Simulation Interoperability Standards Organization

"Simulation Interoperability & Reuse through Standards"

SISO Space Reference FOM 102

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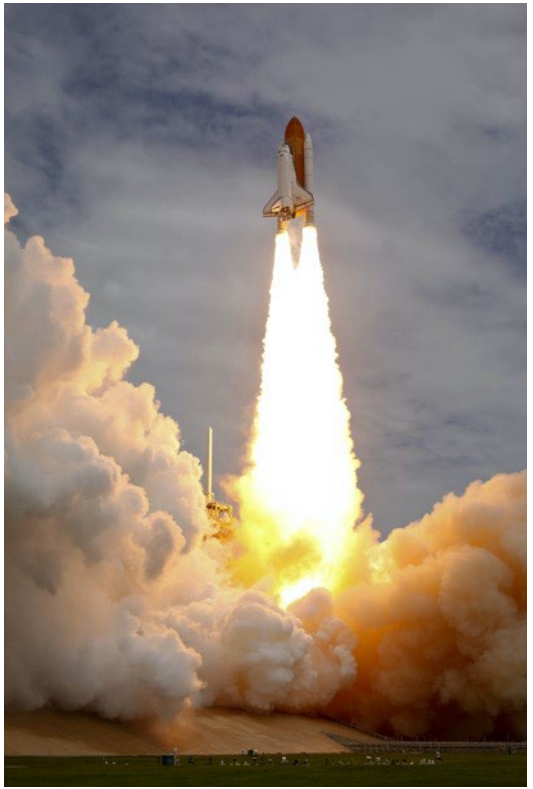
Outline

- Why a Space Reference FOM Standard?
- Quick HLA Recap
- Reference Frames and Standard Reference Frames
- Time and Time Management
- Execution Control
- Physical Entities
- Implementing and Extending the Space Reference FOM
- A Practical Example: Simulation Exploration Experience
- The Future of SpaceFOM
- Summary

Why a SISO Space Reference FOM – 1

- Spaceflight is difficult, dangerous and expensive; human spaceflight even more so
- In order to mitigate some of the danger and expense, professionals in the space domain have relied, and continue to rely, on computer simulation
- Simulation is used at every level including concept, design, analysis, production, testing, training and ultimately flight
- Distributed simulation provides a base technology for segmenting these complex space systems into smaller, and usually simpler, component systems or subsystems



Why a SISO Space Reference FOM – 2

- **Integrating simulations is costly**
  - Need to minimize the integration effort for new and reused systems
- **Open standards offer a more efficient way to combine and reuse systems and tools in new configurations**
  - They also offer a neutral ground that is easier to accept for many participants than proprietary interfaces
  - Open standard can also capture best-practices and help communicate them to new developers
- **HLA is not enough to ensure interoperability, a FOM is also needed; thus, the SISO Space Reference FOM (SpaceFOM)**
- **The SpaceFOM should make collaboration politically, contractually and technically easier**

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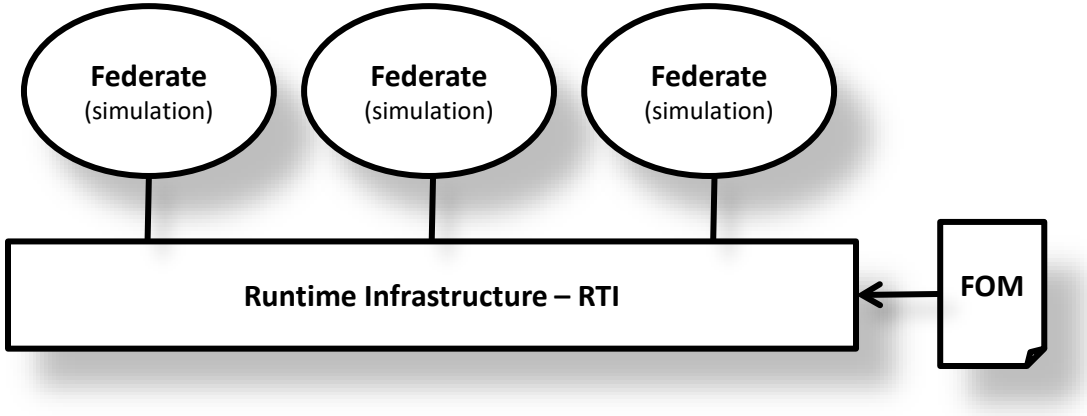
A Quick Recap of the High Level Architecture

Selected features

HLA Terminology



- Each system is called a federate
- Federates connect to a Runtime Infrastructure that provides services
- Together they form a Federation
- Data is exchanged based on a Federation Object Model (FOM)
- A session is called a Federation Execution

Key HLA Services used by SpaceFOM

- **Data exchange using Publish-Subscribe**
  - Federates publish and subscribe to data according to the FOM
  - The RTI makes sure that objects, their attributes and interactions are correctly routed between publishers and subscribers
- **Synchronization points**
  - Ensures that all federates in a federation have reached a required state
- **Time Management**
  - Synchronizes the time advance of federates and time stamped ordered delivery of messages
  - Federates are guaranteed not to get messages in their past

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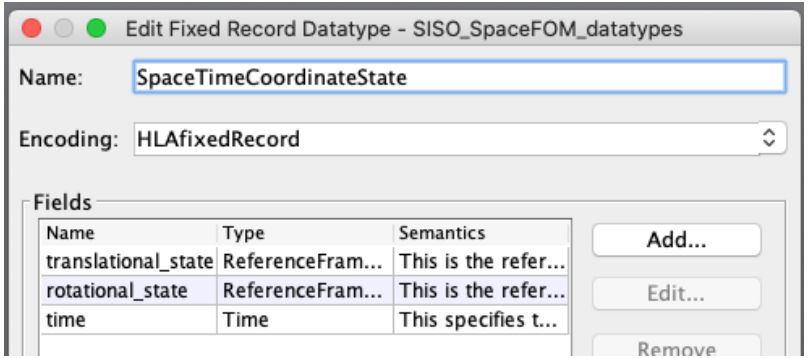
Reference Frames and Standard Reference Frames

Introduction to Spacetime Coordinates

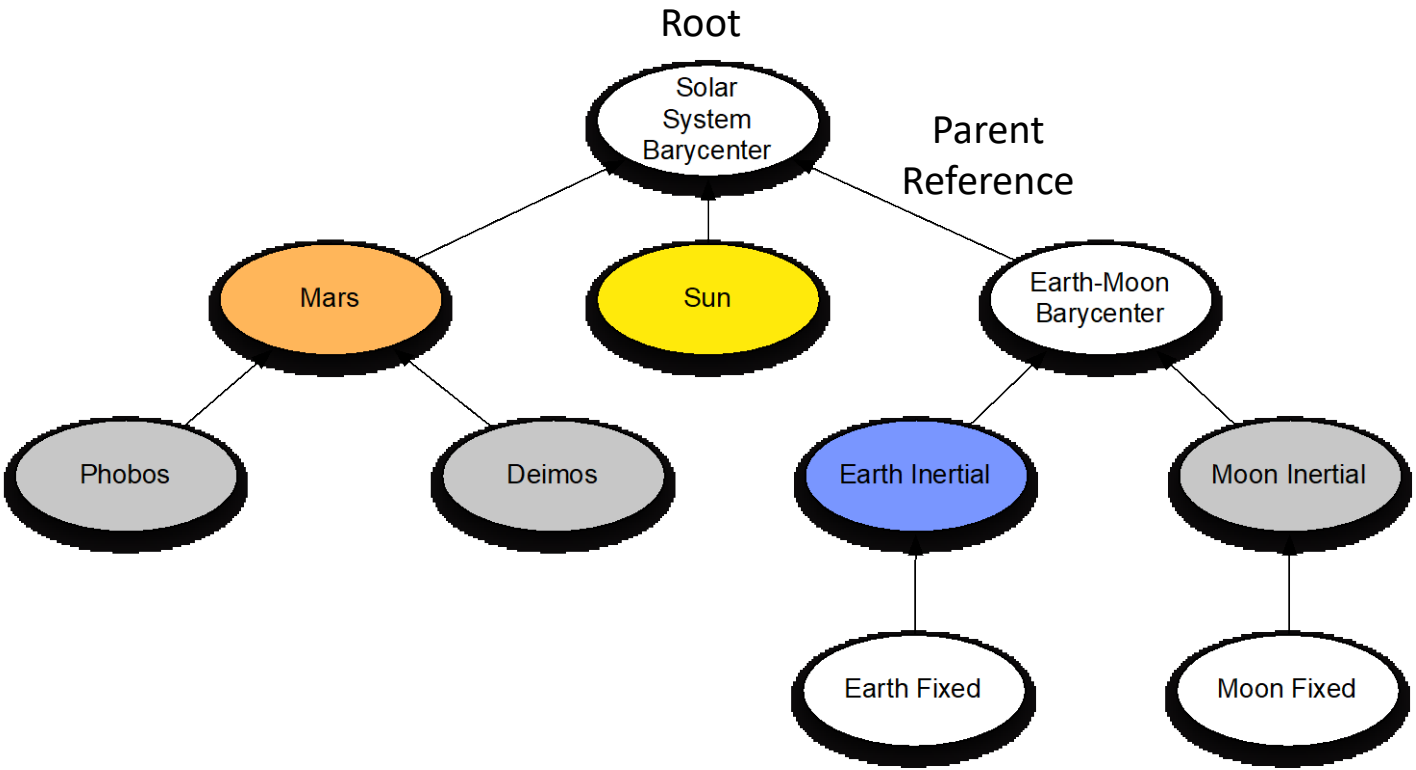
- We need to express where and when a physical entity exists.
- This is done with respect to some time scale and some referent coordinate system.
- This combination of time and coordinate system is referred to as a spacetime coordinate.
- For an entity in the SpaceFOM, a parent reference frame and a spacetime coordinate state is used
  - Translational State (Position)
  - Rotation State (Attitude)
  - Time



Reference Frames

- **Reference frames are the basis for expressing the state of a physical entity.**
- **A reference frame may be more or less computationally convenient for different purposes**
  - Performing a mining operation on the Moon using an Earth centric inertial reference frame would be inconvenient
- **Reference Frames are provided as HLA object instances**
  - Several reference frames can be used
  - A federation can use the reference frames that meets its needs
  - Reference frames are related to each other so that a spacetime state in one reference frame can be represented in another reference frame

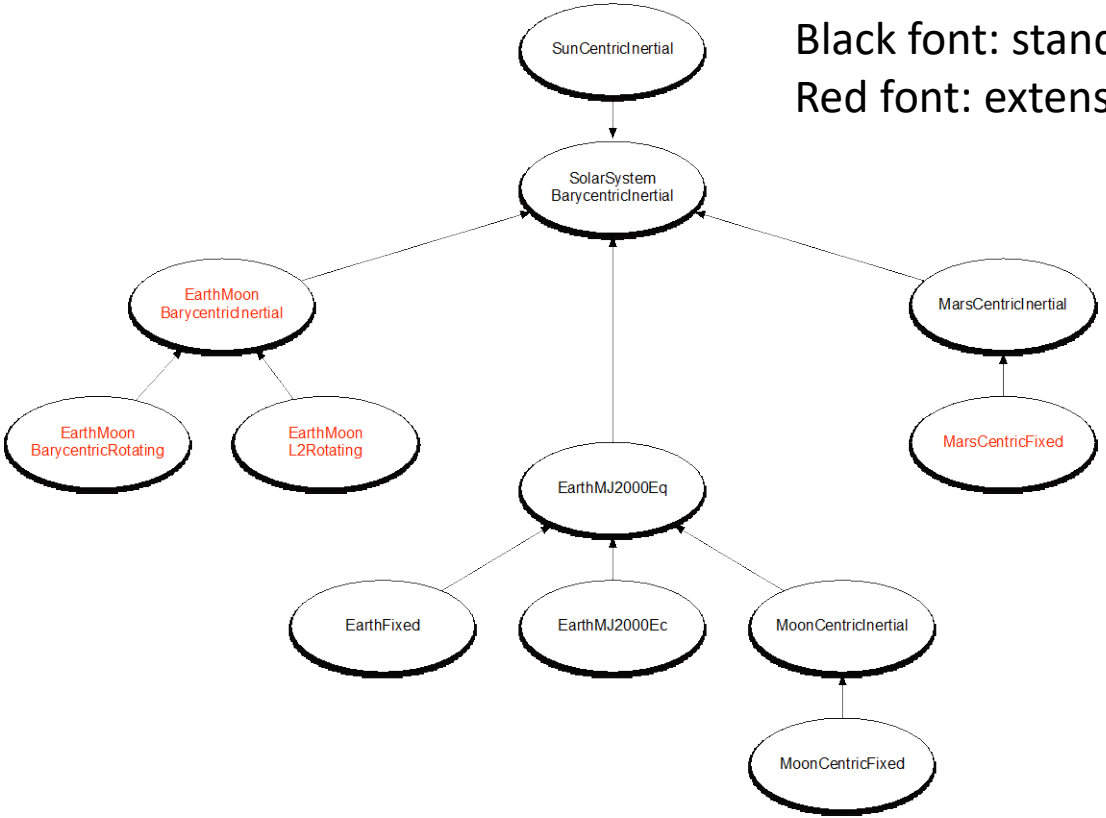
Sample Reference Frame Tree



Reference Naming Conventions

- **The SpaceFOM provides a convention for naming reference frames based on frame origin and frame orientation**
  - Example: SunCentricInertial
- **Frame Origin (simplified)**
  - Celestial body, Lagrange point, Human Made Body or User defined
  - Celestial bodies can be Solar System Bodies (Sun, Planet, Dwarf planet, Natural Satellite or other body) or Extra Solar System Bodies
  - Celestial body name are based on International Astronomical Union DB
- **Frame Orientation (simplified)**
  - Fixed, Inertial, Rotational, Rotating
  - Axes types may be specified

Some Standard Reference Frames and Extensions



Black font: standard reference frames
Red font: extensions

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Time and Time Management

Time – Basics

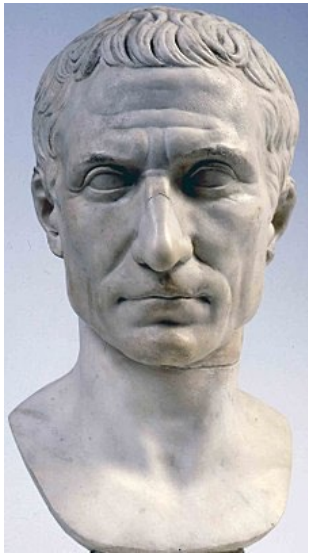
- **The SpaceFOM uses the Newtonian approximation to propagating time**
  - Relativistic time dilatation is on the order of microseconds per day using current space transportation technology. This is insignificant for shorter scenarios.
- **Some important timelines**
  - Physical time
  - Computer clock time
  - Simulation elapsed time
  - Simulation scenario time
  - HLA logical time
  - Federation scenario time

Time – Timeline Definitions

- **Physical Time**
  - The time that ”we” experience. The non-spatial dimension associated with our spacetime continuum in which events are ordered in irreversible succession from the past to the present to the future.
- **Computer Clock Time**
  - The count of oscillation in a ”clock” on the computer that is translated into a representation of the current Physical Time.
- **Simulation Elapsed Time**
  - The time measure associated with an individual simulation starting at zero and advancing monotonically in quantifiable steps.
- **Simulation Scenario Time**
  - A model within a simulation that associates the Simulation Elapsed Time with a representation of the problem’s Physical Time.
- **HLA logical time**
  - The timeline used by HLA to order messages, regulate execution time advance (TAR & TAG), and enable deterministic behavior in distributed simulation.
- **Federation scenario time**
  - A conceptual time associated with the physical systems being modeled in the participating federates in the federation execution.

Time Representation and Interpretation

- **Julian Dates**
  - A Julian day number is the number of days that have elapsed since the Julian Epoch, i.e. noon of January 1, 4713 BC in the Julian calendar
  - Truncated Julian Date (TJD) starts at 00:00:00 May 24, 1968
- **A SpaceFOM federation shall use TJD to specify the epoch (starting point) of a scenario**
- **The Terrestrial Time (TT) time scale shall be used**
  - Uses the SI second unit. No leap seconds (unlike UTC).
- **Time shall be represented using a 64 bit integer that shall be interpreted as microseconds.**



Julius Caesar

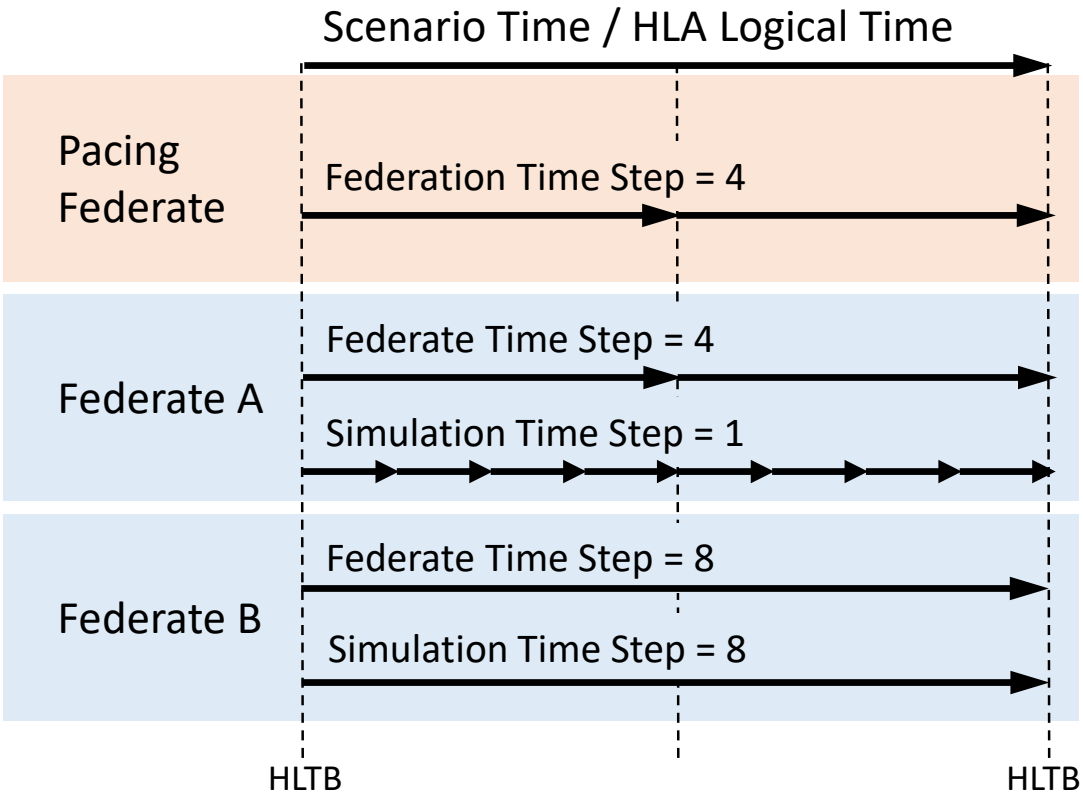
Types of Time Management Supported

- **No Pacing (as-fast-as-possible)**
- **Pacing (regulated by a clock)**
  - Scaled Pacing
  - Real-time Pacing
    - *Strict/Conservative Real-time (no frame overruns)*
    - *Elastic Real-time (catch-up on overruns) with Limited Overruns*
    - *Elastic Real-time (catch-up on overruns) with Unlimited Overruns*
- **Fixed time step is required**
- **As-fast-as-possible is useful for Monte Carlo simulation**
- **Real-time is useful for "man in the loop" or "hardware in the loop"**

Time Steps in a Federation

- **Simulation Time Step**
  - Native time step used inside a simulation
  - Complete simulation states are only available at simulation time steps
- **Federate Time Step**
  - Time step used by a federate for Time Advance Request
- **Federation Time Step**
  - Federate time step of the Pacing federate
- **Least Common Time Step**
  - The smallest time step that all federates can support
- **HLA Logical Time Boundary (HLTB)**
  - HLA logical time (position) that is common to all Time Managed federates
  - Used for late joiners and going to freeze

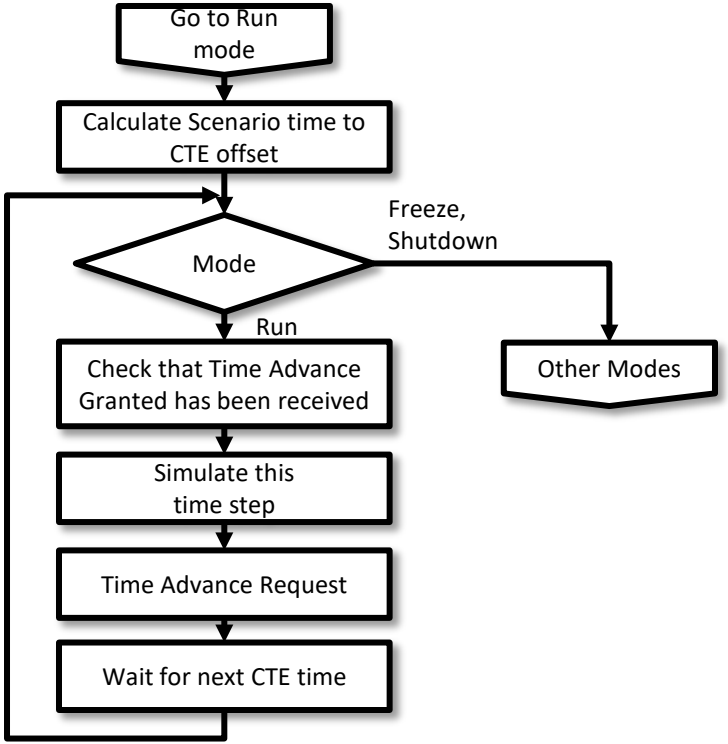
Putting Time Steps Together



Central Timing Equipment (Hard Real-Time)

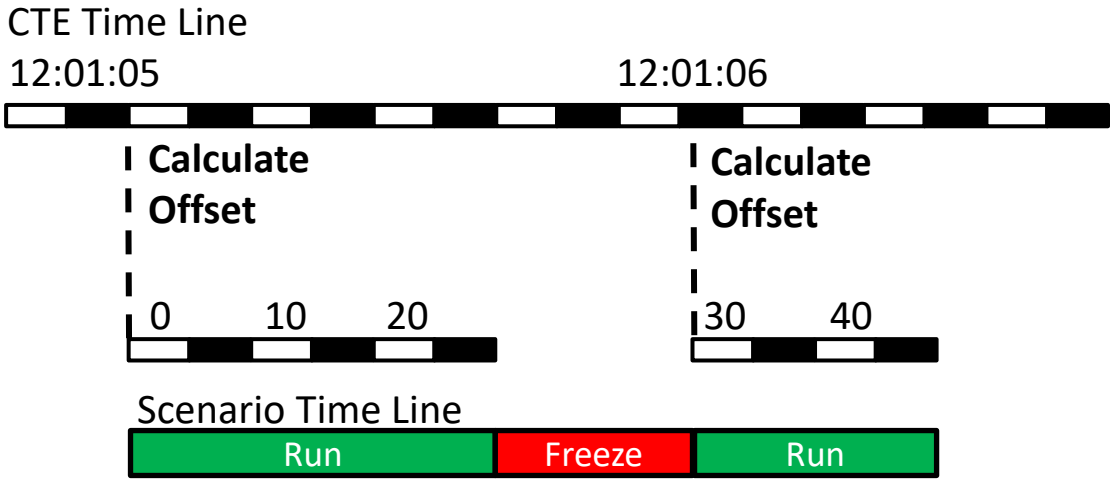
- An HLA federation can accommodate both simulations running in soft real-time and simulators that use central timing equipment (CTE) (e.g., a GPS timing board) for hard real-time synchronization
- The HLA federation is capable of going to freeze, and later resume
- The simulations that synchronize using the CTE, must also be able to handle these mode transitions

Main Loop with CTE (Hard Realtime)



Run and Freeze with CTE

- **The HLA Logical timeline and the CTE physical timeline are connected during Run mode**
  - An offset is calculated when entering Run mode
- **When entering Freeze mode they are disconnected**



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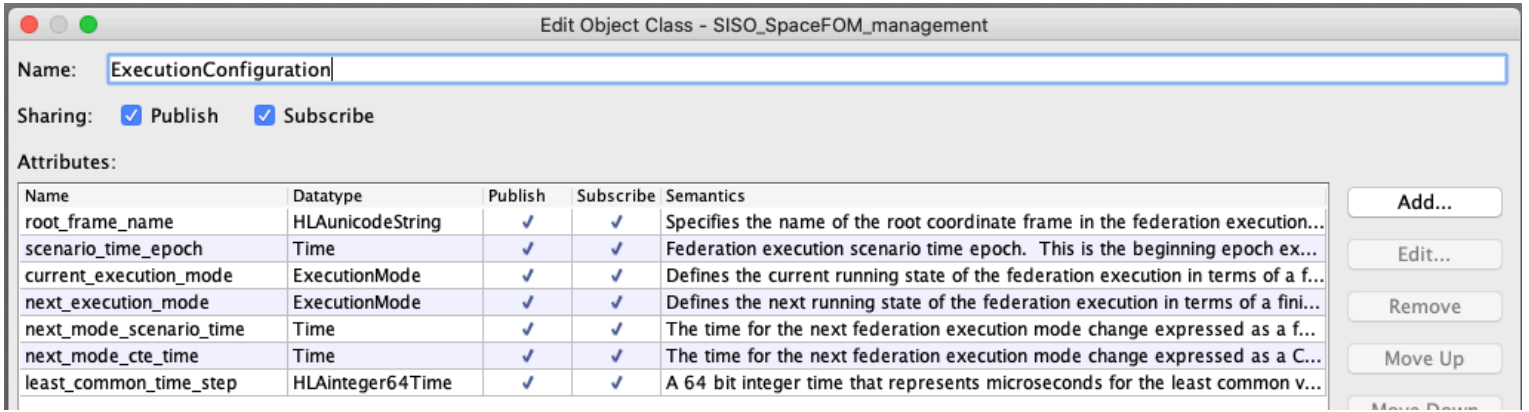
Execution Control

Federate Roles

- **The SpaceFOM defines three required federate roles that must be present in a federation**
- **Master Federate**
  - Manages the startup, initialization and execution control which includes maintaining the Execution Control Object and registering synchronization points.
- **Pacer Federate**
  - Manages the advance of the HLA Logical Time in the federation
- **Root Reference Frame Publisher Federate**
  - Publishes the root reference frame.
- **A particular federate may implement more than one role**

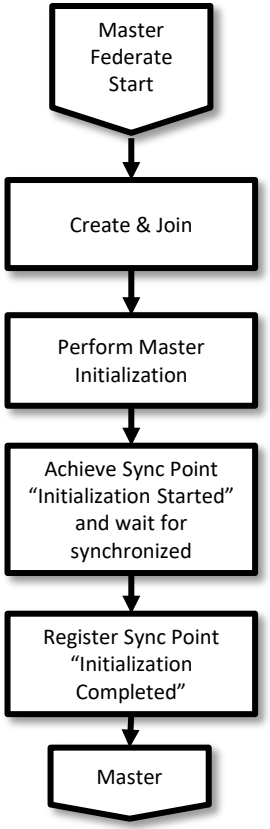
The Execution Control Object (ExCO)

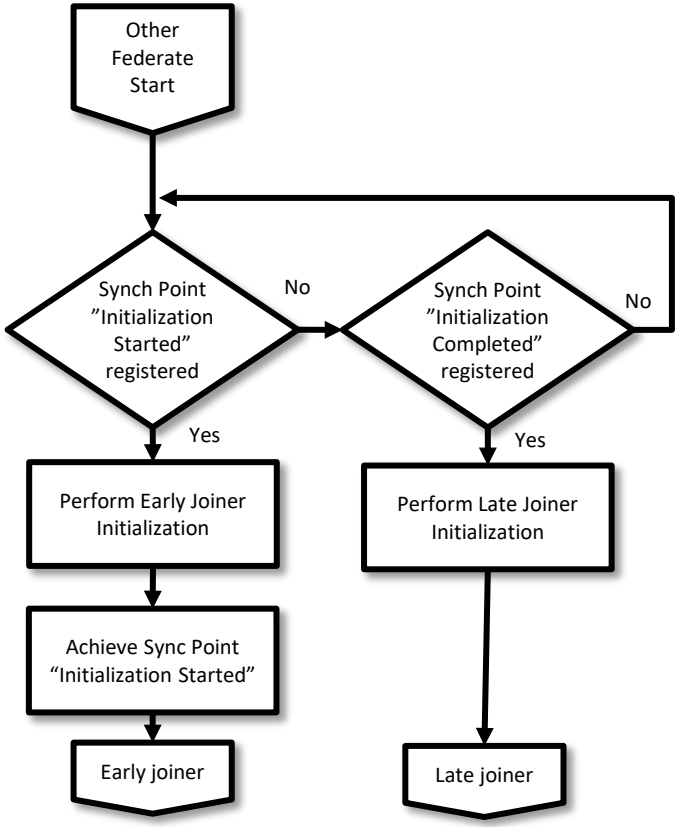
- **A singleton object instance with shared information for Execution Control**
  - Root reference frame name
  - Federation execution scenario time epoch
  - Mode and time information



Early and Late Joiners

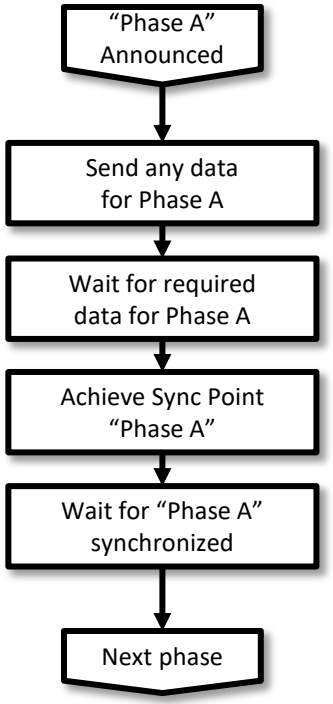
- The Master checks that all required federates have joined
- It then triggers Early Joiner initialization
- Federates joining after that will be put on hold and perform a late join.





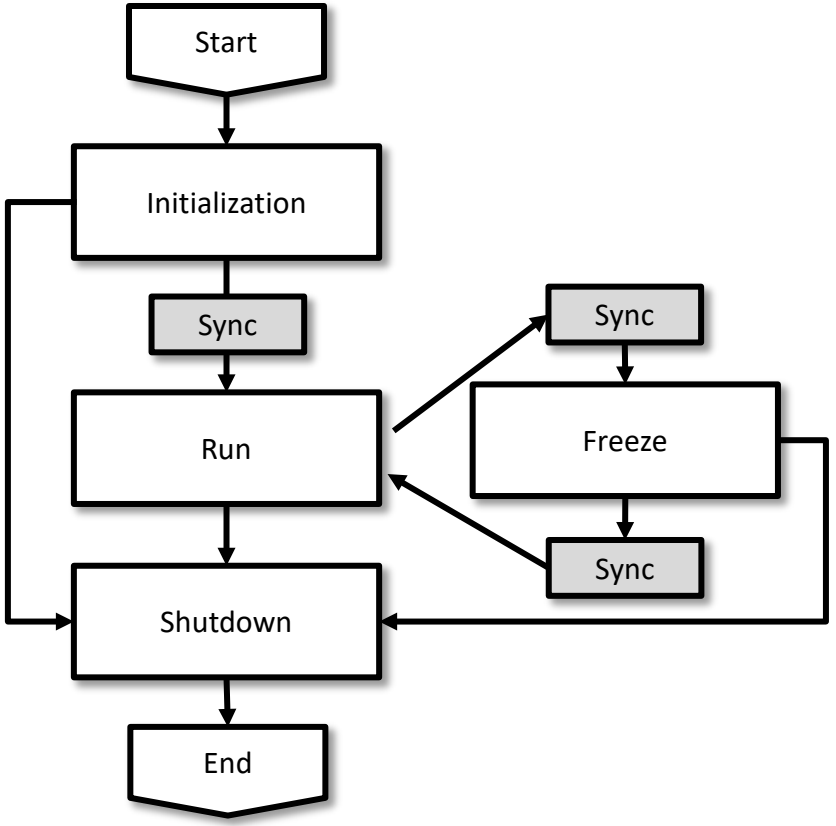
Multi Phase Initialization

- Initialization of a federation may often need to be performed in several discrete steps
- Lift-off simulation example:
    1. Initialize launch pad objects
    2. Initialize first stage objects
    3. Initialize second stage objects
- This is supported in the SpaceFOM using synch points
- The SpaceFOM allows for a configurable set of phases



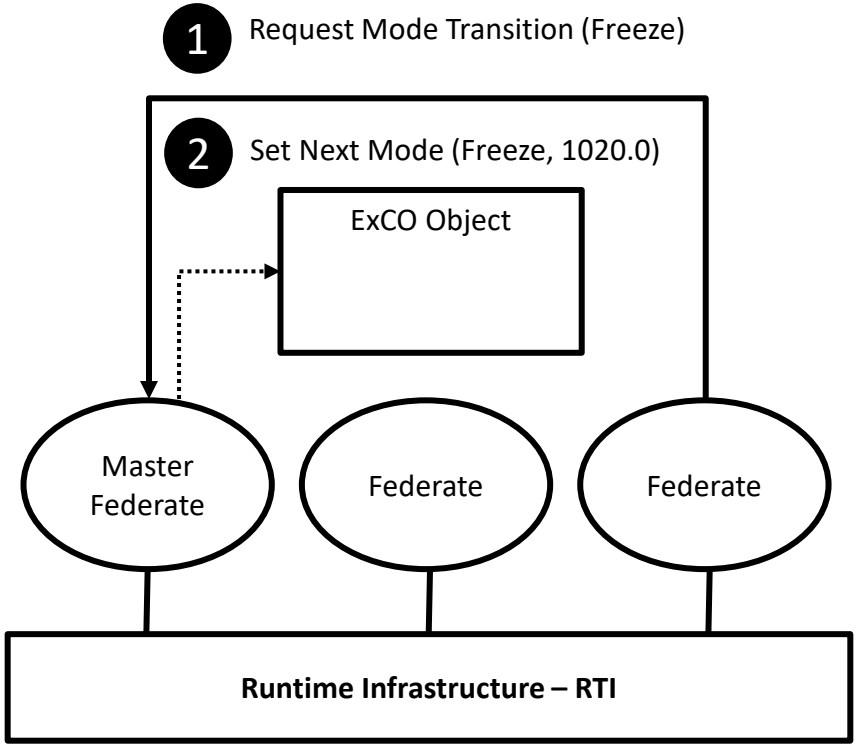
Central Execution Control Flowchart (simplified)

- **Four execution modes exist:**
  - Initialization
  - Run
  - Freeze
  - Shutdown
- **Going to Run, Freeze and Shutdown is controlled by the Master, using the ExCO**
- **Synch Points are used when entering new phase, except Shutdown**



Requesting a Mode Transition (simplified)

- Any federate can request a mode transition using an interaction
- The Master decides if and when a mode transition shall take place
- Can only transition to Freeze or Run on an HLA Logical Time Boundary (HLTB)



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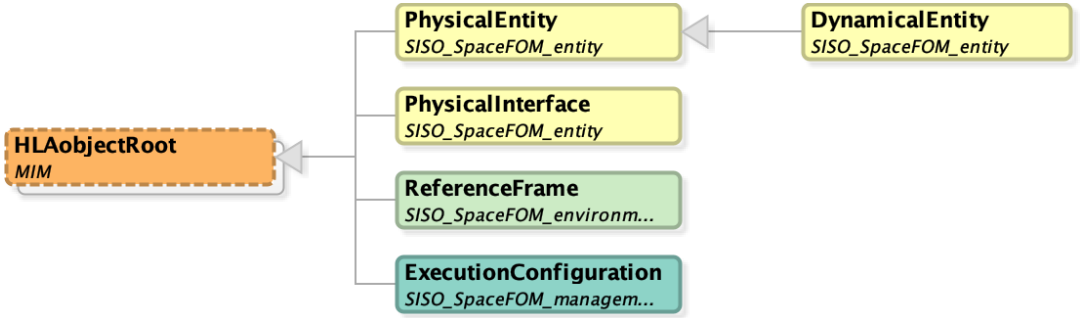
Physical Entities

SpaceFOM classes for Entities



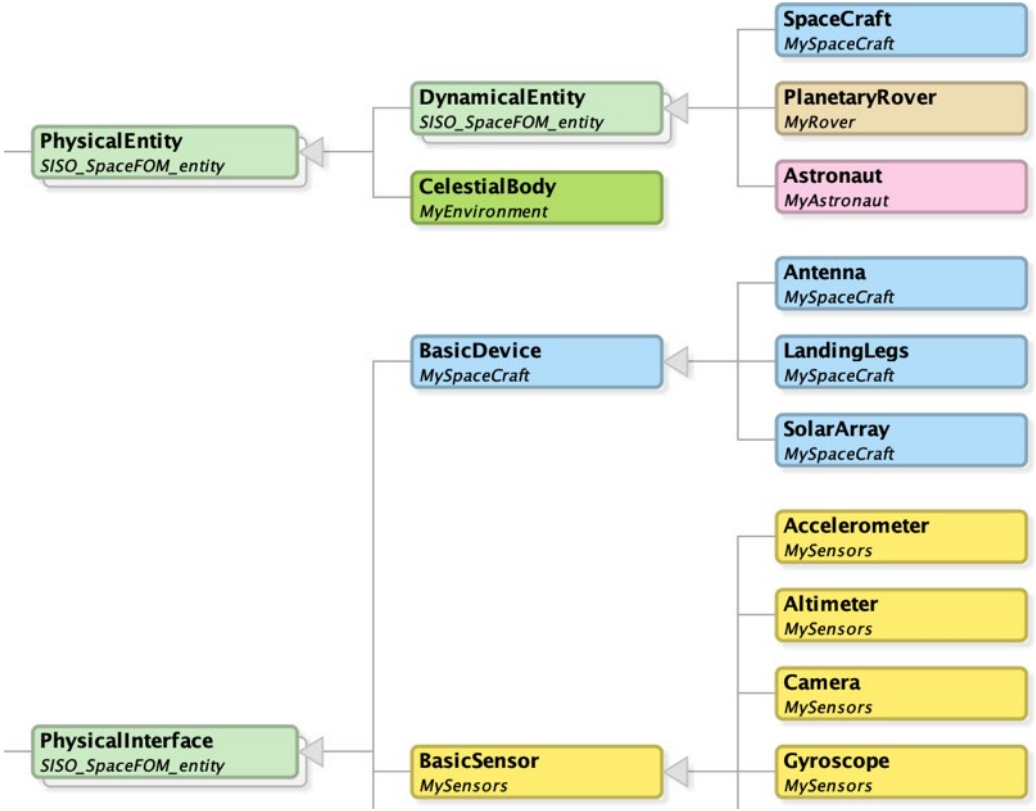
- **Three key classes that can be used or subclassed:**
  - PhysicalEntity – any physical entity
  - DynamicalEntity – a physical entity with dynamic forces and/or torques, such as a space craft.
  - PhysicalInterface – interface of object mounted on an entity, such as a docking port
- **It is also possible to create subclasses of the HLAobjectRoot**

A Sample Dynamical Entity Instance

Attribute	Datatype	Sample Value
name	HLAunicodeString	“DemoRover1945”
type	HLAunicodeString	“Lunar Rover”
status	HLAunicodeString	“Parked”
parent_reference_frame	HLAunicodeString	“MoonCentricFixed”
state	SpaceTimeCoordinateState	(((3, 4, 5), (0, 0, 0)), ((Q*), (0, 0, 0)), 25343225)
acceleration	AccelerationVector	(0, 0, 0)
rotational_acceleration	AngularAccelerationVector	(0, 0, 0)
center_of_mass	PositionVector	(0, 0, 0)
body_wrt_structure	AttitudeQuaternion	IDENTITY_QUATERNION

Q* = Quaternion not expanded here

Sample Extended SpaceFOM



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Implementing and Extending the Space Reference FOM

Common Project Considerations

- Purpose of the simulation, time, budget, other project constraints
- Scenarios
- Conceptual model – entities, events and processes
- Object instances, naming, states
- Datasets, databases, maps, terrain, …
- Reference frames
- Time: epoch, resolution/time step, hard/soft real-time, scaling
- Federates – existing or to be developed
- Allocation of responsibility to federates
- And more…

FESFA and FCD

- **The SpaceFOM is a baseline Federation Agreement to build upon**
- **The Federation Execution Specific Federation Agreement (FESFA) provides additional agreements for your particular federation**
  - Entities, reference frames used, time step used, etc
  - A FESFA template is available in an appendix of the SpaceFOM
- **The Federate Compliance Declaration (FCD) describes capabilities of candidate federates. Useful for assessing suitability.**
  - Entities, reference frames supported, time steps supported, etc
  - An FCD template is available in an appendix of the SpaceFOM

FESFA and FCD contents

FESFA

1. Identification
2. Federation Composition
3. Time Management
4. Reference Frames
5. Object Management
6. Initialization
7. Additional Technical Information

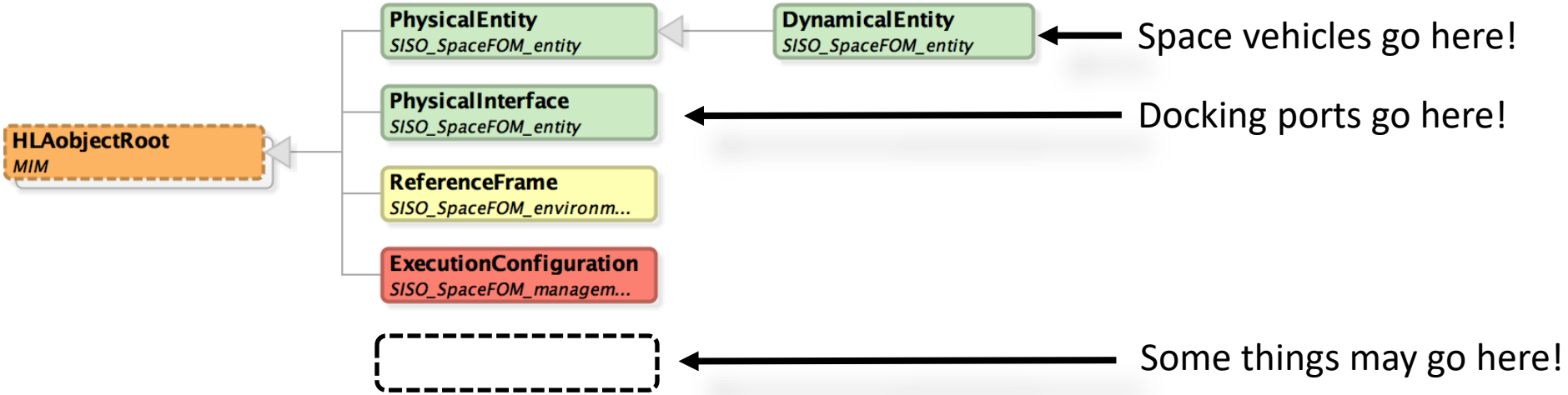
FCD

1. Identification
2. Roles supported
3. Time Management support
4. Reference Frames supported
5. Object Management
6. Initialization
7. Additional Technical Information
8. Compliance statement

More about the FESFA and FCD

- **Reference Frames**
  - FESFA: Root Reference Frame, Additional reference frames
  - FCD: Reference Frames it can publish. Other published or required reference frames
- **Object Management**
  - FESFA: FOM modules, Key object instances. Naming convention. Type and Status tags.
  - FCD: FOM modules, publishes or required object instances, Naming convention, Type and Status tags
- **Initialization**
  - FESFA: Use of Multi-phase Initialization. Specification document
  - FCD: Use of Multi-phase Initialization. Specification document
- **Other**
  - FESFA: Non-standard RTI switches. Common data and databases, etc
  - FCD: Common data and data bases. etc

Extending the FOM – Sample



Tools for SpaceFOM federations

Tool	Description	Developer
Trick	Simulation environment, simulation executive, logging	NASA
TrickHLA	Middleware between Trick and HLA	NASA
HLA Development Kit	Framework for HLA federate development	University of Calabria
SEE HLA Development Kit	Specialized version with SpaceFOM features	University of Calabria
Java Space Dynamics Library	Space dynamics library	University of Calabria
Pitch Visual OMT	FOM development	Pitch
Pitch Developer Studio	Middleware generator (C++, Java, C#)	Pitch
Pitch Recorder	Record, play back, inspect, export data	Pitch
Space Master	Generic Master and Pacer for SpaceFOM federations	Pitch
Space Monitor	Generic monitor of entities and reference frames	Pitch

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A Practical Example: Simulation Exploration Experience

Simulation Exploration Experience

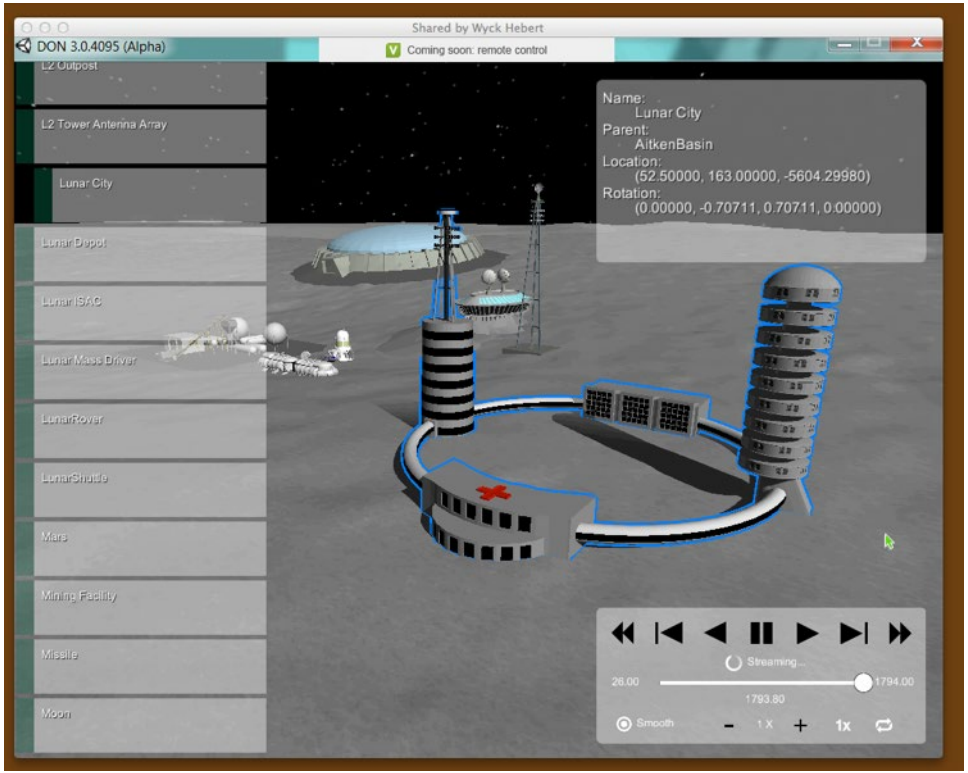
- **Provides international inter-university teams with hands on M&S experience with**
  - Standards & interoperability
  - Distributed HLA and SpaceFOM simulation testing and execution
  - Participation among far-flung international teams
  - Government and industry tutors and mentors

> *"As an experienced M&S educator, SEE allows me to give students practical and educational experience in a very complex area using a uniquely inspiring approach. There is nothing else out there that comes anywhere close to SEE."*

Simon Taylor, Ph.D., faculty Advisor of the Brunel University team

Some SEE Vignettes

- Operations in Aitken Basin on the moon
- Scanning for mining resources
- Constructing a waste management facility
- Astronaut health monitoring
- Operating an asteroid protection systems
- Launching a laser thrust space craft



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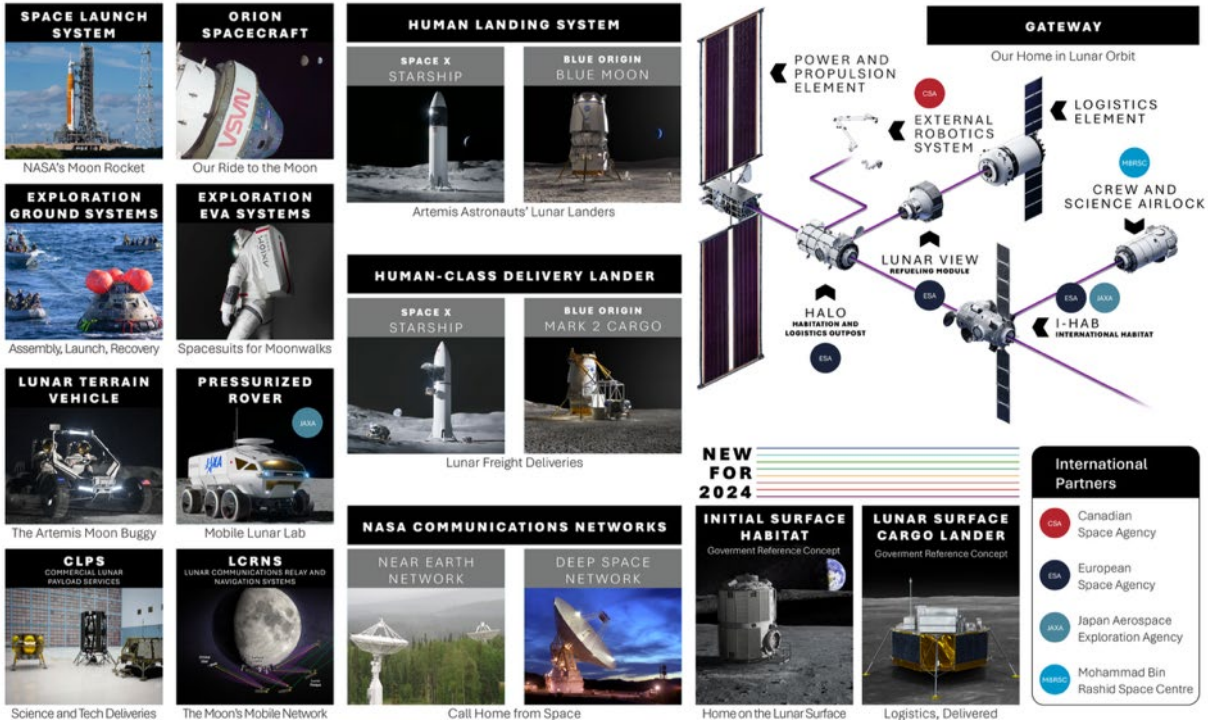
The Future of SpaceFOM

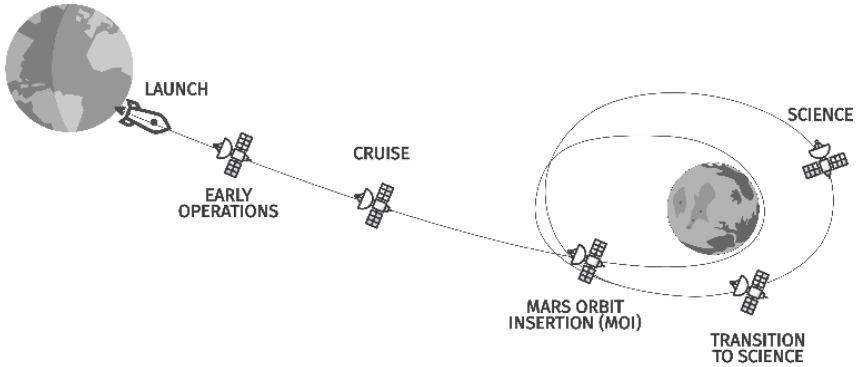
Extension of FOM classes

- SpaceFOM 1.0 has a very generic set of object and interaction classes
- There is now extensive experience from extending the classes from projects like NASA Artemis and European Space Agency HRAF 3.



Time and Time Resolutions

- Configurable time resolution
- Updated Epoch (2000)
- Improved time documentation in FESFA and FCD



Use case for variable time resolution

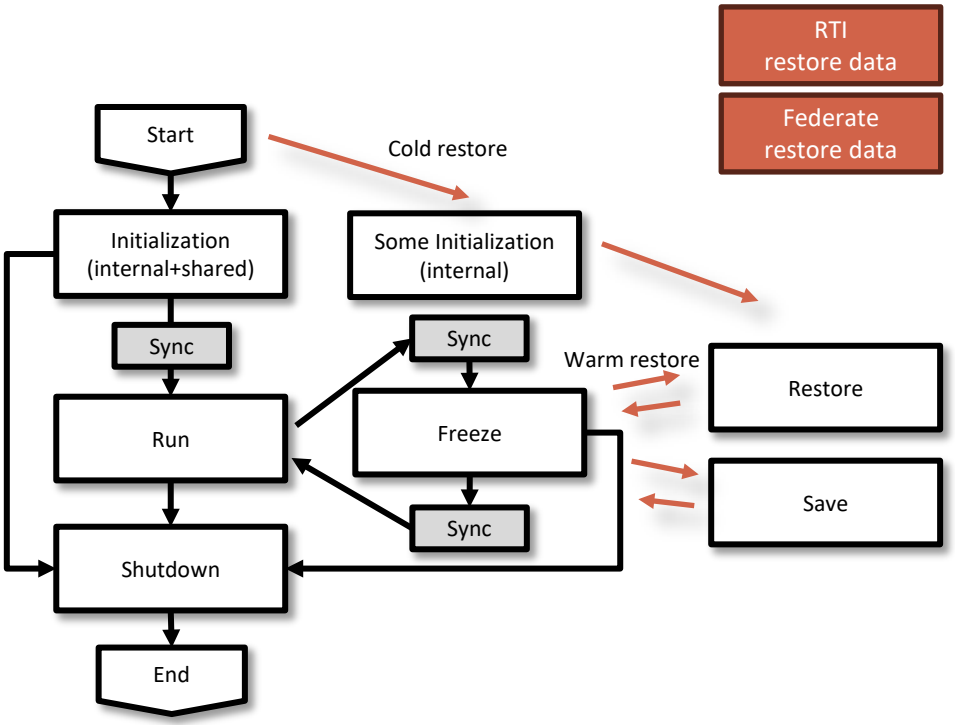
SpaceFOM 1.0 ⇨

BASE_TIME_SECONDS	0
BASE_TIME_100_MILLISECONDS	1
BASE_TIME_10_MILLISECONDS	2
BASE_TIME_MILLISECONDS	3
BASE_TIME_100_MICROSECONDS	4
BASE_TIME_10_MICROSECONDS	5
BASE_TIME_MICROSECONDS	6
BASE_TIME_100_NANOSECONDS	7
BASE_TIME_10_NANOSECONDS	8
BASE_TIME_NANOSECONDS	9
BASE_TIME_100_PICOSECONDS	10
BASE_TIME_10_PICOSECONDS	11
BASE_TIME_PICOSECONDS	12
BASE_TIME_100_FEMTOSECONDS	13
BASE_TIME_10_FEMTOSECONDS	14
BASE_TIME_FEMTOSECONDS	15
BASE_TIME_100_ATTOSECONDS	16
BASE_TIME_10_ATTOSECONDS	17
BASE_TIME_ATTOSECONDS	18

Proposed time resolutions

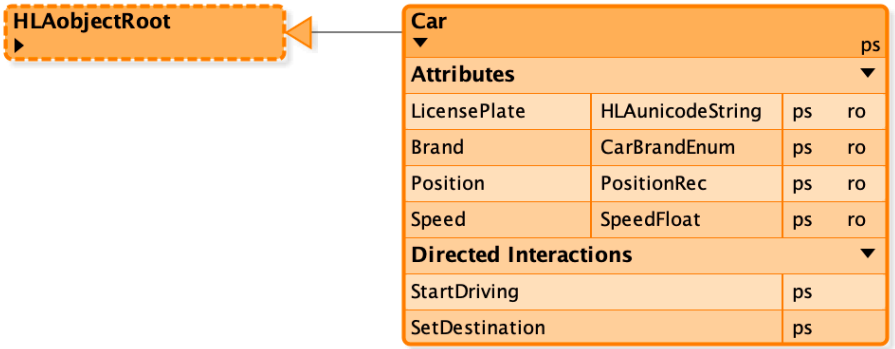
Save and Restore

- **Restore topics**
  - Save in Freeze or Run state?
  - Warm or Cold restore?
  - Does the actual set of federates match the saved data?
  - Error handling?

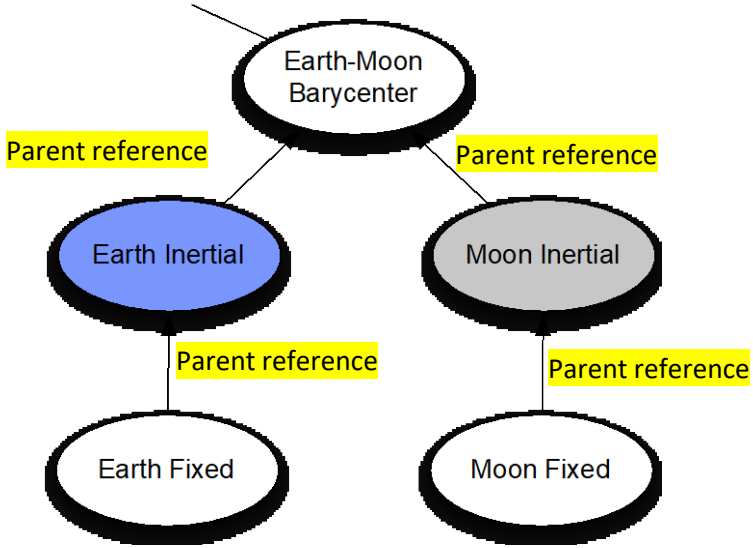


HLA 4

- Directed Interactions
- New data type: Reference



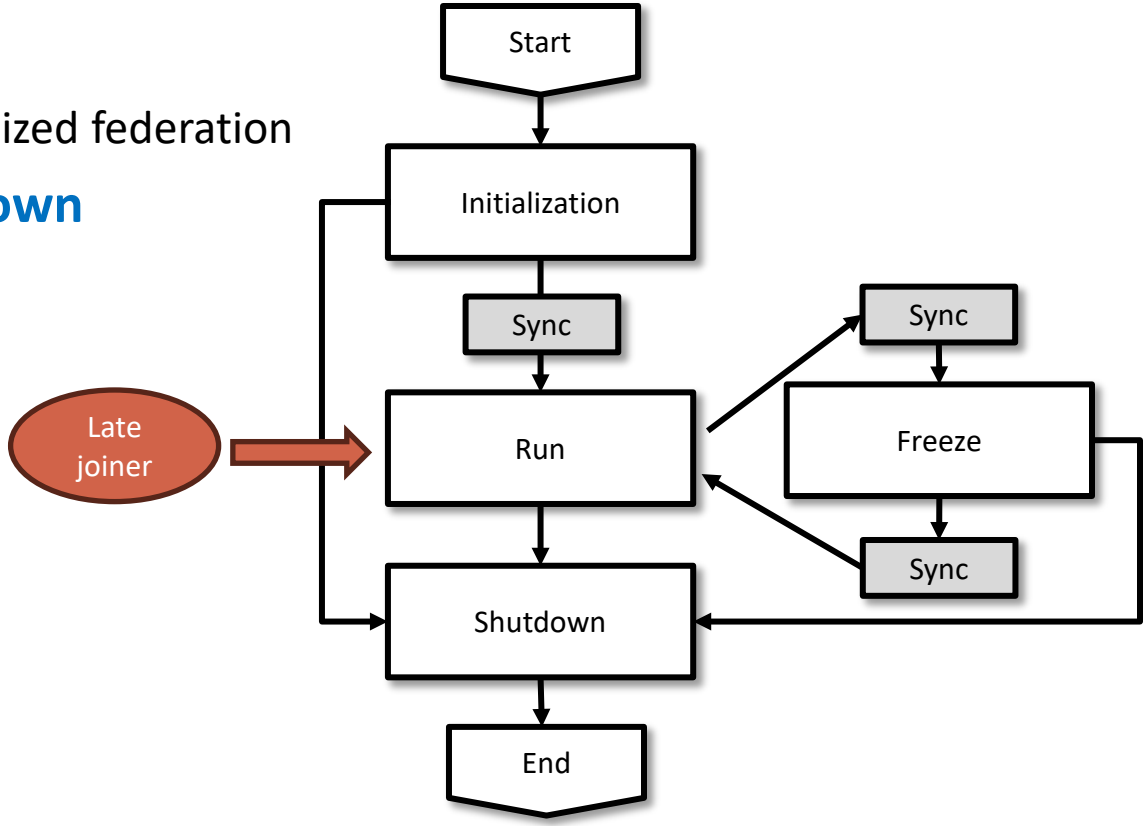
Directed Interaction use case



Sample SpaceFOM reference

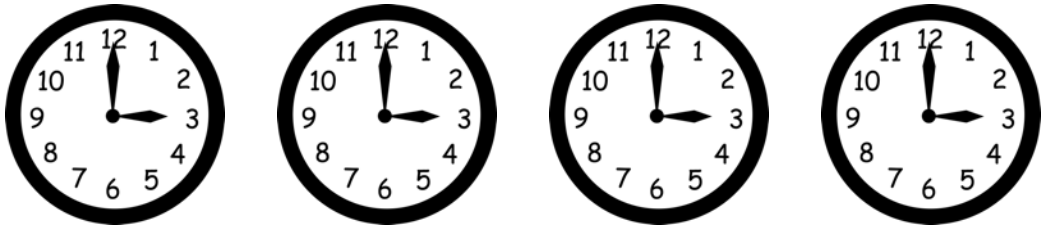
Excution Control

- **Designated late joiners**
  - Will always join an initialized federation
- **Fault tolerance/shut down**



Time Clarifications

- **Some minor nits**
  - Time stamps
  - TAR/TAG and time management questions



Road Ahead for SpaceFOM

- **SISO SpaceFOM 1.0 was published in 2020**
- **A Product Support Group is now in place**
  - Provide guidance and support on the FOM
  - Collect input for future SpaceFOM versions, initiate new versions
- **A number of Product Change Requests (PCRs) for the next SpaceFOM are under development**
- **Starting a Product Development Group (PDG) for SpaceFOM 2.0 will be proposed**

Some References on the SpaceFOM

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QUESTIONS