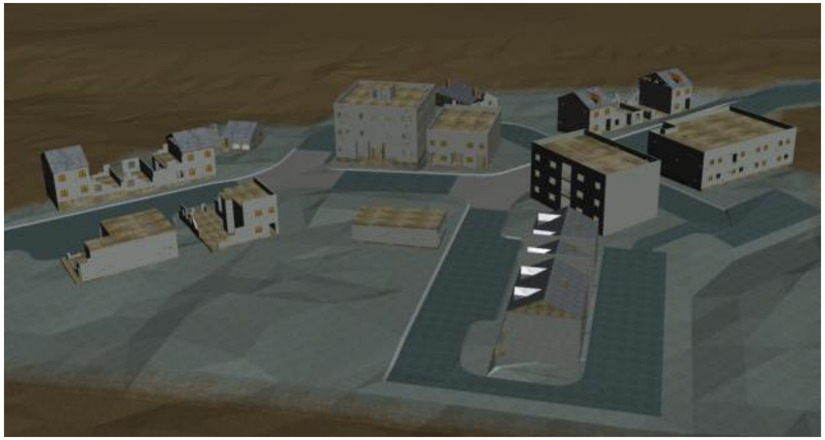
Fort Hood



NTC

Terrain





- Terrain database
  - Represents geographic area of scenario
  - Identical (or correlated) among linked models
- Representation
  - Terrain surface formed from polygons (triangles)
  - Texture, type associated with each triangle
  - x, y, z values at vertices on 2D grid or arbitrary
  - Features (e.g., trees, buildings) separate

Introduction to interoperability protocols

Definition

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

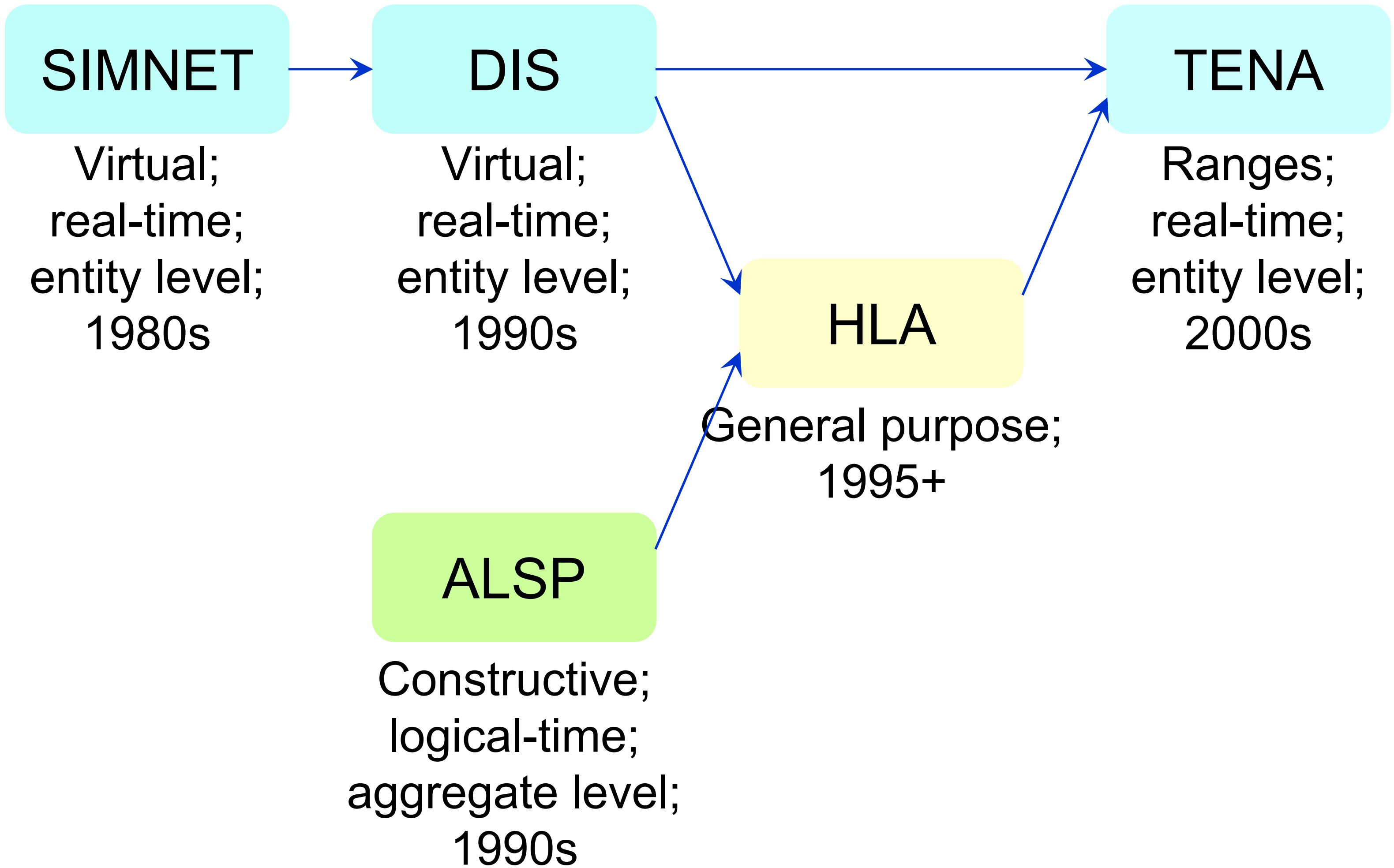
General protocol characteristics

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

Military distributed simulation 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: Simulator Networking (SIMNET)

- Characteristics
  - Mounted combat
  - Distributed, virtual, entity level, real-time
  - Homogenous, proprietary
  - Both protocol and simulation system
- Purpose: team tactics training

M1 turret

M1 driver

Simulator bay

Out-the-window

Distributed simulation protocol: Aggregate Level Simulation Protocol (ALSP)

- Protocol designed to link constructive models
- Time management capabilities
  - Synchronize and advance simulation time, i.e., logical time
  - Simulation time different from wall-clock time
- Some models linked with ALSP
  - CBS (Corps Battle Simulation)
  - AWSIM (Air Warfare Simulation)
  - JTC (Joint Training Confederation)

Distributed Interactive Simulation

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
  - 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

DIS PDU types

PDU Family/Type	DIS Version
Entity Information/Interaction	
Entity State	1278.1
Entity State Update	1278.1a
Collision	1278.1
Collision-Elastic	1278.1a
Warfare	
Fire	1278.1
Detonate	1278.1
Simulation Management	
Create Entity	1278.1
Remove Entity	1278.1
Start/Resume	1278.1
Stop/Freeze	1278.1
Acknowledge	1278.1
Action Request	1278.1
Action Response	1278.1
Data Query	1278.1
Set Data	1278.1
Data	1278.1
Event Report	1278.1
Comment	1278.1

PDU Family/Type	DIS Version
Radio Communications	
Transmitter	1278.1
Signal	1278.1
Receiver	1278.1
Intercom Control	1278.1a
Intercom Signal	1278.1a
Distributed Emission Regeneration	
Electromagnetic Emission	1278.1
Designator	1278.1
IFF/ATC/NAVAIDS	1278.1a
Underwater Acoustic	1278.1a
Supplemental Emissions/Entity State	1278.1a
Logistics Support	
Service Request	1278.1
Re-supply Offer	1278.1
Re-supply Received	1278.1
Re-supply Cancel	1278.1
Repair Complete	1278.1
Repair Response	1278.1
Minefield	
Minefield State	1278.1a
Minefield Query	1278.1a
Minefield Data	1278.1a
Minefield Response NACK	1278.1a

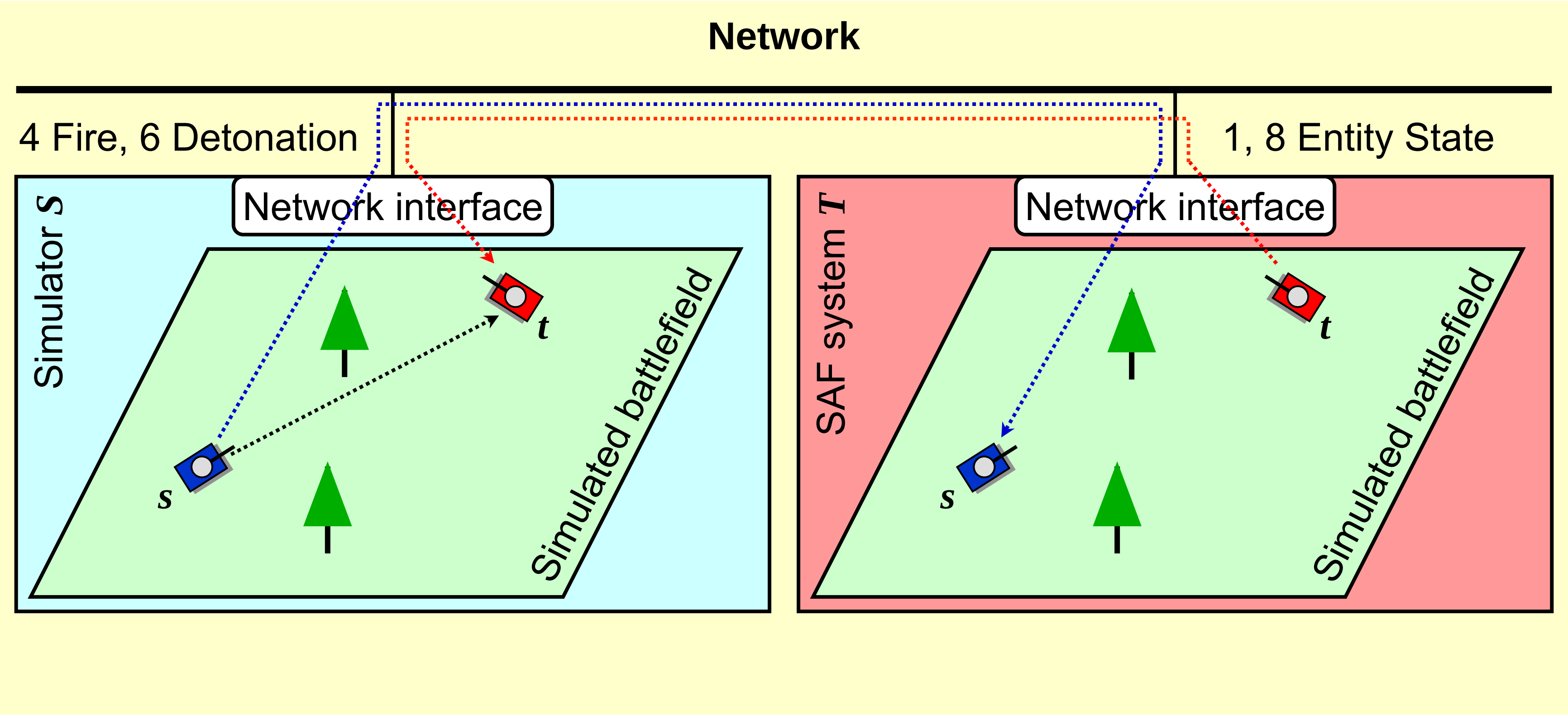
Parts 1 and 2 of 3

PDU Family/Type	DIS Version
Synthetic Environment	
Environmental Process	1278.1a
Gridded Data	1278.1a
Point Object State	1278.1a
Linear Object State	1278.1a
Areal Object State	1278.1a
Entity Management	
Aggregate State	1278.1a
IsGroupOf	1278.1a
Transfer Control Request	1278.1a
IsPartOf	1278.1a
Live Entity	
Time Space Position Information	1278.1a
Appearance	1278.1a
Articulated Parts	1278.1a
LE Fire	1278.1a
LE Detonation	1278.1a
Non-Real Time	
Action Request	1278.1a
Action Response	1278.1a
Set Data	1278.1a
Data Query	1278.1a
Data	1278.1a

Part 3 of 3

Example DIS interaction: direct fire

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



Example DIS direct fire interaction sequence

1. SAF system T sends Entity State PDU for T-72 t at a specific location.
2. Simulator S receives Entity State PDU for T-72 t and uses it to render t in view port of M1 s.
3. The crew of M1 s see T-72 t and fire on it in simulator S.
4. Simulator S sends a Fire PDU announcing that s has fired.

Continued on next slide

5. Simulator *S* determines if a hit was scored. (Assume yes.)
6. Simulator *S* sends a Detonation PDU to SAF system *T* announcing that *t* was hit by *s*; PDU includes details of hit.
7. SAF system *T* determines effect of hit on *t*. (Assume *t* is destroyed.)
8. SAF system *T* sends a new Entity State PDU for *t* with its new appearance (destroyed).

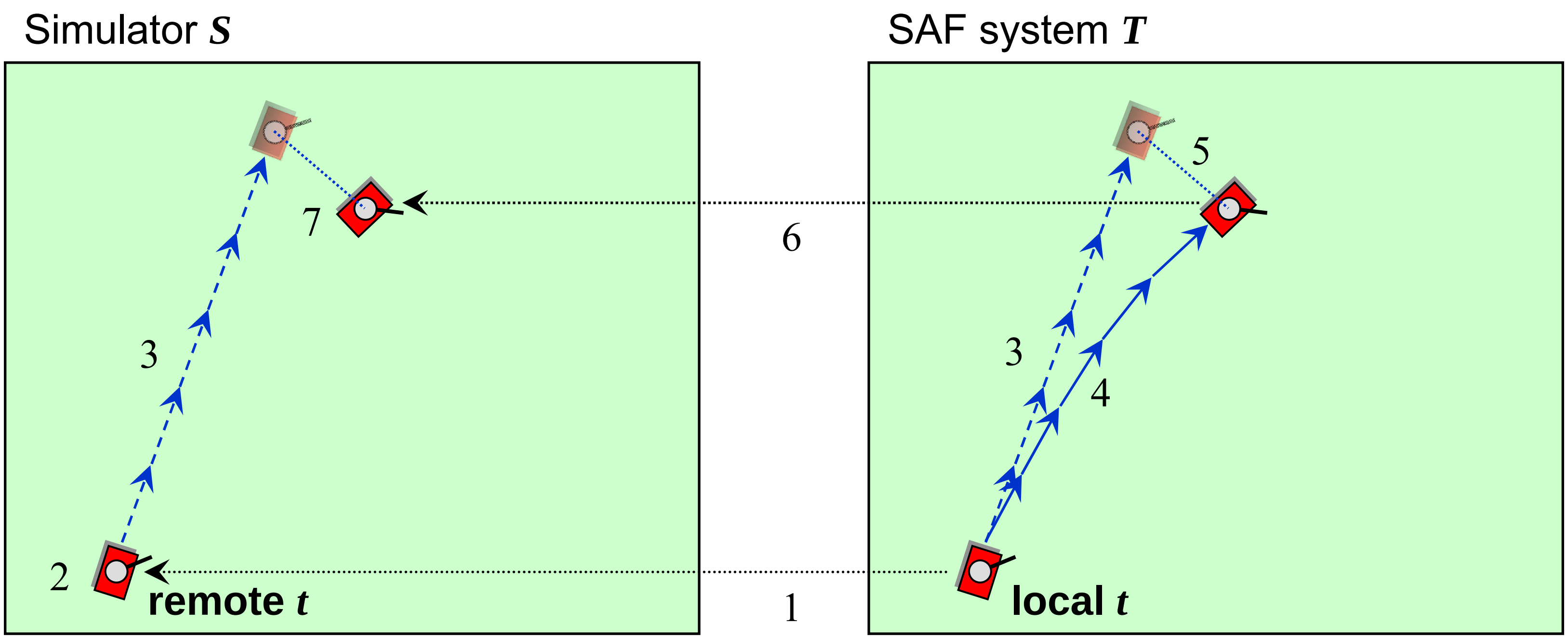
DIS and local copies

- Definition
  - Remote nodes send entity data updates at intervals
  - Local nodes keep copies to use between updates
  - Non-persistent form of redundancy
  - Motivated by performance (vs network query)
- Example uses of local copies
  - Sensing and detection (e.g., intervisibility)
  - Combat (e.g., direct fire)
- Local copies updated via dead reckoning

Example DIS common algorithm: dead reckoning [Lin, 1995]

- Purpose
  - Reduce network message volume
  - Provide remote entity location whenever needed
- Mechanism
  - Node projects (“dead reckons”) location of each remote entity since last ES PDU received
  - Nodes both model and dead reckon local entities, send ES PDU when discrepancy too large

Dead reckoning sequence



1. *T* broadcasts Entity State PDU for *t* with position and velocities
2. *S* receives Entity State PDU for *t*, sets position and velocities
3. *S* and *T* both dead reckon *t* over time
4. *T* models actual movement of *t* over time

(3 and 4: concurrent)

5. *T* finds that discrepancy between actual and dead reckoned positions for *t* exceeds threshold
6. *T* broadcasts Entity State PDU for *t* with position and velocities
7. *S* receives Entity State PDU for *t*, set position and velocities

Example DIS-based Dist Sim system: Close Combat Tactical Trainer

Simulator interior

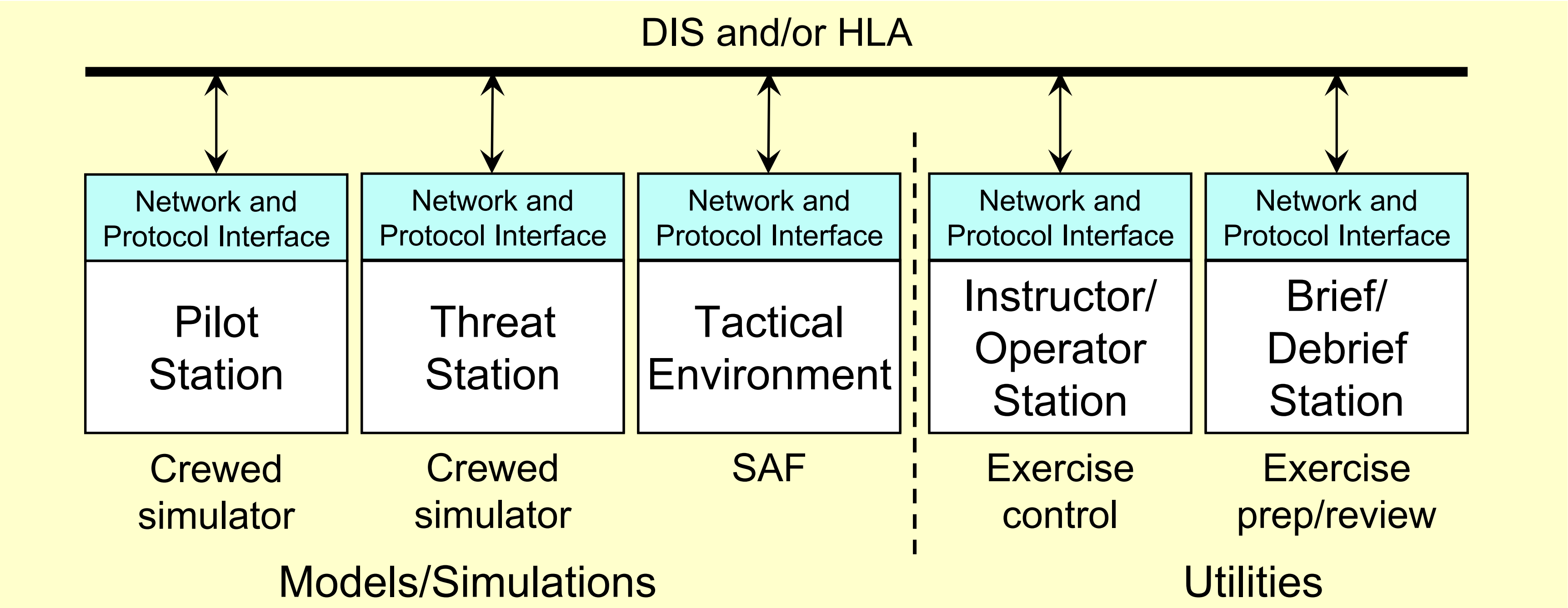
- Models mounted combat
- Virtual, entity level, real-time
- Heterogenous, non-proprietary
- Includes simulators, SAF, utilities
- Uses DIS protocol

Simulator bay

Out-the-window view

Example DIS-based Dist Sim system: Distributed Mission Training (DMT)

- U. S. Air Force flight simulation system
- Used for training: mission and team, not skill
- Distributed sim, connected via DIS and/or HLA

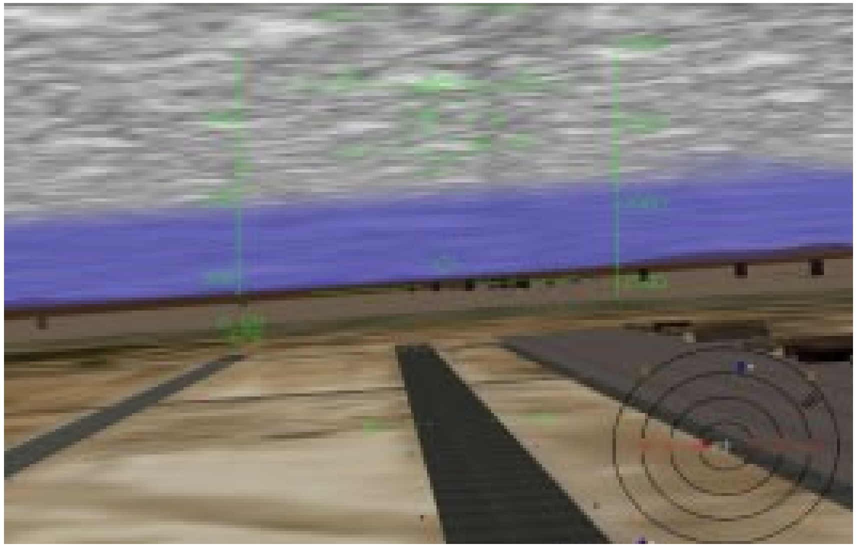


DMT pilot station [Boeing, 2004]

- Simulated cockpit for aircraft pilot
  - F-15C and other aircraft
  - Includes flight dynamics, controls, visuals
- Real-time, virtual environment for trainee

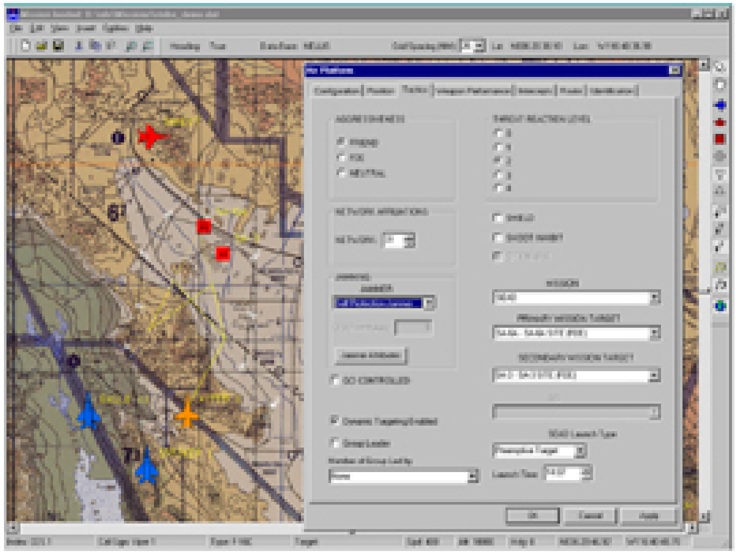
Threat station

- Control friendly/threat aircraft
  - Simple simulated cockpit
  - Used for operator, i.e., non-trainee
- Produce specific aircraft behaviors for exercise



Tactical environment generator

- Simulates mission environment
  - Constructive simulations; SAF for exercise
  - Friendly and threat entities and sensors
- Generates context for training



Instructor/operator station

- Simulation control capabilities
  - Construct scenarios
  - Stop, start, replay, intervene in exercise
- Control and monitor exercise

Brief/debrief station

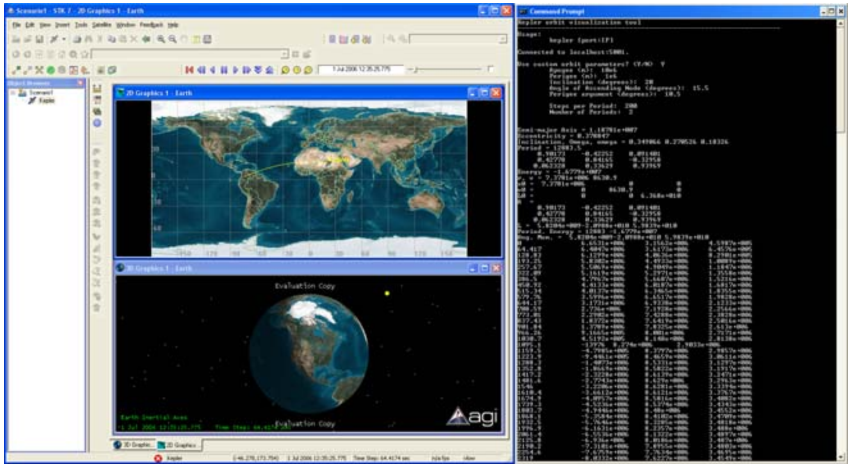
- Briefing and visualization capabilities
  - Map overview of mission/exercise
  - Pilot-generated mission/exercise planning
- Preparation and after-action review

High Level Architecture

Distributed simulation protocol: High Level Architecture (HLA)

HLA is a general purpose distributed simulation protocol and architecture.

“The High Level Architecture is an architecture for reuse and interoperability of simulations.”
[Dahmann, 1998a]



"Major functional elements, interfaces, and design rules, pertaining as feasible to all DOD simulation applications, and providing a common framework within which specific simulation system architectures can be defined." [DOD, 1996] [DOD, 1998]

Design premises of HLA [Dahmann, 1998b]

- 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
- Separation of functionality
  - Application-specific (i.e., data definition)
  - General infrastructure (i.e., data transport)

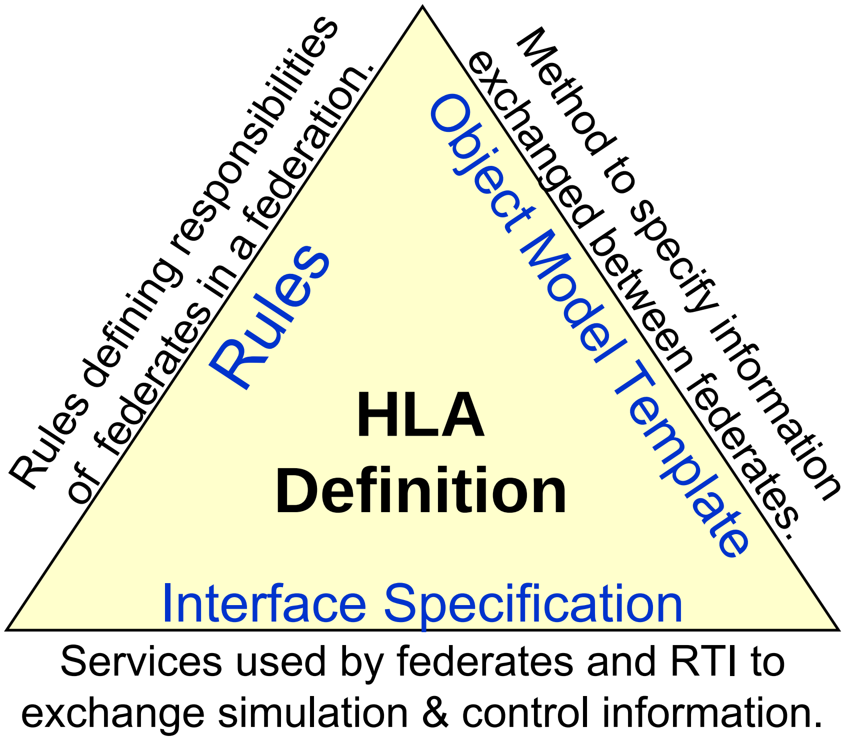
HLA development history

- Initial development [Dahmann, 1998b]
  - Initiated 1995
  - Sponsored and organized by DMSO
  - Design and implementation overseen by Architecture Management Group
- Proto-Federations
  - Test implementations of HLA federations 1996
  - Four proto-federations, different applications: Analysis, Engineering, Joint Training, Platform
  - Each had multiple federates
  - Many lessons [Harkrider, 1996a] [Harkrider, 1996b] [Harkrider, 1997]

- Subsequent developments
  - HLA designated DoD distributed simulation standard ("Kaminski Mandate") 1996
  - DoD 1.3 version made DoD standard 1998
  - IEEE 1516 version made IEEE standard 2000
- Current status
  - Revision to IEEE 1516 standard "HLA Evolved", made standard 2010 [IEEE, 2010a] [IEEE, 2010b] [IEEE, 2010c]
  - HLA widely adopted, extensively used
  - Many federates, federations, tools developed

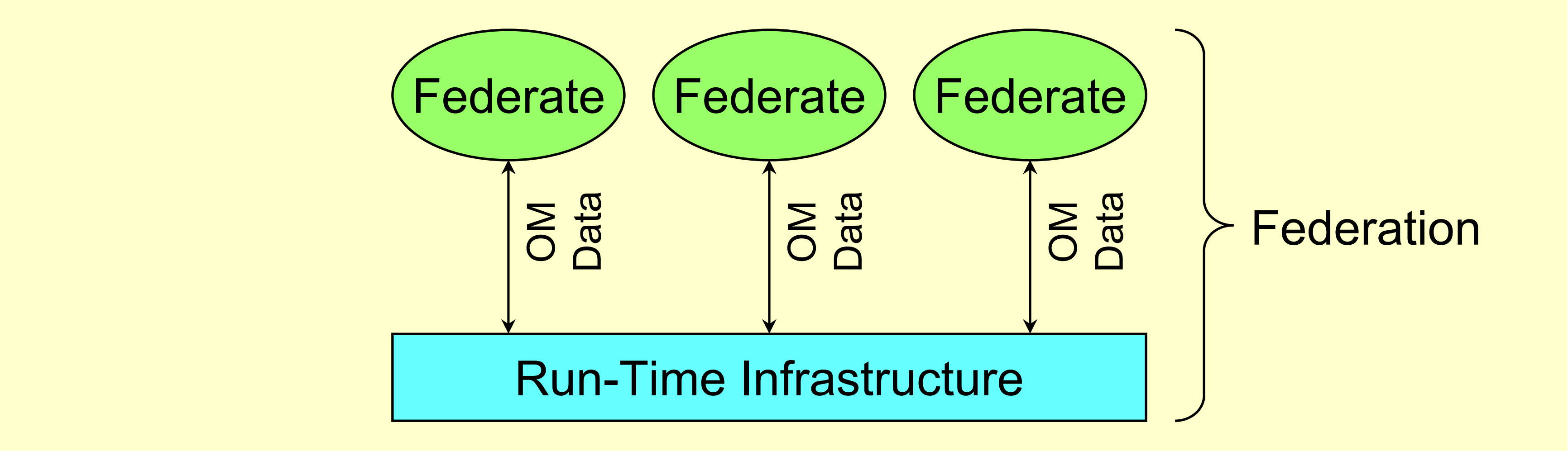
HLA specifications

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

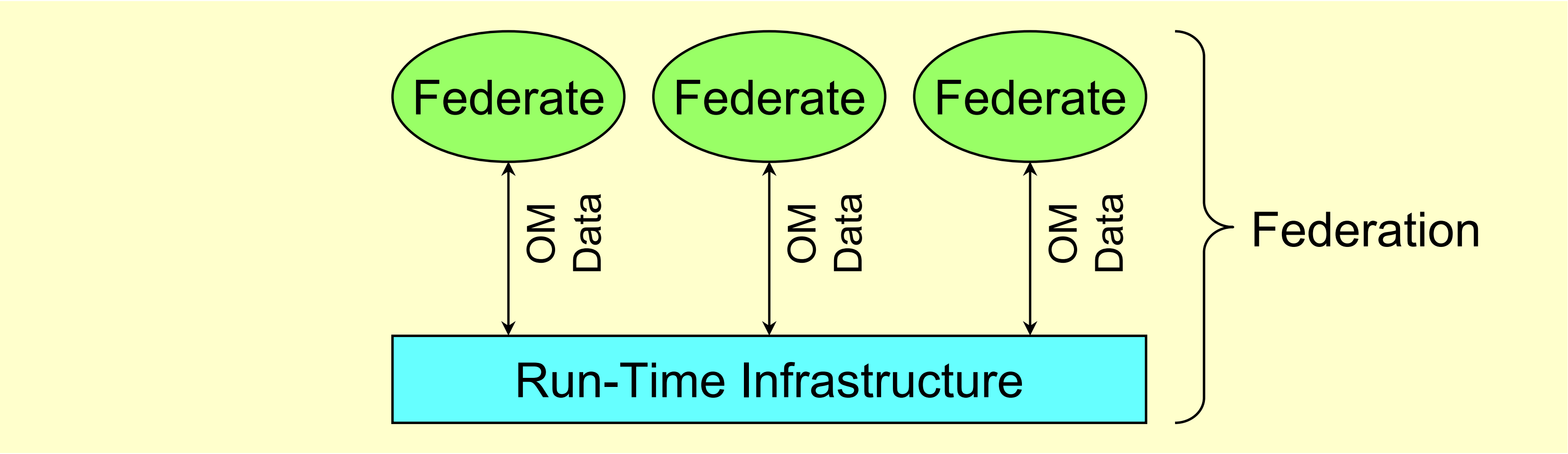


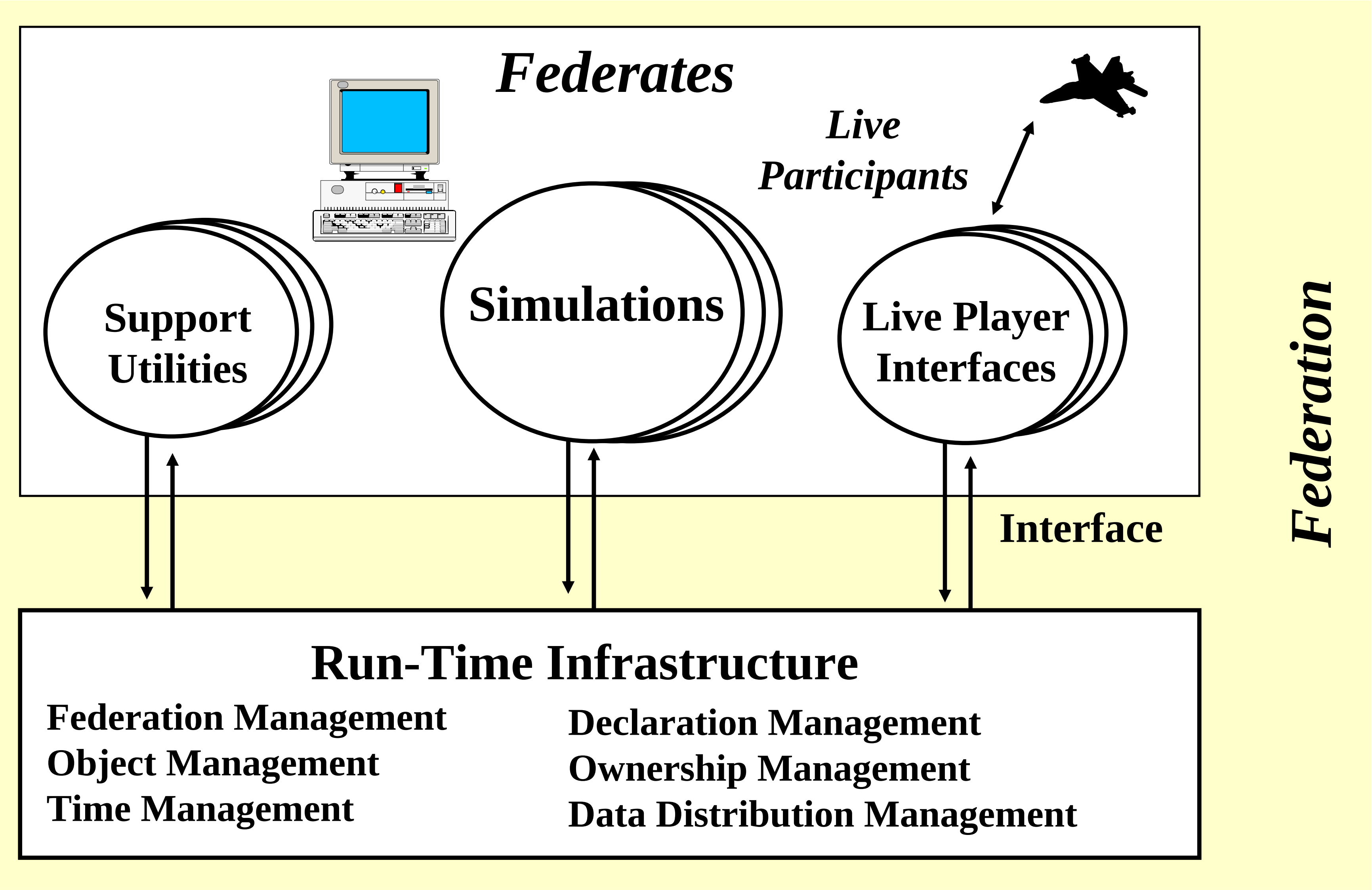
HLA terms

- 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




Federates
Live
Participants
Support
Utilities
Simulations
Live Player
Interfaces
Interface
Federation
Run-Time Infrastructure
Federation Management
Object Management
Time Management
Declaration Management
Ownership Management
Data Distribution Management

HLA Rules

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

Federation rules [IEEE, 2010a]

1) Federations shall have an HLA FOM, documented in accordance with the HLA OMT.
2) In a federation, all simulation-associated object instance representation shall be in the federates, not in the RTI.
3) During a federation execution, all exchange of FOM data among joined federates shall occur via the RTI.
4) During a federation execution, joined federates shall interact with the RTI in accordance with the HLA interface specification.
5) During a federation execution, an instance attribute shall be owned by at most one joined federate at any given time.

Federate rules [IEEE, 2010a]

6) Federates shall have an HLA Simulation Object Model (SOM), documented in accordance with the HLA OMT.
7) Federates shall be able to update and/or reflect any instance attributes and send and/or receive interactions, as specified in their SOMs.
8) Federates shall be able to transfer and/or accept ownership of instance attributes dynamically during a federation execution, as specified in their SOMs.
9) Federates shall be able to vary the conditions (e.g., thresholds) under which they provide updates of instance attributes, as specified in their SOMs.
10) Federates shall be able to manage local time in a way that will allow them to coordinate data exchange with other members of a federation.

HLA object models

- Define federation data to be exchanged
- 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”

HLA object models

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- Similar, not same, as “object-oriented”

Example OM: Class table

HLA object Root (N)	Customer (PS)				
	Bill (PS)				
	Order (PS)				
	Employee (N)	Greeter (PS)			
		Waiter (PS)			
		Cashier (PS)			
		Dishwasher (PS)			
		Cook (PS)			
	Food (S)	MainCourse (PS)			
		Drink (S)	Water (PS)		
			Coffee (PS)		
			Soda (PS)		
		Appetizers (S)	Soup (S)	ClamChowder (PS)	Manhattan (P)
					NewEngland (P)
				BeefBarley (PS)	
			Nachos (PS)		
		Entree (S)	Beef (PS)		
			Chicken (PS)		
			Seafood (S)	Fish (PS)	
				Shrimp (PS)	
				Lobster *[Note1] (PS) *[Note2]	
			Pasta (PS)		
		SideDish (S)	Corn (PS)		
			Broccoli (PS)		
			BakedPotato (PS)		
		Dessert (S)	Cake (PS)		
			IceCream (S)	Chocolate (PS)	
				Vanilla (PS)	
Note	NA				

[IEEE, 2010b]

Example OM: Attribute table

Object	Attribute	Datatype	Update type	Update condition	D/A	P/S	Available dimensions	Transport-ation	Order
HLAobject Root	HLA privilege ToDelete Object	HLAtoken	NA	NA	N	N	NA	HLAreliable	Time-stamp
Employee	PayRate	DollarRate	Conditional	Merit increase *[Note3]	DA	PS	NA	HLAreliable	Time-stamp
	YearsOf Service	Years	Periodic	1/year *[Note4]	DA	PS	NA	HLAreliable	Time-stamp
	Home Number	HLAASCII string	Conditional	Employee request	DA	PS	NA	HLAreliable	Time-stamp
	Home Address	Address Type	Conditional	Employee request	DA	PS	NA	HLAreliable	Time-stamp
Employee. Waiter	Efficiency	Waiter Value	Conditional	Performance review	DA	PS	NA	HLAreliable	Time-stamp
	Cheerful-ness	Waiter Value	Conditional	Performance review	DA	PS	NA	HLAreliable	Time-stamp
	State	Waiter Tasks	Conditional	Work flow	DA	PS	NA	HLAreliable	Time-stamp
Food.Drink	Number Cups	DrinkCount	Conditional	Customer request	N	PS	BarQuantity	HLAreliable	Time-stamp
Food.Drink. Soda	Flavor	FlavorType	Conditional	Customer request	N	PS	SodaFlavor, BarQuantity	HLAreliable	Time-stamp
Note	NA								

[IEEE, 2010b]

Example OM: Interaction and Parameter tables

HLAinteractionRoot (N)	CustomerTransaction (P)	CustomerSeated (PS)	
		OrderTaken (P)	FromKidsMenu (P)
			FromAdultMenu (P)
		FoodServed (P)	DrinkServed (P)
			AppetizerServed (P)
			MainCourseServed (P)
			DessertServed (P)
		CustomerPays (P)	ByCreditCard (P)
			ByCash (P)
		CustomerLeaves (PS)	
Note	NA		

[IEEE, 2010b]

Interaction	Parameter	Datatype	Available dimensions	Transportation	Order
CustomerSeated	NA	NA	NA	HLAreliable	TimeStamp
FoodServed.MainCourseServed	TemperatureOk	ServiceStat	WaiterId	HLAreliable	TimeStamp
	AccuracyOk	ServiceStat			
	TimelinessOk	HLAboolean			
Note	NA				

[IEEE, 2010b]

HLA object attributes

- Redundancy?
  - Multiple objects (instances) of a single object class may be created (instantiated) during execution
  - Same set of data items (attributes) for each object, but different objects, attributes, values
  - No redundancy
- Inconsistency?
  - Ownership (right to update) of an object attribute may be transferred from federate to federate
  - Ownership limited by HLA to one federate at a time
  - No inconsistency

HLA Example DIF

```
<?xml version="1.0"?>
<!DOCTYPE objectModel SYSTEM "HLA.dtd">
<objectModel
   DTDversion="1516.2"
   name="Example"
   type="FOM"
   version="1.0"
   date="2000-04-01"
   purpose="Provide an example of an HLA FOM"
   sponsor="DMSO">
   <objects>
      <objectClass name="HLAobjectRoot"
         sharing="Neither">
         <attribute name="HLAprivilegeToDeleteObject"
            dataType="NA"
            updateType="NA"
            updateCondition="NA"
            ownership="NoTransfer"
            sharing="Neither"
            dimensions="NA"
            transportation="HLAreliable"
            order="TimeStamp"/>
         <objectClass name="UserBaseClass"
            sharing="Neither"
            semantics="This object class is the base of all user-defined object
                       classes">
            <objectClass name="UserSubclass"
               sharing="PublishSubscribe"
               semantics="This is a subclass of UserBaseClass">
               <attribute name="UserAttribute"
                  dataType="UserDatatype"
                  updateType="Static"
                  updateCondition="NA"
                  ownership="NoTransfer"
                  sharing="PublishSubscribe"
                  dimensions="NA"
                  transportation="HLAreliable"
                  order="TimeStamp"
                  semantics="Attribute of UserSubclass"/>
            </objectClass>
```

```
<basicData name="HLAinteger16LE"
   size="16"
   interpretation="Integer in the range [-2^15, 2^15 - 1]"
   endian="Little"
   encoding="16-bit two's complement signed integer. The most
            significant bit contains the sign."/>
<basicData name="HLAinteger32LE"
   size="32"
   interpretation="Integer in the range [-2^31, 2^31 - 1]"
   endian="Little"
   encoding="32-bit two's complement signed integer. The most
            significant bit contains the sign."/>
<basicData name="HLAinteger64LE"
   size="64"
   interpretation="Integer in the range [-2^63, 2^63 - 1]"
   endian="Little"
   encoding="64-bit two's complement signed integer first. The most
            significant bit contains the sign."/>
<basicData name="HLAfloat32LE"
   size="32"
   interpretation="Single-precision floating point number"
   endian="Little"
   encoding="32-bit IEEE normalized single-precision format. See IEEE
            Std 754-1985"/>
<basicData name="HLAfloat64LE"
```

Special HLA object models

- Federation object model (FOM)
  - Shared object model in federation
  - Objects and interactions
- Simulation object model (SOM)
  - Object model for single federate
  - Objects and interactions
  - External only
- Federation's FOM generally a subset of the union of the federates' SOMs
- RPR FOM recreates DIS as HLA OM

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

Federation Management services [IEEE, 2010c]

- Purpose
  - Control federation executions
  - Join and resign from federation executions
- Example services
  - Create Federation Execution
  - Join Federation Execution
  - Resign Federation Execution
  - Destroy Federation Execution
  - Request Federation Save
  - Federation Saved †

Declaration Management services [IEEE, 2010c]

- Purpose
  - Announce intent to send or receive data
  - Based on object and interaction classes
- Example services
  - Publish Object Class Attributes
  - Subscribe Object Class Attributes
  - Publish Interaction Class
  - Subscribe Interaction Class

Object Management services [IEEE, 2010c]

- Purpose
  - Create and delete objects
  - Send and receive object updates & interactions
- Example services
  - Register Object Instance
  - Discover Object Instance †
  - Update Attribute Values
  - Reflect Attribute Values †
  - Delete Object Instance
  - Remove Object Instance †

Ownership Management services [IEEE, 2010c]

- Purpose
  - Transfer ownership of object attributes between federates
- Example services
  - Negotiated Attribute Ownership Divestiture
  - Request Attribute Ownership Assumption †

Time Management services [IEEE, 2010c]

- Purpose
  - Control and synchronize simulation time
- Example services
  - Time Advance Request
  - Time Advance Grant †
  - Retract
  - Request Retraction †

Data Distribution Management services [IEEE, 2010c]

- Purpose
  - Filter data sent between federates
  - Based on data value ranges
- Example services
  - Create Region
  - Register Object Instance With Regions
  - Subscribe Object Class Attributes With Regions

Support services [IEEE, 2010c]

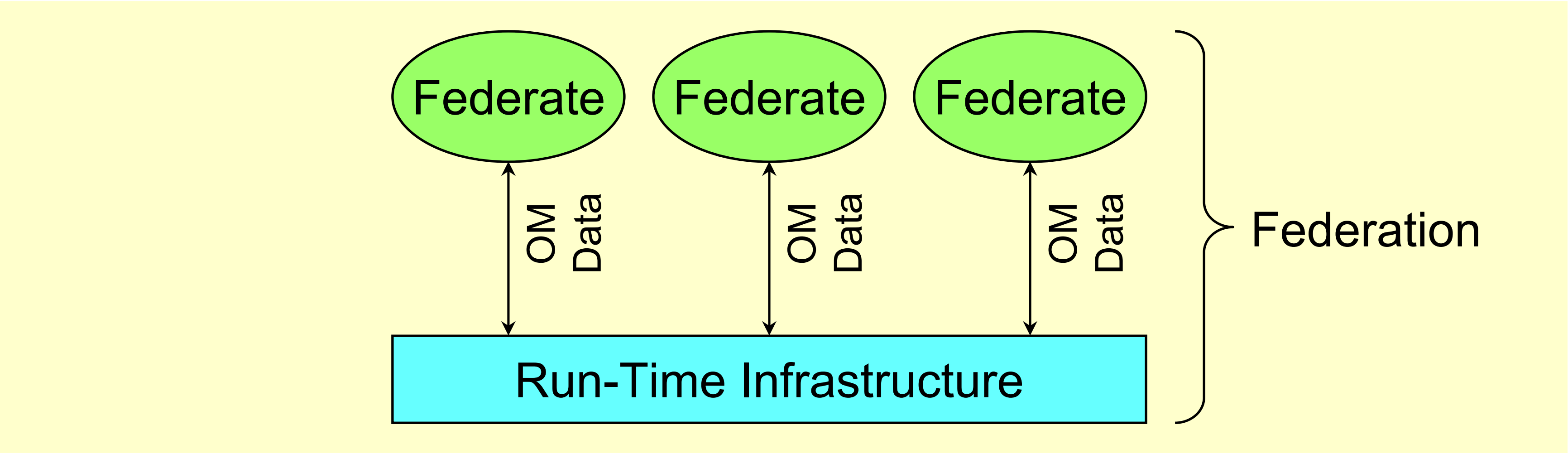
- Purpose
  - Provide infrastructure status information
- Example services
  - Get Object Class Handle
  - Get Attribute Handle
  - Enable Callbacks
  - Disable Callbacks

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

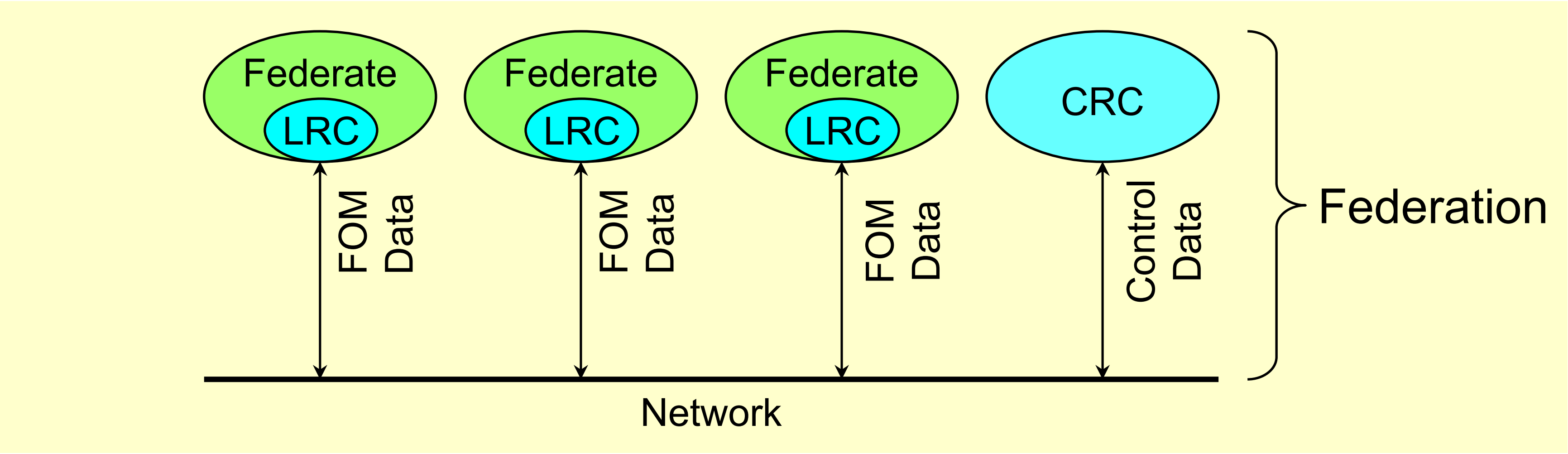
Logical view of a federation

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



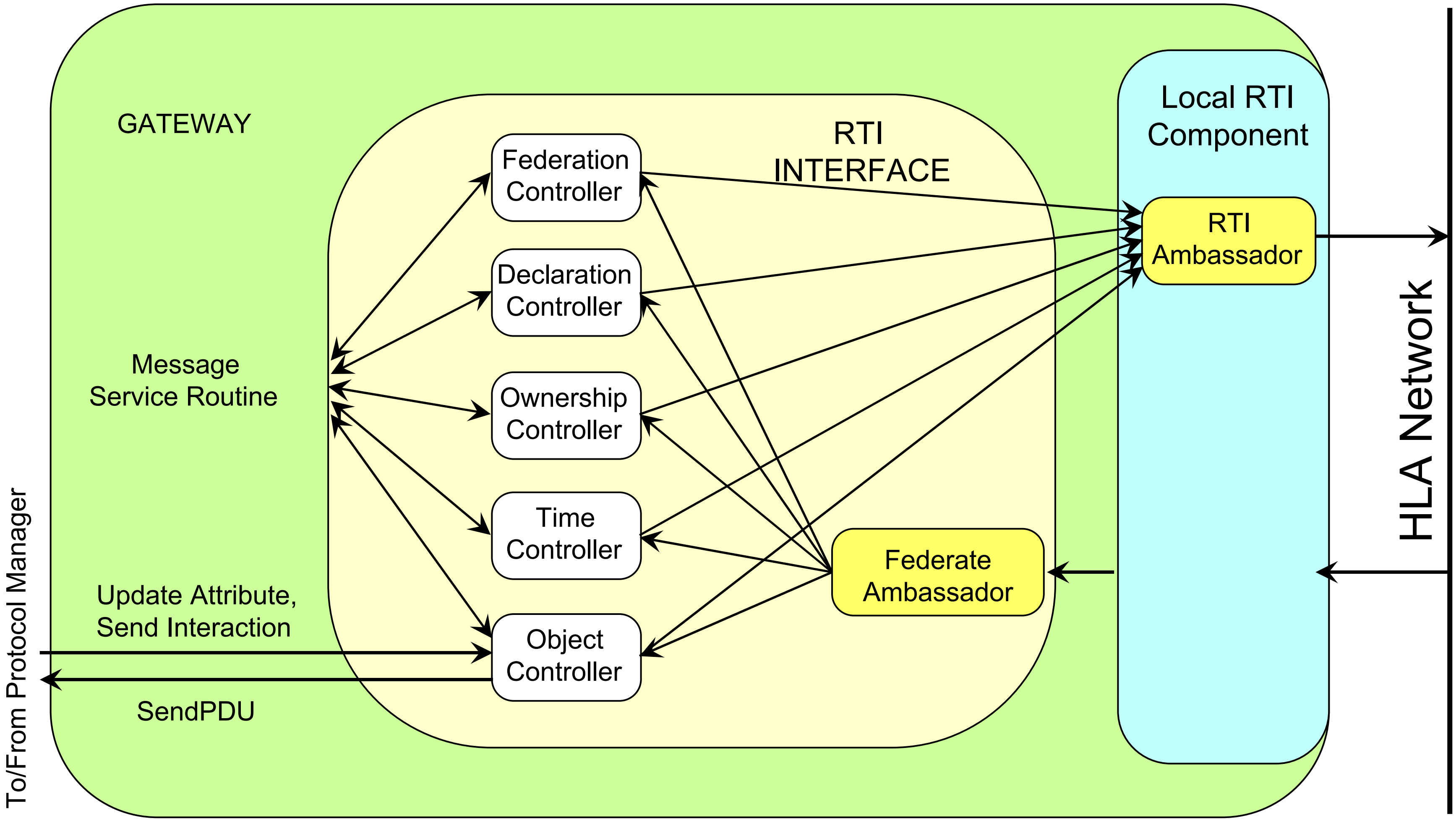
Technical view of a federation

- 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

RTI services invoked via Ambassadors



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, 2004c]
  - Widely used
  - Federates, federations, tools, products available
- HLA 1516-2010
  - Developed from IEEE 1516
  - Standardized 2010 [IEEE, 2010a] [IEEE, 2010b] [IEEE, 2010c]

HLA compliance

- Compliance
  - Independent agencies test HLA federates
  - Successful test certifies “HLA compliance”
  - 1996 mandate connected compliance to funding
- Approaches to compliance
  - Native; use HLA directly
  - Middleware; HLA hidden in software layer
  - Gateway; protocol translator [Wood, 1999]
- Non-compliance
  - Waivers available, compliance less important
  - Non-compliant, non-standard implementations exist, e.g., JFCOM RTI-s

HLA summary

- Goals and premises
  - General-purpose, flexible distributed simulation
  - Architecture, protocol, middleware
  - Provides data transport, other services
  - Semantics in object models, not in HLA
- Defined by specifications
  - Federates and federation follow Rules
  - Data defined per Object Model Template
  - Interface Specification defines services, interfaces
- Run-Time Infrastructure
  - Implements services, transports data
  - Multiple RTI versions available

- Standards and compliance
  - HLA standards (chronological order):
    DoD 1.3, IEEE 1516-2000, IEEE 1516-2010
  - Independent testing for protocol compliance
- Well established
  - Numerous HLA federates, federations, applications
  - Mature IEEE standard

Test and Training Enabling Architecture

Distributed simulation protocol: Test and Training Enabling Architecture (TENA)

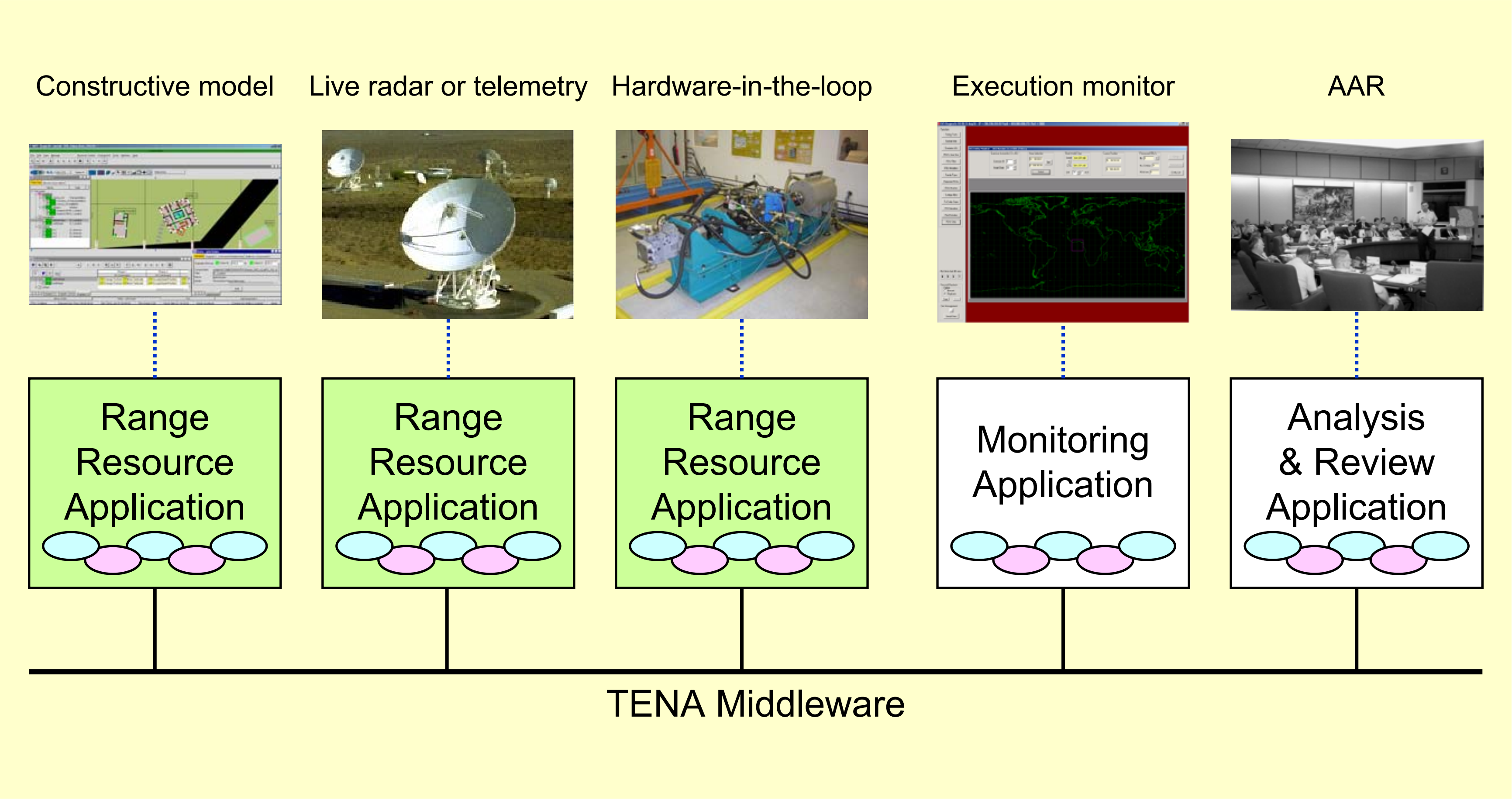
[TENA, 2008]

- Designed for range (test, training) applications
  - Entity level
  - Live, virtual, constructive
  - Real-time response
- Protocol and architecture
  - Protocol; object model, messages
  - Architecture; common middleware
- Goals
  - Iterative improvement based on user feedback
  - Interoperability, reusability, composability

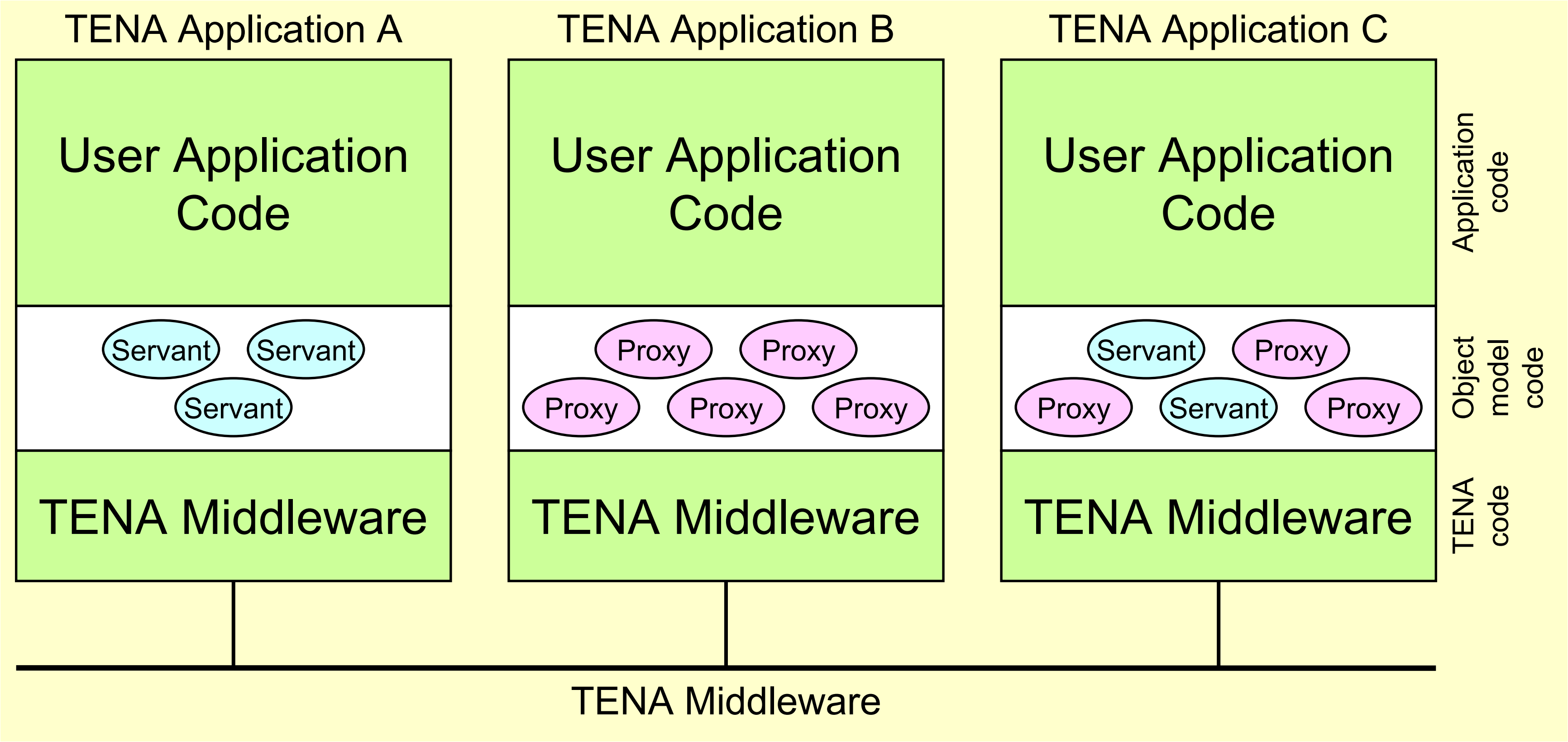
TENA components

- Architecture components
  - TENA Object Model
  - TENA Middleware
- Common context
  - Representation of the environment (SEDRIS)
- Software development support
  - Development process (TENA Technical Process)
  - Reusable tools (object model utilities)
  - Repository (software components)
  - Data archive (execution data)

TENA architecture overview



TENA application architecture



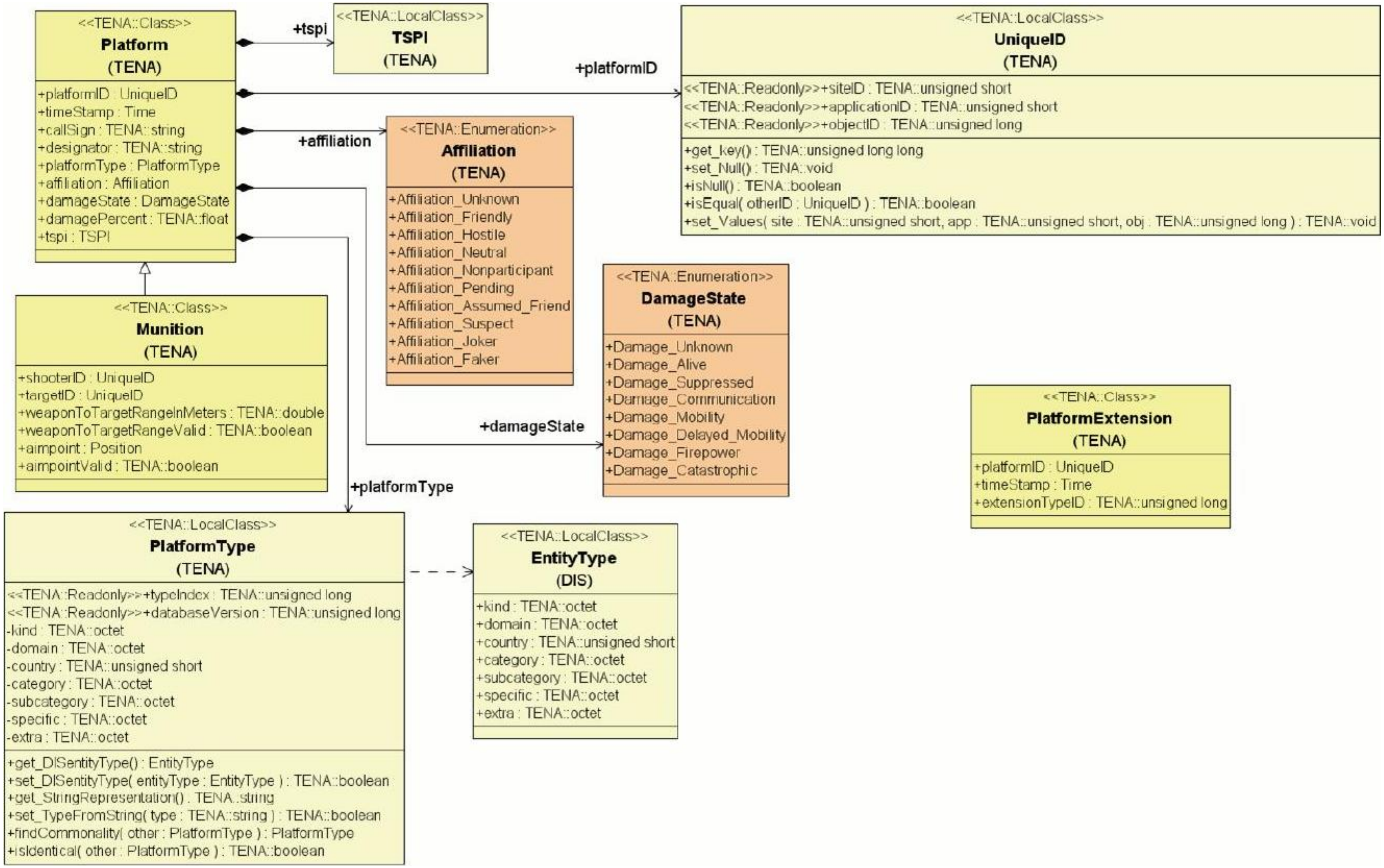
TENA Logical Range Object Model (LROM)

- Object definitions used in logical range execution
  - Contain objects needed in execution
  - LROM may come from multiple sources
- Common object model
  - Shared by all applications in logical range
  - Provides “common language”
- Incrementally enhanced
  - User developed objects, custom for logical range
  - Supported objects, available for reuse
  - Standard objects, approved for standardization
  - Latter expected to increase over time

TENA standard object models

- TENA-Radar-v2
- TENA-GPS-v1
- TENA-Platform
  - TENA-Platform-v3.1
  - TENA-PlatformDetails-v3
  - TENA-Affiliation-v1
  - TENA-UniqueID-v2
  - TENA-PlatformType-v1
  - DIS-EntityType-v2
  - TENA-Munition-v2.1
  - TENA-Engagement-v3.1
  - TENA-Organization-v1
  - TENA-EmbeddedSystem-v2
  - TENA-EmbeddedSensor-v21
  - TENA-EmbeddedWeapon-v2
- TENA-TSPI
  - TENA-TSPI-v4
  - TENA-Time-v1.1
  - TENA-Position-v1
  - TENA-Velocity-v1
  - TENA-Acceleration-v1
  - TENA-Orientation-v1
  - TENA-AngularVelocity-v1
  - TENA-AngularAcceleration-v1
  - TENA-ORM-v1
  - TENA-SRF-v1
  - TENA-SRFserver-v1
- TENA-AMO
  - TENA-AMO-v1

TENA standard object model example

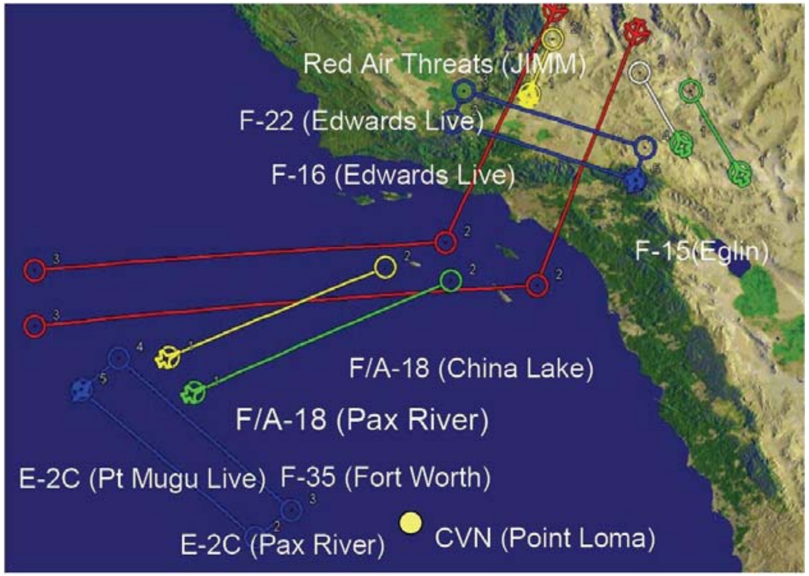


TENA code generator

- Generates code for TENA Middleware
  - Input: TDL (TENA Description Language)
  - Output: C++
- Accessed via web front end
- Promotes interoperability via homogeneity
  - Same source code for every TENA application
  - Common algorithms embedded in generated code, e.g., coordinate conversion, unit conversion, data marshalling/demarshalling

TENA logical range example: InterTEC

- Large distributed LVC C4I Link-16 test
- TENA used for
  - Distribution of instrumentation data
  - Test control
  - Distributed simulation across multiple sites



10 locations
12 different applications
56 instances of applications

TENA summary

- Protocol and architecture designed for ranges
- Common middleware provides data transport
- Standard object models at entity level and below
- Numerous applications since development

Implementing interoperability

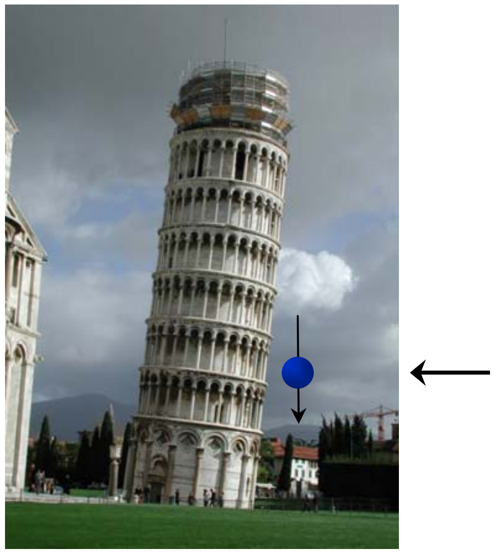
Achieving interoperability

- Native
  - Federate/application code uses protocol directly
  - e.g., most DIS applications
- Middleware
  - Common software layer used by all federates
  - Application uses protocol indirectly via middleware
  - e.g., TENA, arguably HLA
- Gateway
  - Application uses one protocol, e.g., DIS
  - Gateway translates application protocol to another, e.g., DIS/HLA gateway

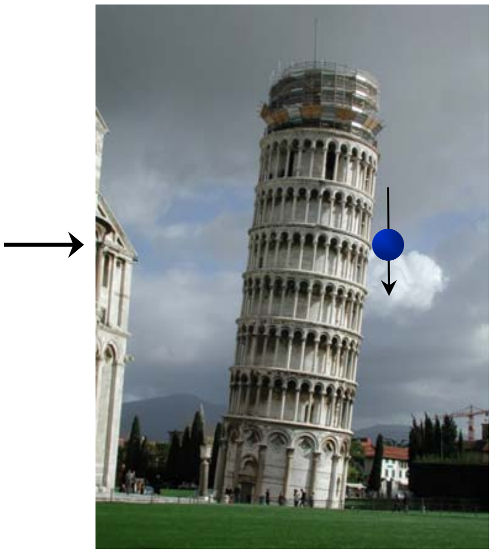
General interoperability issues

- Protocol compliance
  - Properly formatted data items and messages
  - Correct send and receive processing
- Model consistency issues
  - Terrain correlation
  - Consistent weapons effects
  - Consistent object models
- Technical issues
  - Coordinate systems and coordinate conversions
  - Byte alignment and endianness
  - Ambiguities in protocol standard

Interoperability issue: model consistency



Model *A*
Free fall without air resistance
$h(t) = -4.9t^2 + vt + s$



Model *B*
Free fall with air resistance
$h(t) = -4.9t^2 + vt + s + r(t)$

$r(t)$ is a notional model of air resistance

Example interoperability implementation: 1992 I/ITSEC DIS Interoperability Demonstration

- First large scale use demonstration of DIS
  - 39 heterogeneous simulations and utilities
  - Demonstrated on I/ITSEC exhibit floor
- Testing
  - IST CGF used as protocol “gold standard” [Loper, 1993]
  - Each simulation tested for interoperability against it
  - 7 days, 24 hours, 12 hour shifts
- Demonstration
  - Network cabling crushed; replaced after midnight
  - Backup demo scripted in IST CGF system, not used
  - Demo successful

1992 I/ITSEC DIS Interoperability Demo, testing

Testing work floor

Network monitor

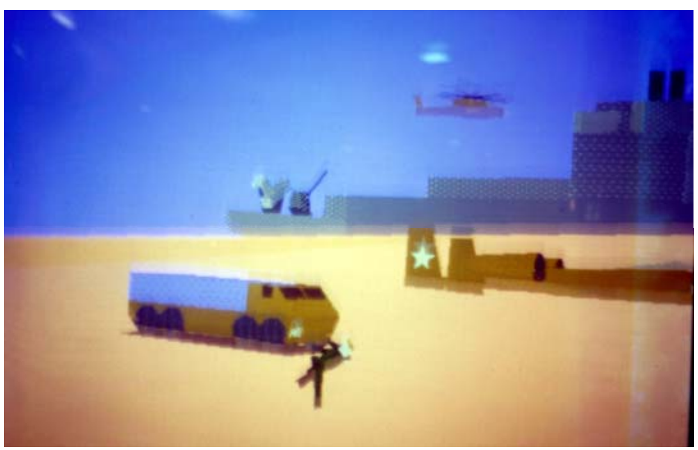
Testing work floor

Network sniffer

1992 I/ITSEC DIS Interoperability Demo, event

Replacing cabling

Developing backup



Out-the-window

Post-event

1992 I/ITSEC DIS Interoperability Demo, *Wired*

Wired, Premiere issue, March/April 1993

"The demo'd the new standard on a network link-up I/ITSEC … live.

The had to rip up some of the Ethernet wiring that they'd laid before the show because it had so many crimp-failures …

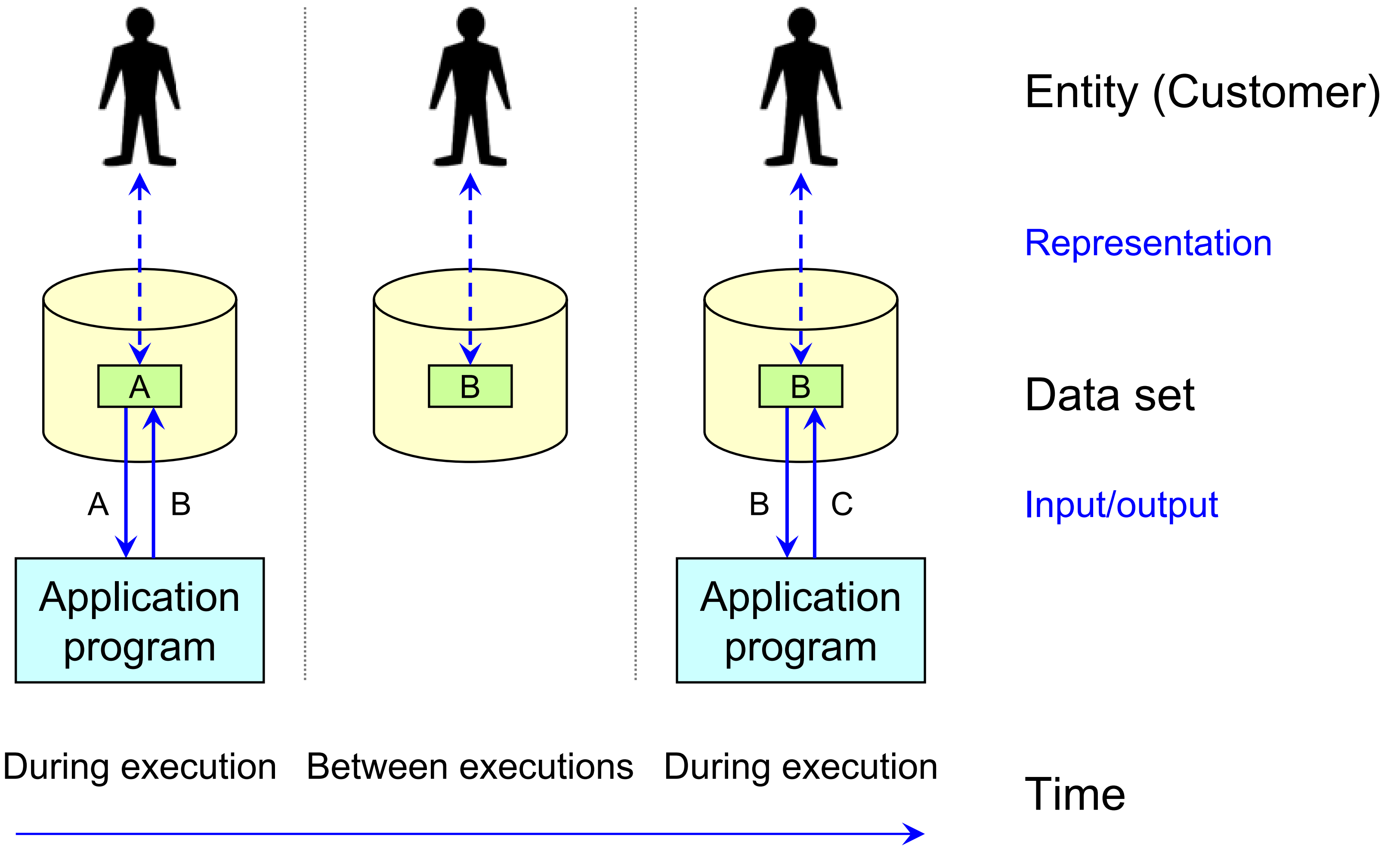
It got hairy for a while there. But they got the demo to run. The protocol worked just fine.

There was some interesting stuff backstage … There was a handscrawled brag on a backstage chalkboard, written by the techies from Orlando: "DIS Interoperability Demonstration. Today's feature: DIS. Tomorrow: the holodeck."

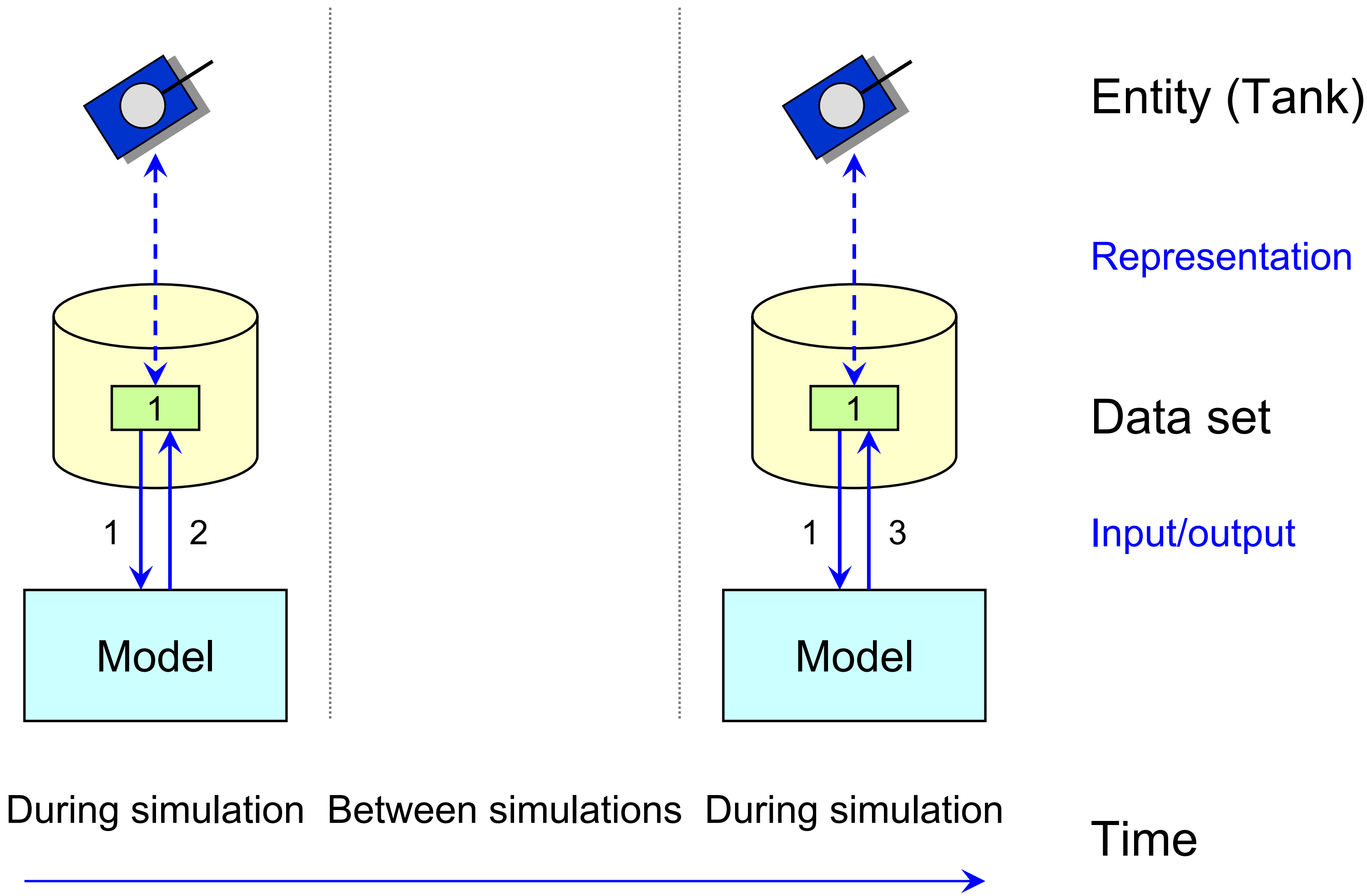
[Sterling, 1993]

In depth:
Terrain issues in distributed simulation

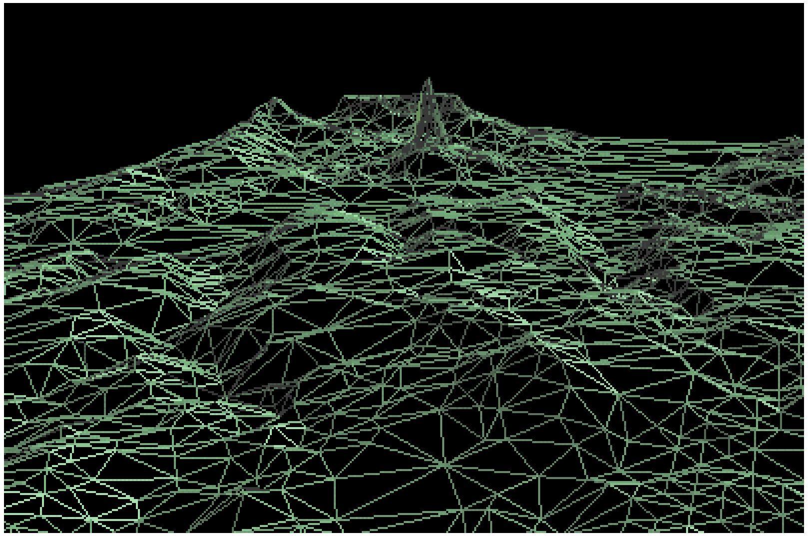
Persistent data in IT

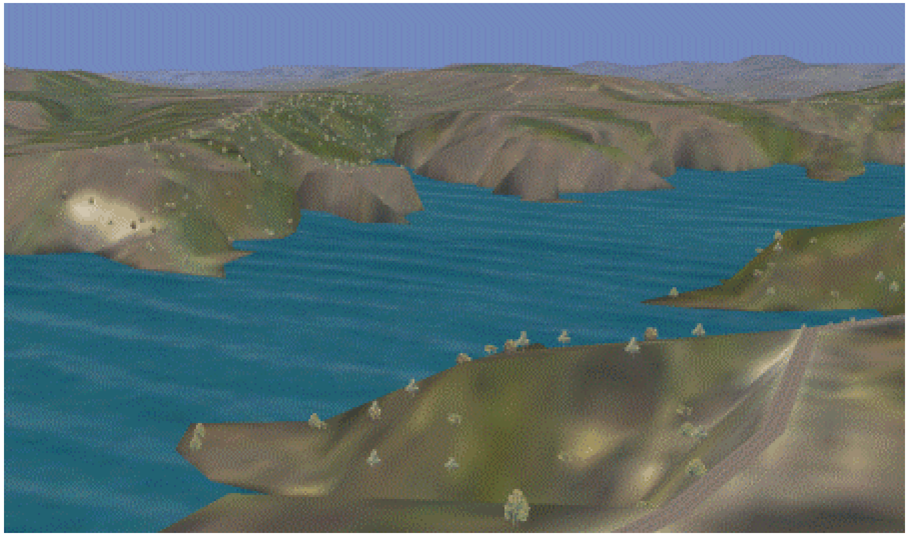


Non-persistent data in M&S



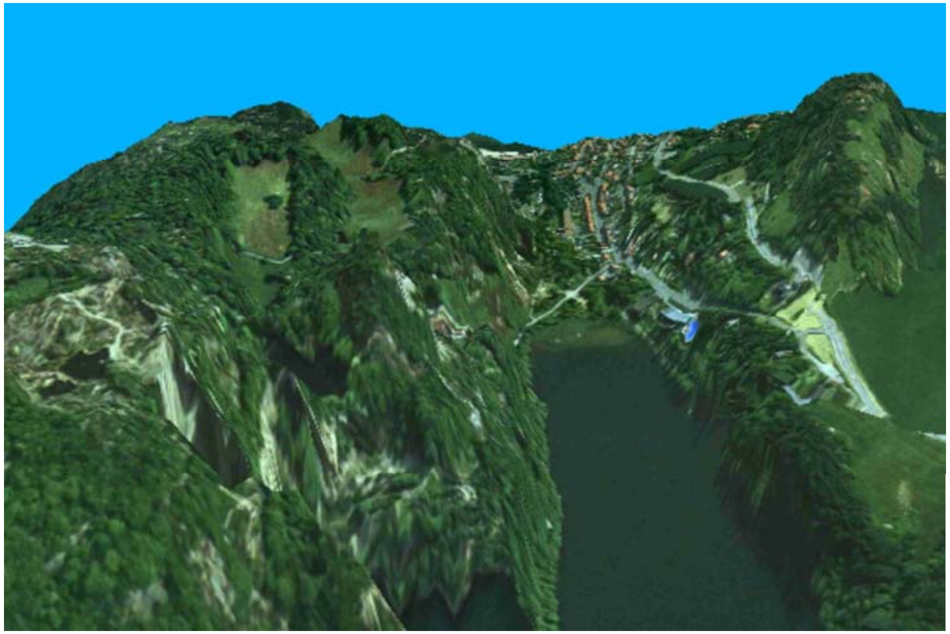
Terrain representation and terrain databases

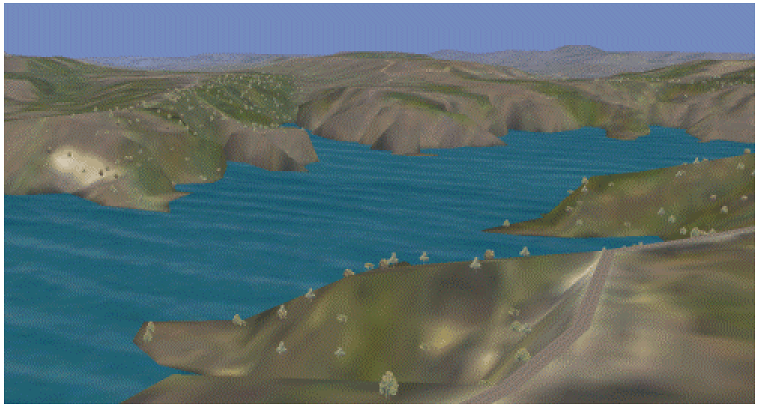




- Terrain representation
  - Polygons (usually triangles) form surface of earth
  - Texture, type associated with each polygon
  - Features (e.g., trees, buildings) located on polygons
- Terrain database
  - Data set containing terrain data (e.g., vertex x, y, z coordinates)
  - Several standard formats (e.g., CTDB)

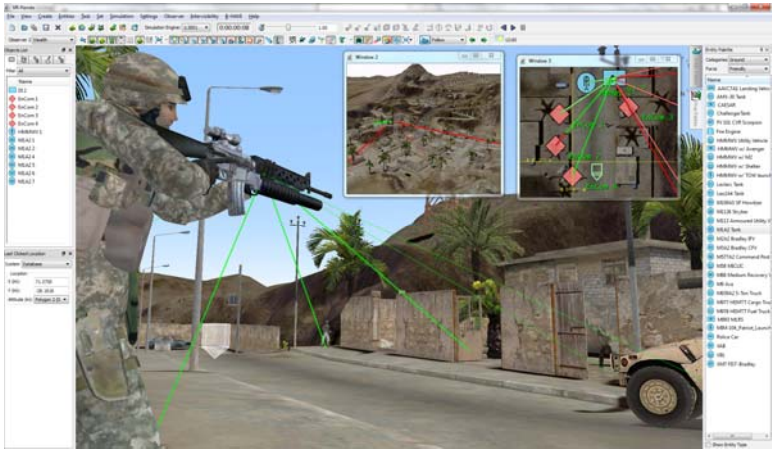
Terrain images: Rural

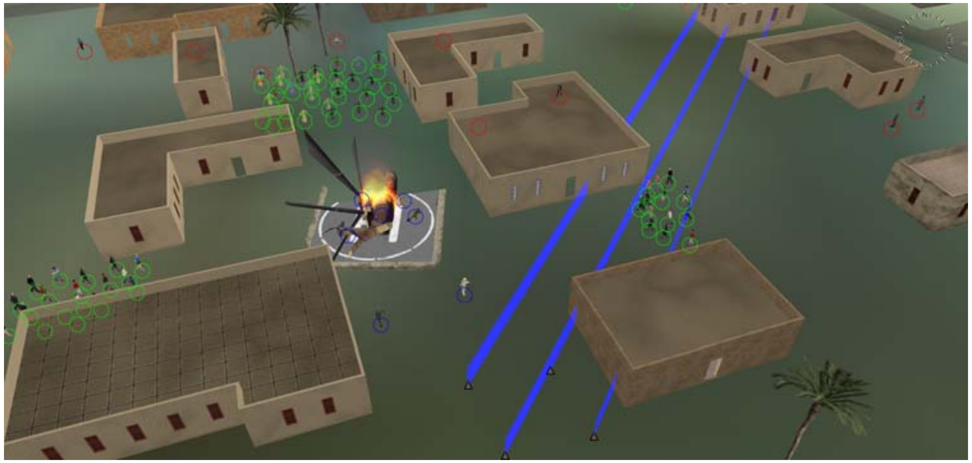




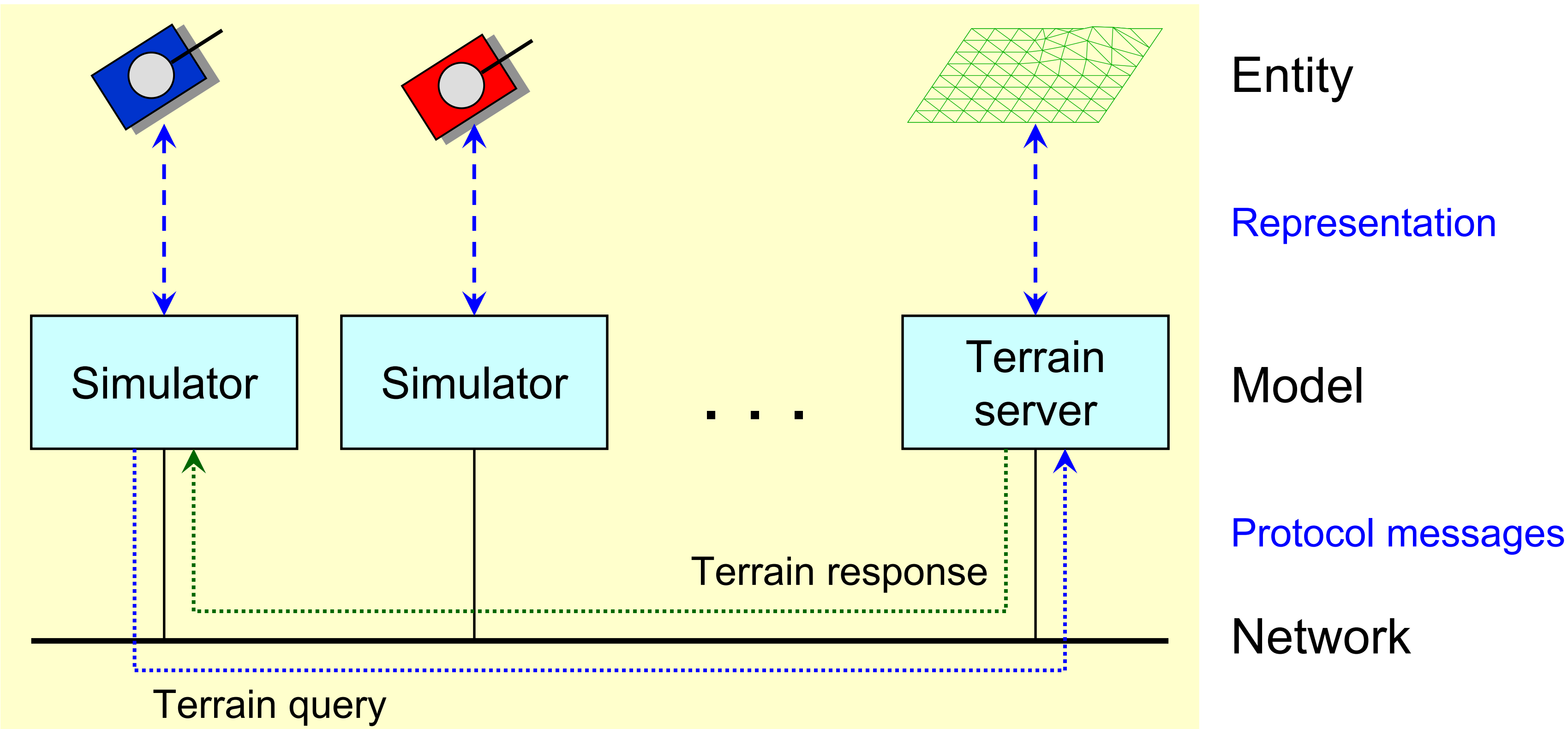
- Surface polygons may have digital photos as textures
- Used for visualization, not simulation

Terrain images: Urban



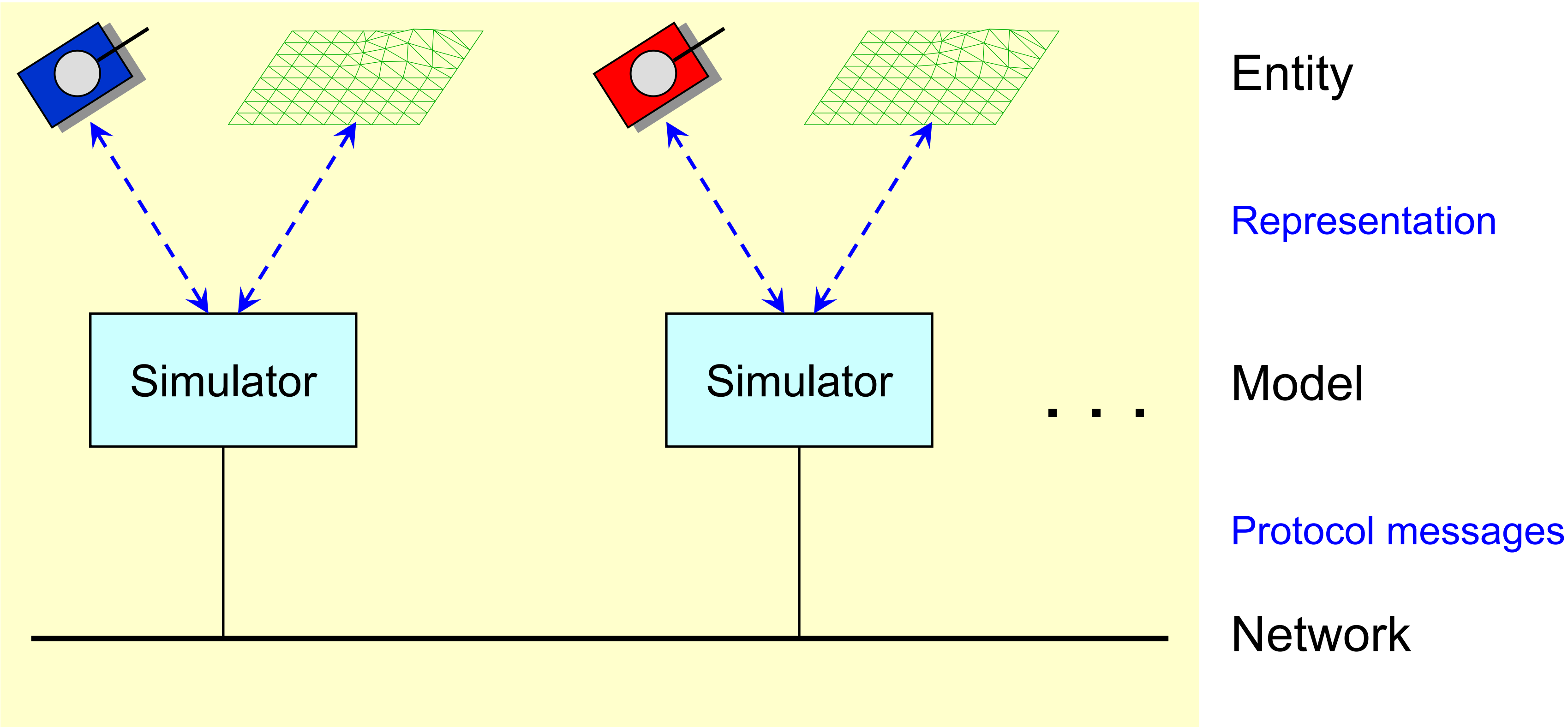


Terrain alternative 1: integrated



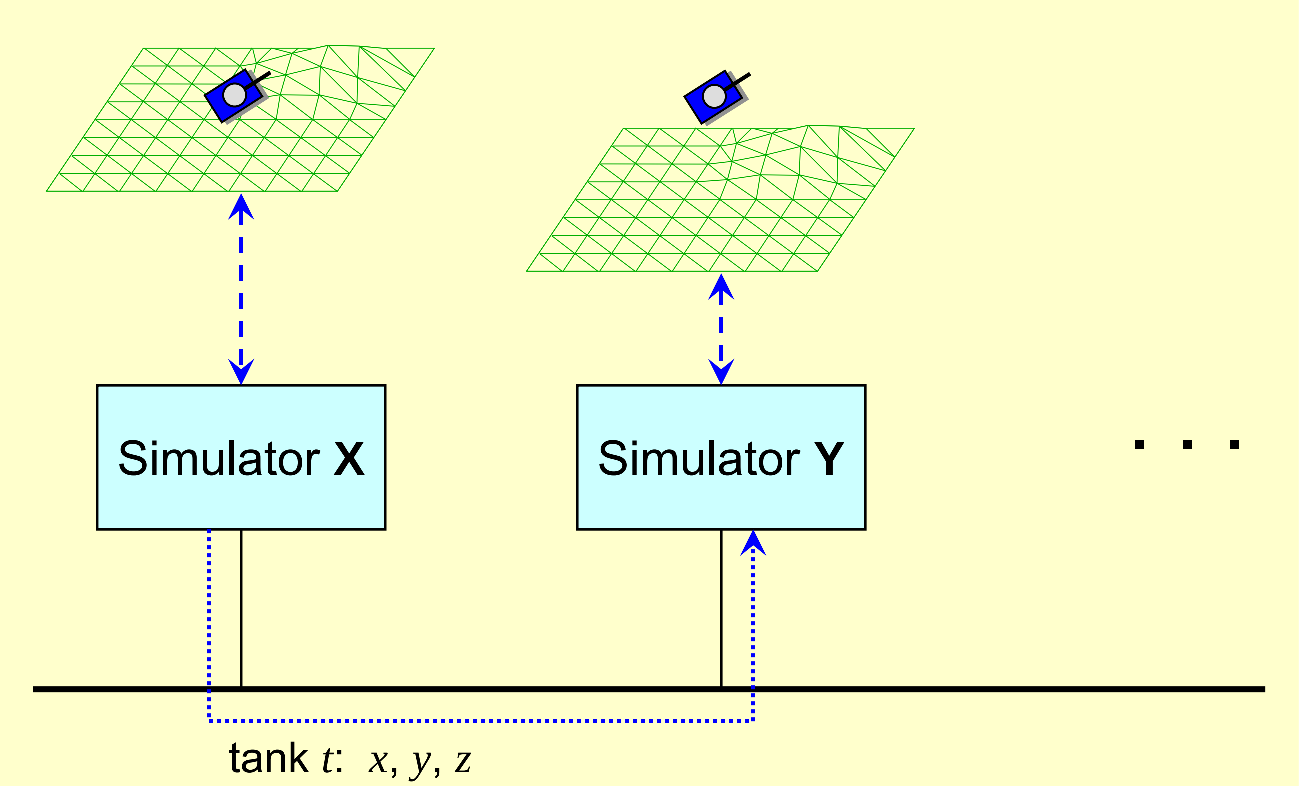
- Single copy of terrain database at single nodes
- Other nodes request terrain data via queries

Terrain alternative 2: replicated



- Each node has its own copy of the terrain database
- No network queries required to retrieve terrain data
- Resulting issues: terrain correlation, dynamic terrain

Terrain correlation issue: floating entities



Entity

Representation

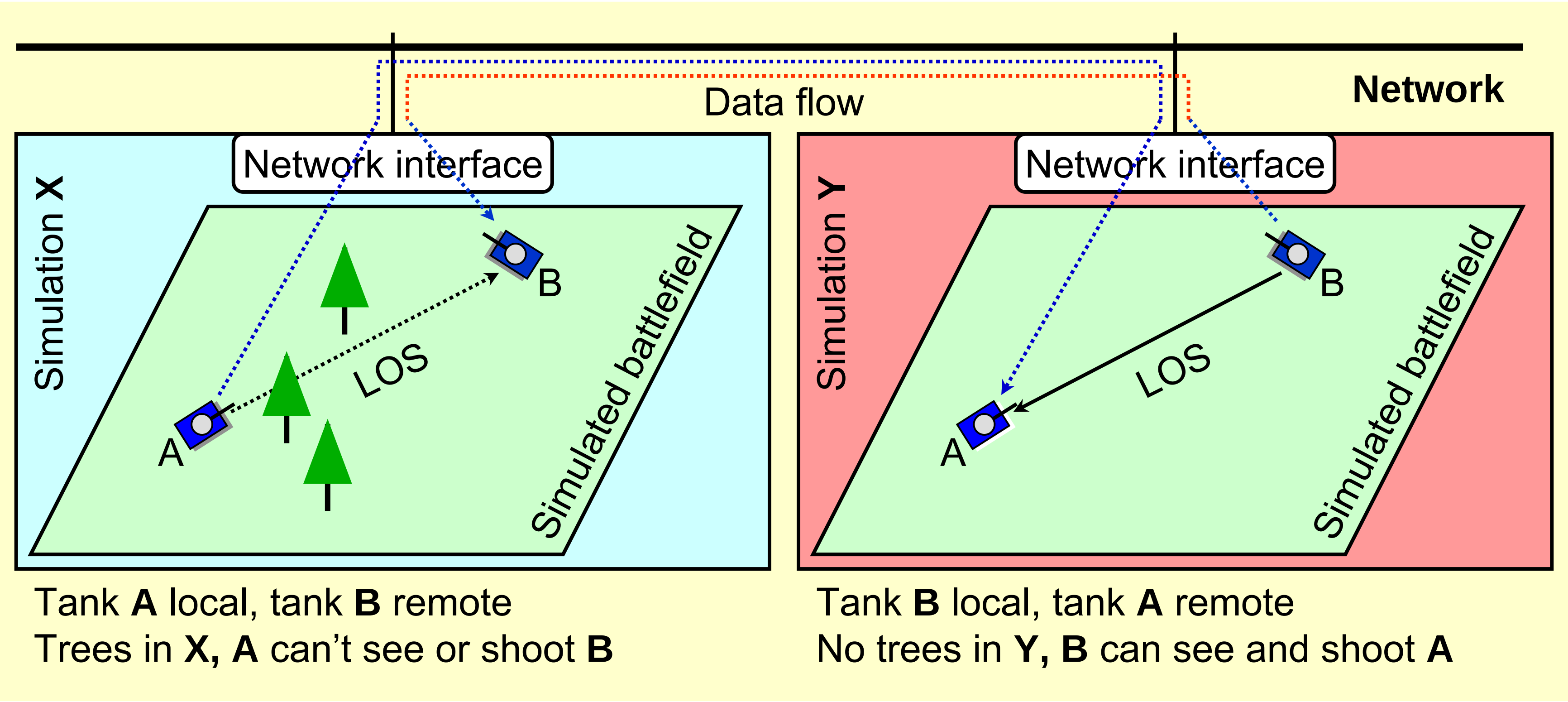
Model

Protocol messages

Network

- Inconsistent terrain database heights [Schiavone, 1995]
- Causes ground entities to "float"

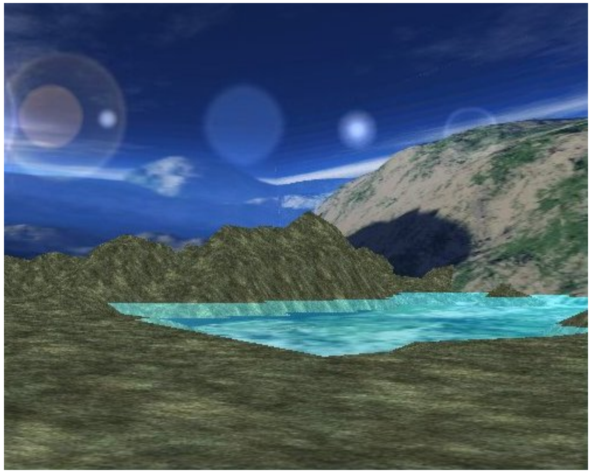
Terrain correlation issue: fair fight



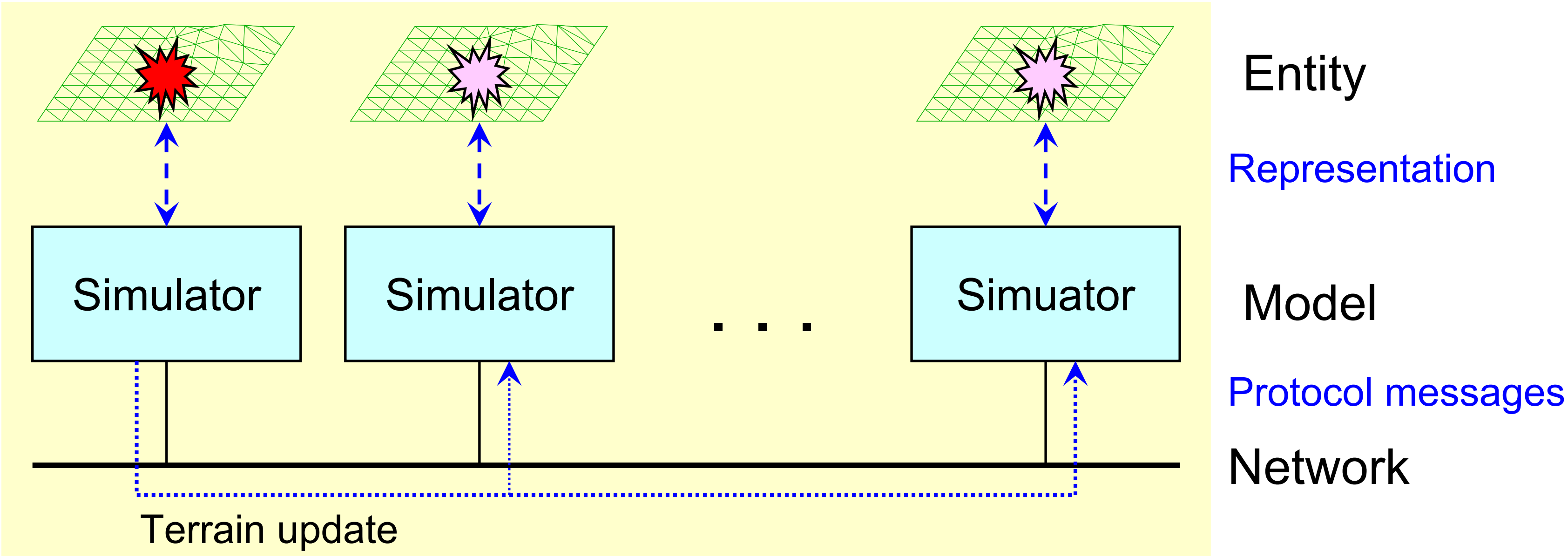
- Inconsistent terrain database features [Petty, 1996]
- Causes "fair fight" problems

Dynamic terrain

- Definition
  - Some simuland actions can change terrain
  - Changes must be applied to all replicated TDBs
- Examples
  - Bulldozer digs entrenchment
  - Bomb creates crater



Dynamic terrain issues



- Describing terrain changes in the protocol
- Algorithms for inserting terrain changes into local TDBs
- Time required to generate, send, receive, apply updates

Summary and references

Concepts and Protocols summary

- Distributed simulation
  - Architecture for networking simulations
  - Combines simulations and support nodes
- Interoperability protocols
  - Define data content, data transport, interaction sequences
  - Some require specific simulation architectures
  - Military examples: SIMNET, DIS, ALSP, HLA, TENA
- Related issues
  - Implementing interoperability
  - Terrain representation and correlation
  - Semi-automated forces

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