OMG Systems Modeling Language
(OMG SysML™)
Tutorial

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(emails included in references at end)

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OMG SysML™ Specification

- Specification status
  - Adopted by OMG in May ’06
  - Available Specification v1.0 in Sept ‘07
  - Revision task force for v1.1 in July ‘07

- This tutorial is based on the OMG SysML available specification (formal/2007-09-01)

- This tutorial, the specifications, papers, and vendor info can be found on the OMG SysML Website at http://www.omgsysml.org/
Objectives & Intended Audience

At the end of this tutorial, you should have an awareness of:

• Motivation of model-based systems engineering approach
• SysML diagrams and language concepts
• How to apply SysML as part of a model based SE process
• Basic considerations for transitioning to SysML

This course is not intended to make you a systems modeler!
You must use the language.

Intended Audience:

• Practicing Systems Engineers interested in system modeling
• Software Engineers who want to better understand how to integrate software and system models
• Familiarity with UML is not required, but it helps
Topics

• Motivation & Background
• Diagram Overview and Language Concepts
• SysML Modeling as Part of SE Process
  – Structured Analysis – Distiller Example
  – OOSEM – Enhanced Security System Example
• SysML in a Standards Framework
• Transitioning to SysML
• Summary
Motivation & Background
SE Practices for Describing Systems

**Past**
- Specifications
- Interface requirements
- System design
- Analysis & Trade-off
- Test plans

**Future**

Moving from Document centric to Model centric
System Modeling

Requirements

Functional/Behavioral Model

Start ➔ Shift ➔ Accelerate ➔ Brake

Performance Model

Control Input ➔ Power Equations ➔ Vehicle Dynamics

System Model

Engine ➔ Transmission ➔ Transaxle

Structural/Component Model

Other Engineering Analysis Models

Integrated System Model Must Address Multiple Aspects of a System
Model Based Systems Engineering

Benefits

• Shared understanding of system requirements and design
  – Validation of requirements
  – Common basis for analysis and design
  – Facilitates identification of risks

• Assists in managing complex system development
  – Separation of concerns via multiple views of integrated model
  – Supports traceability through hierarchical system models
  – Facilitates impact analysis of requirements and design changes
  – Supports incremental development & evolutionary acquisition

• Improved design quality
  – Reduced errors and ambiguity
  – More complete representation

• Supports early and on-going verification & validation to reduce risk

• Provides value through life cycle (e.g., training)

• Enhances knowledge capture
System-of-Systems

Modeling Needed to Manage System Complexity
Modeling at Multiple Levels of the System
Stakeholders Involved in System Acquisition

Customers

Developers/Integrators

Project Managers

Regulators

Testers

Vendors

Modeling Needed to Improve Communications
What is SysML?

• A graphical modelling language in response to the UML for Systems Engineering RFP developed by the OMG, INCOSE, and AP233
  – a UML Profile that represents a subset of UML 2 with extensions

• Supports the specification, analysis, design, verification, and validation of systems that include hardware, software, data, personnel, procedures, and facilities

• Supports model and data interchange via XML Metadata Interchange (XMI®) and the evolving AP233 standard (in-process)
What is SysML (cont.)

• *Is* a visual modeling language that provides
  – Semantics = meaning
  – Notation = representation of meaning

• *Is not* a methodology or a tool
  – SysML is methodology and tool independent
UML/SysML Status

• UML V2
  – Updated version of UML that offers significant capability for systems engineering over previous versions
  – Issued in 2005 with on-going minor revisions

• UML for Systems Engineering (SE) RFP
  – Established the requirements for a system modeling language
  – Issued by the OMG in March 2003

• SysML
  – Industry Response to the UML for SE RFP
  – Adopted by OMG in May ’06
Diagram Overview & Language Concepts
Relationship Between SysML and UML

- UML not required by SysML (UML - UML4SysML)
- UML reused by SysML (UML4SysML)
- SysML extensions to UML (SysML Profile)

SysML Extensions
- Blocks
- Item flows
- Value properties
- Allocations
- Requirements
- Parametrics
- Continuous flows
- …
SysML Diagram Taxonomy

- Activity Diagram
- Sequence Diagram
- State Machine Diagram
- Use Case Diagram
- Block Definition Diagram
- Internal Block Diagram
- Package Diagram

- Behavior Diagram
- Requirement Diagram
- Structure Diagram
- Parametric Diagram

Same as UML 2
Modified from UML 2
New diagram type
4 Pillars of SysML – ABS Example

1. Structure

- ABS Activation Sequence [Sequence Diagram]
  - d1: Traction Detector
  - m1: Brake Modulator
  - detTrkLos()
  - modBrkFrc()
  - sendSignal()
  - modBrkFrc(traction_signal:boolean)
  - sendAck()

- Tire Traction [State Diagram]
  - Gripping
  - Slipping
  - LossOfTraction
  - RegainTraction

- Straight Line Vehicle Dynamics [Parameters]
  - e1: Braking Force Equation
    \[ f = (f_0 t^2) (1 - d) \]
  - e2: Acceleration Equation
    \[ a = m/s^2 \]
  - e3: Velocity Equation
    \[ v = m/sec \]
  - e4: Distance Equation
    \[ x = m \]

2. Behavior

- Interaction
- State
- Machine
- Activity/Function

3. Requirements

- Vehicle System Specification
  - Stopping Distance
    - Id = "10.2"
    - Text = "The vehicle shall stop from 60 miles per hour within 150 ft on a clean dry surface."

- Braking Subsystem Specification
  - Anti-Lock Performance
    - Id = "33.7"
    - Text = "The braking system shall prevent wheel lockup under all braking conditions."

4. Parametrics
SysML Diagram Frames

- Each SysML diagram represents a model element
- Each SysML Diagram must have a Diagram Frame
- Diagram context is indicated in the header:
  - Diagram kind (act, bdd, ibd, sd, etc.)
  - Model element type (package, block, activity, etc.)
  - Model element name
  - User defined diagram name or view name
- A separate diagram description block is used to indicate if the diagram is complete, or has elements elided

```
«diagram usage»
diagramKind [modelElementType] modelElementName [diagramName]
```

Header

Contents

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Structural Diagrams

- **SysML Diagram**
  - **Behavior Diagram**
    - Activity Diagram
    - Sequence Diagram
    - State Machine Diagram
    - Use Case Diagram
  - **Requirement Diagram**
    - Block Definition Diagram
    - Internal Block Diagram
    - Package Diagram
  - **Structure Diagram**
    - Parametric Diagram

Legend:
- Same as UML 2
- Modified from UML 2
- New diagram type
Package Diagram

- Package diagram is used to organize the model
  - Groups model elements into a name space
  - Often represented in tool browser
  - Supports model configuration management (check-in/out)
- Model can be organized in multiple ways
  - By System hierarchy (e.g., enterprise, system, component)
  - By diagram kine (e.g., requirements, use cases, behavior)
  - Use viewpoints to augment model organization
- Import relationship reduces need for fully qualified name (package1::class1)
Package Diagram
Organizing the Model

**pkg SampleModel [by diagram type]**

- Use Cases
- Requirements
- Behavior
- Structure
- EngrAnalysis

**pkg SampleModel [by level]**

- Enterprise
- System
- Logical Design
- Physical Design
- Verification

**pkg SampleModel [by IPT]**

- Architecture Team
- Requirements Team
- IPT A
- IPT B
- IPT C

By Diagram Type  By Hierarchy  By IPT
• Viewpoint represents the stakeholder perspective
• View conforms to a particular viewpoint
  – Imports model elements from multiple packages
  – Can represent a model query based on query criteria
• View and Viewpoint consistent with IEEE 1471 definitions
Blocks are Basic Structural Elements

• Provides a unifying concept to describe the structure of an element or system
  – System
  – Hardware
  – Software
  – Data
  – Procedure
  – Facility
  – Person

<table>
<thead>
<tr>
<th>«block»</th>
<th>BrakeModulator</th>
</tr>
</thead>
<tbody>
<tr>
<td>allocatedFrom</td>
<td>«activity» Modulate BrakingForce</td>
</tr>
<tr>
<td>values</td>
<td>DutyCycle: Percentage</td>
</tr>
</tbody>
</table>

• Multiple standard compartments can describe the block characteristics
  – Properties (parts, references, values, ports)
  – Operations
  – Constraints
  – Allocations from/to other model elements (e.g. activities)
  – Requirements the block satisfies
  – User defined compartments
Property Types

- **Property** is a structural feature of a block
  - **Part property** aka. part (typed by a block)
    - Usage of a block in the context of the enclosing (composite) block
    - Example - right-front:wheel
  - **Reference property** (typed by a block)
    - A part that is not owned by the enclosing block (not composition)
    - Example – aggregation of components into logical subsystem
  - **Value property** (typed by value type)
    - A quantifiable property with units, dimensions, and probability distribution
    - Example
      - *Non-distributed value*: tirePressure:psi=30
      - *Distributed value*: «uniform» {min=28,max=32} tirePressure:psi
Using Blocks

• Based on UML Class from UML Composite Structure
  – Supports unique features (e.g., flow ports, value properties)

• Block definition diagram describes the relationship among blocks (e.g., composition, association, specialization)

• Internal block diagram describes the internal structure of a block in terms of its properties and connectors

• Behavior can be allocated to blocks
Block Definition vs. Usage

**Block Definition Diagram**

**Internal Block Diagram**

**Definition**
- Block is a definition/type
- Captures properties, etc.
- Reused in multiple contexts

**Usage**
- Part is the usage of a block in the context of a composing block
- Also known as a role
Internal Block Diagram (ibd)
Blocks, Parts, Ports, Connectors & Flows

Internal Block Diagram Specifies Interconnection of Parts

Enclosing Block
Connector
Item Flow
Port
Part
Reference Property Explained

- S1 is a reference part*
- Shown in dashed outline box

*Actual name is reference property
SysML Ports

• Specifies interaction points on blocks and parts
  – Integrates behavior with structure
  – portName:TypeName

• Kinds of ports
  – Standard (UML) Port
    • Specifies a set of required or provided operations and/or signals
    • Typed by a UML interface
  – Flow Port
    • Specifies what can flow in or out of block/part
    • Typed by a block, value type, or flow specification
    • Atomic, non-atomic, and conjugate variations

Standard Port and Flow Port
Support Different Interface Concepts
Port Notation

**Standard Port**

- **provided interface**
  - (provides the operations)

- **required interface**
  - (calls the operations)

**Flow Port**

- **item flow**

Part 1:  
Part 2:  
Part 1:  
Part 2:  
Delegation Through Ports

- Delegation can be used to preserve encapsulation of block (black box vs white box)
- Interactions at outer ports of Block1 are delegated to ports of child parts
- Ports must match (same kind, type, direction, etc.)
- Connectors can cross boundary without requiring ports at each level of nested hierarchy
Parametrics

• Used to express constraints (equations) between value properties
  – Provides support for engineering analysis (e.g., performance, reliability)
  – Facilitates identification of critical performance properties
• Constraint block captures equations
  – Expression language can be formal (e.g., MathML, OCL) or informal
  – Computational engine is provided by applicable analysis tool and not by SysML
• Parametric diagram represents the usage of the constraints in an analysis context
  – Binding of constraint parameters to value properties of blocks (e.g., vehicle mass bound to parameter ‘m’ in F= m × a)
Defining Vehicle Dynamics

Defining Reusable Equations for Parametrics
Vehicle Dynamics Analysis

Using the Equations in a Parametric Diagram to Constrain Value Properties
Behavioral Diagrams

SysML Diagram

Behavior Diagram

Requirement Diagram

Structure Diagram

Activity Diagram
Sequence Diagram
State Machine Diagram
Use Case Diagram
Block Definition Diagram
Internal Block Diagram
Package Diagram

Same as UML 2
Modified from UML 2
New diagram type
Activities

- Activity specifies transformation of inputs to outputs through a controlled sequence of actions
- Secondary constructs show responsibilities for the activities using activity partitions (i.e., swim lanes)
- SysML extensions to Activities
  - Support for continuous flow modeling
  - Alignment of activities with Enhanced Functional Flow Block Diagram (EFFBD)
Activity Diagram

Activity Diagram Specifies Controlled Sequence of Actions
Routing Flows

**Initial Node** – On execution of parent control token placed on outgoing control flows

**Activity Final Node** – Receipt of a control token terminates parent

**Flow Final Node** – Sink for control tokens

**Fork Node** – Duplicates input (control or object) tokens from its input flow onto all outgoing flows

**Join Node** – Waits for an input (control or object) token on all input flows and then places them all on the outgoing flow

**Decision Node** – Waits for an input (control or object) token on its input flow and places it on one outgoing flow based on guards

**Merge Node** – Waits for an input (control or object) token on any input flows and then places it on the outgoing flow

*Guard expressions can be applied on all flows*
Actions Process Flow of Control and Data

- Two types of flow
  - Object / Data
  - Control
- Unit of flow is called a “token”
  (consumed & produced by actions)

Actions Execution Begins When Tokens Are Available on “all” Control Inputs and Required Inputs
An Action Can Invoke Another Activity

Activity is Invoked When an Action Begins to Execute
Semantics for Activity Invocation

A call behavior action can have
- 0..* control inputs & outputs
- 0 ..* optional item inputs & outputs
- 0..* required item inputs & outputs
- 0..* streaming (and continuous) item inputs & outputs

Starting an action:
- An action starts when a token is placed on all of its control inputs and all of its required inputs (must meet minimum multiplicity of its input pins) and the previous invoked activity has completed
- An action invokes an activity when it starts, and passes the tokens from its input pins to the input parameter nodes of the invoked activity

During an execution:
- An action continues to accept streaming inputs and produce streaming outputs

Terminating an action:
- An action terminates when its invoked activity reaches an activity final, or when the action receives a control disable, or as a side effect of other behaviors of the parent activity
- The tokens on the output parameter nodes of the activity are placed on the output pins of the action and a control token is placed on each of the control outputs of the action

Following action termination:
- The tokens on the output pins and control outputs of the action are moved to the input pins of the next actions when they are ready to start per above
- The action can restart and invoke the activity again when the starting conditions are satisfied per above
Common Actions

- **Call Operation Action**
  - (can call leaf level function)

- **Call Behavior Action**

- **Accept Event Action**
  - (Event Data Pin often elided)

- **Send Signal Action**
  - (Pins often elided)
Activity Diagram Example
With Streaming Inputs and Outputs

Streaming Inputs and Outputs Continue to Be Consumed and Produced While the Action is Executing
Continuous Flow Is Representative of Many Physical Processes

Continuous flow means $\Delta$Time between tokens approaches zero.

Actions are enabled by default when activity is enabled.

Accept Event Action Will Terminate Execution

Interruptible Region

Continuous Flow
Example – Operate Car

Enabling and Disabling Actions
With Control Operators
Activity Diagrams

Pin vs. Object Node Notation

• Pins are kinds of Object Nodes
  – Used to specify inputs and outputs of actions
  – Typed by a block or value type
  – Object flows connect object nodes

• Object flows between pins have two diagrammatic forms
  – Pins shown with object flow between them
  – Pins elided and object node shown with flow arrows in and out

Pins must have same characteristics (name, type etc.)
Explicit Allocation of Behavior to Structure Using Swimlanes

Activity Diagram (without Swimlanes)

Activity Diagram (with Swimlanes)
**Activity Decomposition**

### Definition

- **Prevent Lockup**
  - **a1**: Detect Loss of Traction
  - **p1**: TractLoss
- **a2**: Modulate Braking Force
  - **p2**: TractLoss

### Use

- **a1**: Detect Loss of Traction
  - **p1**: TractLoss of1
- **a2**: Modulate Braking Force
  - **p2**: TractLoss
SysML EFFBD Profile

EFFBD - Enhanced Functional Flow Block Diagram

Aligning SysML with Classical Systems Engineering Techniques

4/15/2008

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Interactions

• Sequence diagrams provide representations of message based behavior
  – represent flow of control
  – describe interactions between parts

• Sequence diagrams provide mechanisms for representing complex scenarios
  – reference sequences
  – control logic
  – lifeline decomposition

• SysML does not include timing, interaction overview, and communications diagram
Black Box Interaction (Drive)

UML 2 Sequence Diagram Scales by Supporting Control Logic and Reference Sequences
Black Box Sequence (StartVehicle)

Simple Black Box Interaction
White Box Sequence (StartVehicle)

Decomposition of Black Box Into White Box Interaction
Primary Interaction Operators

- **ref** name
  - reference to a sequence diagram fragment defined elsewhere
- **opt** [condition]
  - has 1 part that may be executed based on a condition/state value
- **alt**
  - has 2 or more parts, but only one executes based on a condition/state
  - an operand fragment labeled [else] is executed if no other condition is true
- **par**
  - has 2 or more parts that execute concurrently
    - Concurrence indicates does not require simultaneous, just that the order is undetermined. If there is only one processor the behavior could be (A then B), (B then A), or (A and B interleaving) ...
- **loop** min..max [escape]
  - Has a minimum # of executions, and optional maximum # of executions, and optional escape condition
- **break** [condition]
  - Has an optional guard. If true, the contents (if any) are executed, and the remainder of the enclosing operator is not executed
Other Interaction Operators

- **critical**
  - The sequence diagram fragment is a critical region. It is treated as atomic – no interleaving with parallel regions

- **neg**
  - The sequence diagram fragment is forbidden. Either it is impossible to occur, or it is the intent of the requirements to prevent it from occurring

- **assert**
  - The sequence diagram fragment is the only one possible (or legal)

- **seq** (weak, the default)
  - **strict**
    - Strict: The message exchange occurs in the order described
    - Weak: Each lifeline may see different orders for the exchange (subject to causality)

- **consider** (list of messages)
  - **ignore** (list of messages)
    - Consider: List the messages that are relevant in this sequence fragment
    - Ignored: List the messages that may arrive, but are not interesting here

*Provided by Michael Chonoles*
Trial Result of Vehicle Dynamics

Typical Example of a Timing Diagram

Lifeline are value properties

Timing Diagram Not Part of SysML
State Machines

- Typically used to represent the life cycle of a block
- Support event-based behavior (generally asynchronous)
  - Transition with trigger, guard, action
  - State with entry, exit, and do-activity
  - Can include nested sequential or concurrent states
  - Can send/receive signals to communicate between blocks during state transitions, etc.

- Event types
  - Change event
  - Time event
  - Signal event
Operational States (Drive)

stm HSUVOperationalStates

Off
keyOff/

start[in neutral]/start engine
shutOff/stop engine

Nominal states only

Operate

Idle

accelerate/

when (speed = 0)

releaseBrake/

Accelerating/Cruising

engageBrake/

Braking

Transition notation: trigger[guard]/action
Use Cases

• Provide means for describing basic functionality in terms of usages/goals of the system by actors
  – Use is methodology dependent
  – Often accompanied by use case descriptions
• Common functionality can be factored out via «include» and «extend» relationships
• Elaborated via other behavioral representations to describe detailed scenarios
• No change to UML
Operational Use Cases

uc HSUV_UseCases [Operational Use Cases]

HybridSUV

Driver

- Drive_The_Vehicle
  - Accelerate
  - Steer
  - Brake
  - Park
  - Flat_Tire
  - «extend»
  - «include»
  - «include»
  - «include»
Cross-cutting Constructs

- Allocations
- Requirements
Allocations

• Represent general relationships that map one model element to another

• Different types of allocation are:
  – Behavioral (i.e., function to component)
  – Structural (i.e., logical to physical)
  – Software to Hardware
  – ….

• Explicit allocation of activities to structure via swim lanes (i.e., activity partitions)

• Both graphical and tabular representations are specified
Different Allocation Representations
(Tabular Representation Not Shown)

Allocate Relationship

Explicit Allocation of
Action to Part Property

Compartment Notation

Callout Notation

Read as follows: “part name has constraints that are allocated to/from an <<element type>> Element Name”
SysML Allocation of SW to HW

- In UML, the deployment diagram is used to deploy artifacts to nodes
- In SysML, «allocation» on an ibd and bdd is used to deploy software/data to hardware

```
ibd [node] SF Residence

- «hardware»: Site Processor
  - allocatedFrom
    - «software» Device Mgr
    - «software» Event Mgr
    - «software» Site Config Mgr
    - «software» Site RDBMS
    - «software» Site Status Mgr
    - «software» User I/F
    - «software» User Valid Mgr

- «hardware»: Site Hard Disk
  - allocatedFrom
    - «data» Site Database

- «hardware»: Optical Sensor

- «hardware»: Video Camera
  - allocatedFrom
    - «software» SF Comm I/F

- «hardware»: NW Hub
  - allocatedFrom
    - «software» SF Comm I/F

- «hardware»: DSL Modem

- «hardware»: DVD-ROM Drive
  - allocatedFrom
    - «data» Video File

- «hardware»: User Console

- «hardware»: Alarm
  - allocatedFrom
    - «hardware»: DSL Modem

- «hardware»: NW Hub
  - allocatedFrom
    - «hardware»: Site Hard Disk
```

Requirements

• The «requirement» stereotype represents a text based requirement
  – Includes id and text properties
  – Can add user defined properties such as verification method
  – Can add user defined requirements categories
    (e.g., functional, interface, performance)

• Requirements hierarchy describes requirements contained in a specification

• Requirements relationships include DeriveReqt, Satisfy, Verify, Refine, Trace, Copy
Requirements Breakdown

req [package] HSUVRequirements [HSUV Specification]

- «requirement» Eco-Friendliness
- «requirement» Performance
- «requirement» Braking
- «requirement» FuelEconomy
- «requirement» Acceleration
- «requirement» Emissions

Id = "R1.2.1"
text = "The vehicle shall meet Ultra-Low Emissions Vehicle standards."

RefinedBy
«useCase» HSUVUseCases::Accelerate

SatisfiedBy
«block» PowerSubsystem

VerifiedBy
«testCase» MaxAcceleration

Requirement Relationships Model the Content of a Specification
Example of Derive/Satisfy Requirement Dependencies

Client depends on supplier (i.e., a change in supplier results in a change in client)

Arrow Direction Opposite Typical Requirements Flow-Down
Problem and Rationale can be attached to any Model Element to Capture Issues and Decisions.

The master cylinder in previous version leaked.

The best-practice solution consists in assigning one reservoir per brake line.

See "automotive_d32_hdb.doc"
Stereotypes & Model Libraries

- Mechanisms for further customizing SysML
- Profiles represent extensions to the language
  - Stereotypes extend meta-classes with properties and constraints
    - Stereotype properties capture metadata about the model element
  - Profile is applied to user model
  - Profile can also restrict the subset of the meta-model used when the profile is applied
- Model Libraries represent reusable libraries of model elements
Stereotypes

Defining the Stereotype

Applying the Stereotype
Applying a Profile and Importing a Model Library

pkg ModelingDomain [Establishing HSUV Model]

«profile» SysML

«apply» {strict}

«modelLibrary» SI Definitions

«import»

HSUVModel
Cross Connecting Model Elements

1. Structure

2. Behavior

3. Requirements

4. Parametrics

allocate

value binding

satisfy

Verify
SysML Modeling as Part of the SE Process
Distiller Sample Problem
Distiller Problem Statement

- The following problem was posed to the SysML team in Dec ’05 by D. Oliver:
  - Describe a system for purifying dirty water.
    - Heat dirty water and condense steam are performed by a Counter Flow Heat Exchanger
    - Boil dirty water is performed by a Boiler
    - Drain residue is performed by a Drain
    - The water has properties: vol = 1 liter, density 1 gm/cm³, temp 20 deg C, specific heat 1 cal/gm deg C, heat of vaporization 540 cal/gm.

- A crude behavior diagram is shown.

What are the real requirements? How do we design the system?
Distiller Types

Batch Distiller

Continuous Distiller

Note: Not all aspects of the distiller are modeled in the example
Distiller Problem – Process Used

- Organize the model, identify libraries needed
- List requirements and assumptions
- Model behavior
  - In similar form to problem statement
  - Elaborate as necessary
- Model structure
  - Capture implied inputs and outputs
    - segregate I/O from behavioral flows
  - Allocate behavior onto structure, flow onto I/O
- Capture and evaluate parametric constraints
  - Heat balance equation
- Modify design as required to meet constraints
- Model the user interaction
- Modify design to reflect user interaction
Distiller Problem – Package Diagram:
Model Structure and Libraries
Distiller Example Requirements Diagram

Source_Requirements

Original Statement

Id = "S0.0"
Text = "Describe a system for purifying dirty water.
- Heat dirty water and condense steam are performed by a Counter Flow Heat Exchanger
- Boil dirty water is performed by a Boiler. Drain residue is performed by a Drain.
The water has properties: vol = 1 liter, density 1 g/m/cm^3, temp 20 deg C, specific heat 1 cal/gm deg C, heat of vaporization 540 cal/gm."

Purify Water

Id = "S1.0"
Text = "The system shall purify dirty water."

Heat Exchanger

Id = "S2.0"
Text = "Heat dirty water and condense steam are performed by a Counter Flow Heat Exchanger."

Boiler

Id = "S3.0"
Text = "Boil dirty water is performed by a Boiler."

Drain

Id = "S4.0"
Text = "Drain residue is performed by a Drain."

Water Properties

Id = "S5.0"
Text = "Water has properties: density 1 g/m/cm^3, temp 20 deg C, specific heat 1 cal/gm deg C, heat of vaporization 540 cal/gm."

Water Initial Temp

Id = "S5.1"
Text = "Water has an initial temp 20 deg C."

Distill Water

(Id = "D1.0"
Text = "The system shall purify water by boiling it.

Rationale

The requirement for a boiling function and a boiler implies that the water must be purified by distillation.

4/15/2008

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### Distiller Example: Requirements Tables

**Table 1: Original Statement and Decomposition**

<table>
<thead>
<tr>
<th>id</th>
<th>name</th>
<th>text</th>
</tr>
</thead>
<tbody>
<tr>
<td>S0.0</td>
<td>OriginalStatement</td>
<td>Describe a system for purifying dirty water. ...</td>
</tr>
<tr>
<td>S1.0</td>
<td>PurifyWater</td>
<td>The system shall purify dirty water.</td>
</tr>
<tr>
<td>S2.0</td>
<td>HeatExchanger</td>
<td>Heat dirty water and condense steam are performed by a ...</td>
</tr>
<tr>
<td>S3.0</td>
<td>Boiler</td>
<td>Boil dirty water is performed by a Boiler.</td>
</tr>
<tr>
<td>S4.0</td>
<td>Drain</td>
<td>Drain residue is performed by a Drain.</td>
</tr>
<tr>
<td>S5.0</td>
<td>WaterProperties</td>
<td>water has properties: density 1 gm/cm3, temp 20 deg C, ...</td>
</tr>
<tr>
<td>S5.1</td>
<td>WaterInitialTemp</td>
<td>water has an initial temp 20 deg C</td>
</tr>
</tbody>
</table>

**Table 2: PurifyWater Requirements Tree**

<table>
<thead>
<tr>
<th>id</th>
<th>name</th>
<th>relation</th>
<th>id</th>
<th>name</th>
<th>Rationale</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1.0</td>
<td>PurifyWater</td>
<td>deriveReqt</td>
<td>D1.0</td>
<td>DistillWater</td>
<td>The requirement for a boiling function and a boiler implies that the water must be purified by distillation</td>
</tr>
</tbody>
</table>
Distiller Example – Activity Diagram: Initial Diagram for DistillWater

- This activity diagram applies the SysML EFFBD profile, and formalizes the diagram in the problem statement.
**Distiller Example – Activity Diagram: Control-Driven: Serial Behavior**

- **coldDirty**: H2O (liquid)
- **hotDirty**: H2O (gas)
- **steam**: H2O (liquid)
- **pure**: H2O (liquid)
- **recovered**: Heat
- **external**: Heat
- **discharge**: Residue
- **predischarge**: Residue
- **a1**: HeatWater
- **a2**: BoilWater
- **a3**: CondenseSteam
- **a4**: DrainResidue

**Batch Distiller**
Distiller Example – Block Definition

Diagram: DistillerBehavior

Activities (Functions)

- **Heat Water**
- **Boil Water**
- **Condense Steam**
- **Drain Residue**

Control (not shown on BDD)

**Things that flow (ObjectNodes)**

- **H2O**
  - water temp: °C (unit = degrees celcius, dimension = temperature)
  - specific heat: cal/gm (nonunique unit = calories per gram, dimension = latent heat)
  - latent heat: cal/(gm°C) (nonunique unit = calories per gram degree celcius, dimension = specific heat)
  - water press: N/m² (unit = newtons per square meter, dimension = pressure)
  - mass flow rate: gm/sec (unit = grams per second, dimension = mass flow rate)

Values:

- dQ/dt: calories per second
- sludge temp: °C (unit = degrees celcius, dimension = temperature)
- sludge press: N/m² (unit = newtons per square meter, dimension = pressure)
Distiller Example – State Machine
Diagram: States of H2O

States

Transitions

when (water temp == 100 & latent heat of vaporization added)

when (water temp == 100 & latent heat of vaporization removed)

when (water temp == 0 & latent heat of fusion added)

when (water temp == 0 & latent heat of fusion removed)
Distiller Example – Activity Diagram:
No Control Flow, ActionPin Notation,
Simultaneous Behavior

Distiller Example – Activity Diagram (with Swimlanes): DistillWater

Distiller Example – Block Definition
Diagram: DistillerStructure
Distiller Example – Block Definition Diagram: Heat Exchanger Flow Ports

Distiller Structure [distiller breakdown (ports)]

Constraints (on Ports)

Flow Ports (typed by things that flow)
Distiller Example – Internal Block Diagram: Distiller Initial Design
### Distiller Example – Table: Functional Allocation

<table>
<thead>
<tr>
<th>Initial Distiller Structure</th>
<th>Distiller</th>
<th>-condenser</th>
<th>-drain</th>
<th>-evaporator</th>
<th>-main1</th>
<th>-main2</th>
<th>-main3</th>
<th>-main4</th>
<th>-q1</th>
<th>-sludge1</th>
<th>-sludge2</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="Image1" alt="Swimlane Diagram" /></td>
<td><img src="Image2" alt="Swimlane Diagram" /></td>
<td><img src="Image3" alt="Swimlane Diagram" /></td>
<td><img src="Image4" alt="Swimlane Diagram" /></td>
<td><img src="Image5" alt="Swimlane Diagram" /></td>
<td><img src="Image6" alt="Swimlane Diagram" /></td>
<td><img src="Image7" alt="Swimlane Diagram" /></td>
<td><img src="Image8" alt="Swimlane Diagram" /></td>
<td><img src="Image9" alt="Swimlane Diagram" /></td>
<td><img src="Image10" alt="Swimlane Diagram" /></td>
<td><img src="Image11" alt="Swimlane Diagram" /></td>
<td><img src="Image12" alt="Swimlane Diagram" /></td>
</tr>
</tbody>
</table>

**Exercise for student:**
- Is allocation complete?
- Where is “objectFlow” of 8?”
Distiller Example – Heat Balance Results

<table>
<thead>
<tr>
<th>Table: IsobaricHeatBalance</th>
<th>Results of Isobaric Heat Balance</th>
</tr>
</thead>
<tbody>
<tr>
<td>specific heat cal/gm-°C</td>
<td>1</td>
</tr>
<tr>
<td>latent heat cal/cm</td>
<td>540</td>
</tr>
<tr>
<td>mass flow rate gm/sec</td>
<td>6.8</td>
</tr>
<tr>
<td>temp °C</td>
<td>20, 100, 100, 100, 100</td>
</tr>
<tr>
<td>dQ/dt cooling water cal/sec</td>
<td>540</td>
</tr>
<tr>
<td>dQ/dt steam-condensate cal/sec</td>
<td>540</td>
</tr>
<tr>
<td>condenser efficiency</td>
<td>1</td>
</tr>
<tr>
<td>heat deficit</td>
<td>0</td>
</tr>
<tr>
<td>dQ/dt condensate-steam cal/sec</td>
<td>540</td>
</tr>
<tr>
<td>boiler efficiency</td>
<td>1</td>
</tr>
<tr>
<td>dQ/dt in boiler cal/sec</td>
<td>540</td>
</tr>
</tbody>
</table>

Note: Cooling water needs to have 6.75x flow of steam!
Need bypass between hx_water_out and bx_water_in!

1. Set these (steady state)
2. Solve for these

Satisfies «requirement» WaterSpecificHeat
Satisfies «requirement» WaterHeatOfVaporization
Satisfies «requirement» WaterInitialTemp
Distiller Example – Use Case and Sequence Diagrams

Operational Sequence

1: Turn On
2: Power Lamp On
3: Operating Lamp On

[while state=Operating]

[loop]

4: High Level Lamp On
5: Low Level Lamp On
6: Draining Lamp On

[alt]

[while state=draining residue]

[loop]

7: Turn Off
8: Power Lamp Off

Use Case: Operate Distiller

Operator

Distiller

Distiller Use Cases

Operator

Distiller

Operate Distiller
Distiller Example – State Machine
Diagram: Distiller Controller

stm Controller State Machine [ simple diagram ]

Off

do Power Light Off

[ bx level low ]

[ power = on ]

Filling
do open feed : Valve

[ NOT bx level low ]

Warming Up
do bx1 heater on

[ bx1 temp = 100 ]

Operating

do bx1 heater on

[ NOT bx1 level low ]

Level Low
do open feed : Valve

level ok
do shut all Valves

Level High
do open drain : Valve

[ NOT bx1 level high ]

[ bx1 level low ]

[ bx1 level high ]

[ residue timer ]

[ drain timer ]

Building Up Residue
do close drain : Valve

Purging Residue
do open drain : Valve

[ shutdown command ]

Draining
do open drain : Valve

[ bx1 temp = 30 ]

Cooling Off

test bx1 heater OFF
do open feed : Valve, open drain : Valve

[ bx1 temp = 30 ]

[ NOT bx1 level low ]

[ NOT bx1 level high ]
OOSEM – ESS Example
System Development Process

**Integrated Product Development (IPD) is essential to improve communications**

**A Recursive V process that can be applied to multiple levels of the system hierarchy**

System Modeling Activities – OOSEM
Integrating MBSE into the SE Process

Analyse Needs

Define
System Requirements

- Mission use cases/scenarios
- Enterprise model

Define Logical Architecture

- System use cases/scenarios
- Elaborated context
- Req’ts diagram

Optimize & Evaluate Alternatives

Synthesize Physical Architecture

- Logical architecture

Validate & Verify System

- Test cases/procedures

- Node diagram
- HW, SW, Data architecture

Requirements Traceability is Managed Through the Entire MBSE Process
Enhanced Security System Example

• The Enhanced Security System is the example for the OOSEM material
  – Problem fragments used to demonstrate principles
  – Utilizes Artisan RTS™ Tool for the SysML artifacts
Operational View Depiction

---

bdd [package] Enterprise (As Is)

- Central Monitoring Station As-Is
- Comm Network
- Residence
- Dispatcher
- Police
- Intruder
ESS Enterprise As-Is Model

bdd [package] ESS Enterprise (As Is)

Domain As-Is

Residence

Customer As-Is

Intruder

1

Enterprise As-Is

«enterprise» Comm Network

«external» Emergency Services As-Is

«system» Sec Sys

Site Installation As-Is

Central Monitoring Station As-Is

Dispatcher

Police

ESS Operational Enterprise To-Be Model
System Use Cases - Operate

uc [package] System Use Cases

Activate/Deactivate

Operate

«include»

Monitor Site

«include»

«extend»

Respond

Respond to Break-In

Respond to Fire

Respond to Medical
System Scenario: Activity Diagram
Monitor Site (Break-In)
ESS Elaborated Context Diagram

- **System**: ESS
  - **Performance**: Power \(\leq 100\) watts
  - **Reliability**
  - **Physical**: SiteInstallation
  - **Store**: EventLog, SystemState

- **External**
  - **Emergency Services**
  - **Property**
  - **Customer**
  - **Intruder**

- **Domain**
  - **Environmental Input**
  - **Power**
  - **Door Input**
  - **Window Input**
  - **Alarm Signal**
  - **Intruder Signal**

- **Actions**
  - DetectEntry()
  - DetectExit()
  - ReportEntry()
  - ReportExit()
  - GenerateAlarm()
  - ValidateEntry()
  - InternalMonitor()
  - DetectFire()
  - DetectMedicalEmergency()
  - RequestUserID()
  - ValidateUserID()
  - SetTimer()
  - ActivateSystem()
  - ProtectPrivacy()
  - StatusUpdate()
  - DetectFault()
ESS Logical Decomposition (Partial)

```
[package] ESS Logical Decomposition

«system» ESS

- «logical» Entry Sensor
- «logical» Exit Sensor
- «logical» Perimeter Sensor
- «logical» Environment Sensor
- «logical» Emer Serv I/F
- «logical» Customer I/F
- «logical» Alarm Generator
- «logical» Alarm I/F
- «logical» Fault Mgr
- «logical» User Validation Mgr
- «logical» Sys Config Mgr

- «logical» Customer Output Mgr
- «logical» Customer Input Mgr
- «logical» Entry/Exit Monitor
- «logical» Emergency Monitor
- «logical» Event Monitor
- «logical» Emer Serv I/F
- «logical» Customer I/F
- «logical» External I/F Manager
- «logical» Support Service Manager
```

Detect Entry Subsystem Scenario

act detectEntry

«logical»
entry/exit subsystem

«logical»
Entry Sensor

«logical»
Entry/Exit Monitor

«logical»
Event Monitor

Door Input
«continuous»
Window Input
«continuous»

Sense State Change

Detect Event

Record Event

 Alert Status

[State=BreakInResponse]

[Else]

Event Log

«store»

«subsystem»

• Added operations from Detect Entry / Detect Exit logical scenario

• These operations support entry/exit subsystem
ESS Logical Design – Example Subsystem

ibd [subsystem]Entry/Exit Subsystem

Door Input : Door Input
Window Input : Window Input

«logical» : Entry Sensor
«logical» : Exit Sensor
m+n : SensedEntry
m+n : SensedExit

«logical» : Entry/Exit Monitor
«logical» : Event Monitor
«store» : Event Log

: Entry/Exit Alert Status
: Alert Status

: SensedExit

ESS Logical Design (Partial)
ESS Allocation Table (partial)

- Allocating Logical Components to HW, SW, Data, and Procedures components

<table>
<thead>
<tr>
<th>Logical Components</th>
<th>Entry Sensor</th>
<th>Exit Sensor</th>
<th>Perimeter Sensor</th>
<th>Entry/Exit Monitor</th>
<th>Event Monitor</th>
<th>Site Comms I/F</th>
<th>Event Log</th>
<th>Customer I/F</th>
<th>Customer Output Mgr</th>
<th>System Status</th>
<th>Fault Mgr</th>
<th>Alarm Generator</th>
<th>Alarm I/F</th>
</tr>
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<tbody>
<tr>
<td><strong>Type</strong></td>
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<td>Device Mgr</td>
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<td>SF Comm I/F</td>
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<td>User Console</td>
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<td>Video Camera</td>
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<td>Alarm</td>
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</tr>
</tbody>
</table>
ESS Parametric Diagram
To Support Trade-off Analysis

\[
\text{ObjectiveFunction} = \sum(w_1 \cdot u(\text{OA}) + w_2 \cdot u(\text{MRT}) + w_3 \cdot u(\text{OC}))
\]

\par\text{EnterpriseEffectivenessModel}

- «moe» MissionResponseTime
- «moe» OperationalAvailability
- «moe» OperationalCost

\text{CostEffectiveness}

Entry/Exit Test Case

sd Entry/Exit Detection Test

Description

Intruder enters through front door
Door sensor detects entry
New alert status sent to central system
Intruder leaves through lounge window
Window sensor detects exit
Changed alert status sent to central system

seq

Intruder Entry : Alert Status

seq

Intruder Exit : Alert Status
SysML in a Standards Framework
Systems Engineering Standards Framework (Partial List)

- **Process Standards**
  - EIA 632
  - ISO 15288
  - IEEE 1220
  - CMMI

- **Architecture Frameworks**
  - FEAF
  - DoDAF
  - MODAF
  - Zachman FW

- **Modeling Methods**
  - HP
  - OOSE
  - SADT
  - Other

- **Modeling & Simulation Standards**
  - IDEF0
  - SysML
  - MARTE
  - HLA
  - MathML

  - System Modeling
  - Simulation & Analysis

- **Interchange & Metamodelling Standards**
  - MOF
  - XMI
  - STEP/AP233

Note: This diagram represents a partial list of systems engineering standards and frameworks.
ISO/IEC 15288
System Life Cycle Processes

Enterprise Processes
- 5.3.2 Enterprise Environment Management Process
- 5.3.3 Investment Management Process
- 5.3.4 System Life Cycle Processes Management
- 5.3.5 Quality Management Process
- 5.3.6 Resource Management Process

Agreement Processes
- 5.2.2 Acquisition Process
- 5.2.3 Supply Process

Project Processes
- 5.4.2 Project Planning Process
- 5.4.3 Project Assessment Process
- 5.4.4 Project Control Process
- 5.4.5 Decision-Making Process
- 5.4.6 Risk Management Process
- 5.4.7 Configuration Management Process
- 5.4.8 Information Management Process

Technical Processes
- 5.5.2 Stakeholder Reqs Definition Process
- 5.5.3 Reqs Analysis Process
- 5.5.4 Architectural Design Process
- 5.5.5 Implementation Process
- 5.5.6 Integration Process
- 5.5.7 Verification Process
- 5.5.8 Transition Process
- 5.5.9 Validation Process
- 5.5.10 Operation Process
- 5.5.11 Maintenance Process
- 5.5.12 Disposal Process
Standards-based Tool Integration with SysML

Systems Modeling Tool

Model/ Data Interchange

Other Engineering Tools

AP233/ XMI

AP233/ XMI
Participating SysML Tool Vendors

- Artisan (Studio)
- EmbeddedPlus (SysML Toolkit)
  - 3rd party IBM vendor
- No Magic (Magic Draw)
- Sparx Systems (Enterprise Architect)
- IBM / Telelogic (Tau and Rhapsody)
- TopCased
- Visio SysML template
Transitioning to SysML
Using Process Improvement To Transition to SysML

Plan Improvement

Assess & Measure Improvement

Define Improvement

Continuous Improvement Cycle

Deploy Improvement

Pilot Improvement

MBSE Transition Plan

• MBSE Scope
• MBSE Responsibilities/Staffing
• Process guidance
  – High level process flow (capture in SEMP)
  – Model artifact checklist
  – Tool specific guidance
• Tool support
  – Modeling tool
  – Requirements management
  – CM
• Training
• Schedule
Typical Integrated Tool Environment

- CM/DM
- Product Data Management
- Requirements Management
- Verification & Validation
- Project Management
  - SoS/ DoDAF / Business Process Modeling
  - System Modeling
    - SysML
  - Software Modeling
    - UML 2.0
  - Hardware Modeling
    - VHDL, CAD, ..
- Simulation & Visualization
- Engineering Analysis
Summary and Wrap up
Summary

- SysML sponsored by INCOSE/OMG with broad industry and vendor participation and adopted in 2006
- SysML provides a general purpose modeling language to support specification, analysis, design and verification of complex systems
  - Subset of UML 2 with extensions
  - 4 Pillars of SysML include modeling of requirements, behavior, structure, and parametrics
- Multiple vendor implementations available
- Standards based modeling approach for SE expected to improve communications, tool interoperability, and design quality
- Plan SysML transition as part of overall MBSE approach
- Continue to evolve SysML based on user/vendor/researcher feedback and lessons learned
References

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