Engine Modeling with Modelica

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Modelica Automotive Workshop
Engine Modeling Session
November 19, 2002

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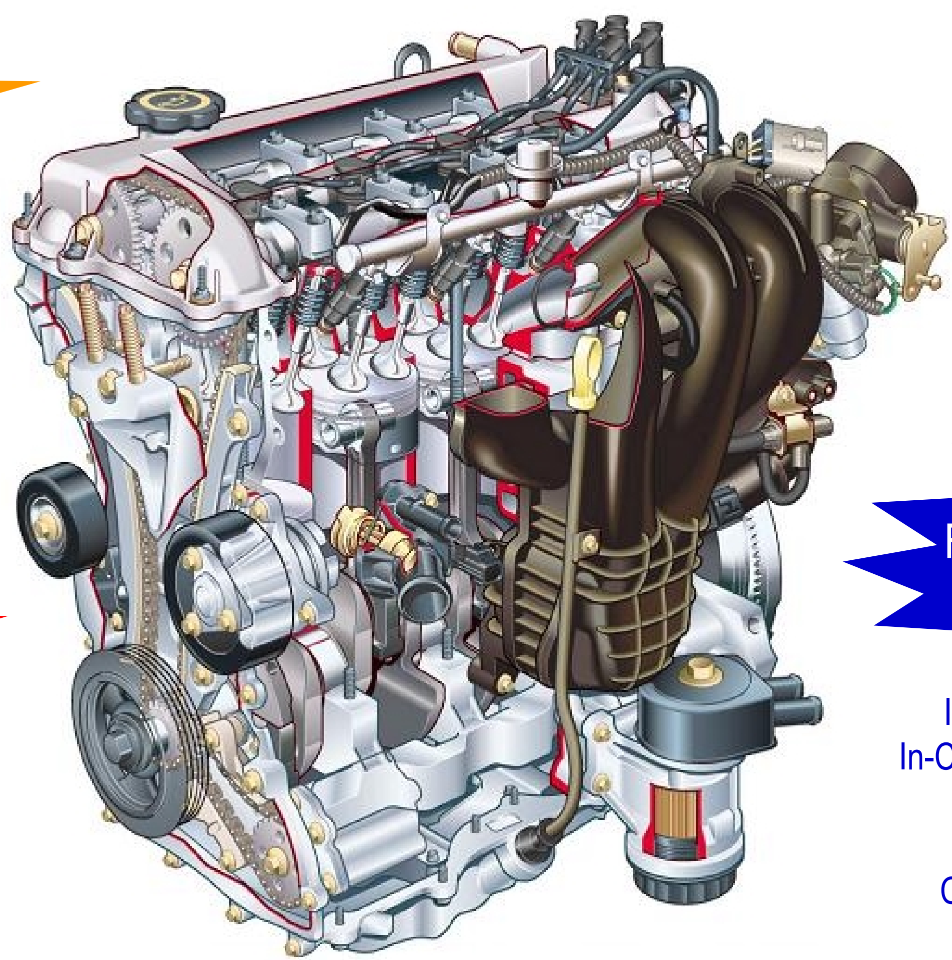
Engine Physics

Thermodynamics

Engine Performance
Mixture Properties
Combustion Prediction
Compressible Flow

Heat Transfer

Metal-Gas Interactions
Metal-Fluid Interactions



Mechanics

Valvetrain Actuation
Engine Motion
Friction Effects

Fluid Mechanics

Intake/Exhaust Flow
In-Cylinder Fluid Dynamics
Manifold Dynamics
Liquid Fuel Effects
Coolant and Oil Flow

Engine analysis requires multi-domain physical models!!

Model Applications

- **Engine-level analyses**
  - Throttle response
  - Liquid fuel effects (wall wetting)
  - Spark control response
  - Valve timing response
  - Manifold dynamics
  - Thermal warm-up characterization
- **Vehicle-level analyses**
  - Drive cycle analyses
    - Fuel economy
    - Emissions
  - Vehicle control strategy development
  - Energy management studies
  - Powertrain analyses
    - Efficiency
    - NVH/shift quality

Wide array of applications necessitates flexibility!!

Model Characteristics

- **Transient**
- **Flexible**
  - **Predictive vs. fixed combustion**
  - **Fidelity of component models**
    - **Accuracy-speed tradeoff?**
  - **Working fluid calculations (medium models)**
  - **Fuel and air composition**
- **Configurable**
  - **Single vs. multi-cylinder**
- **Reusable**
  - **Same interfaces and similar basic components across different analyses**
- **User-friendly**

Outline

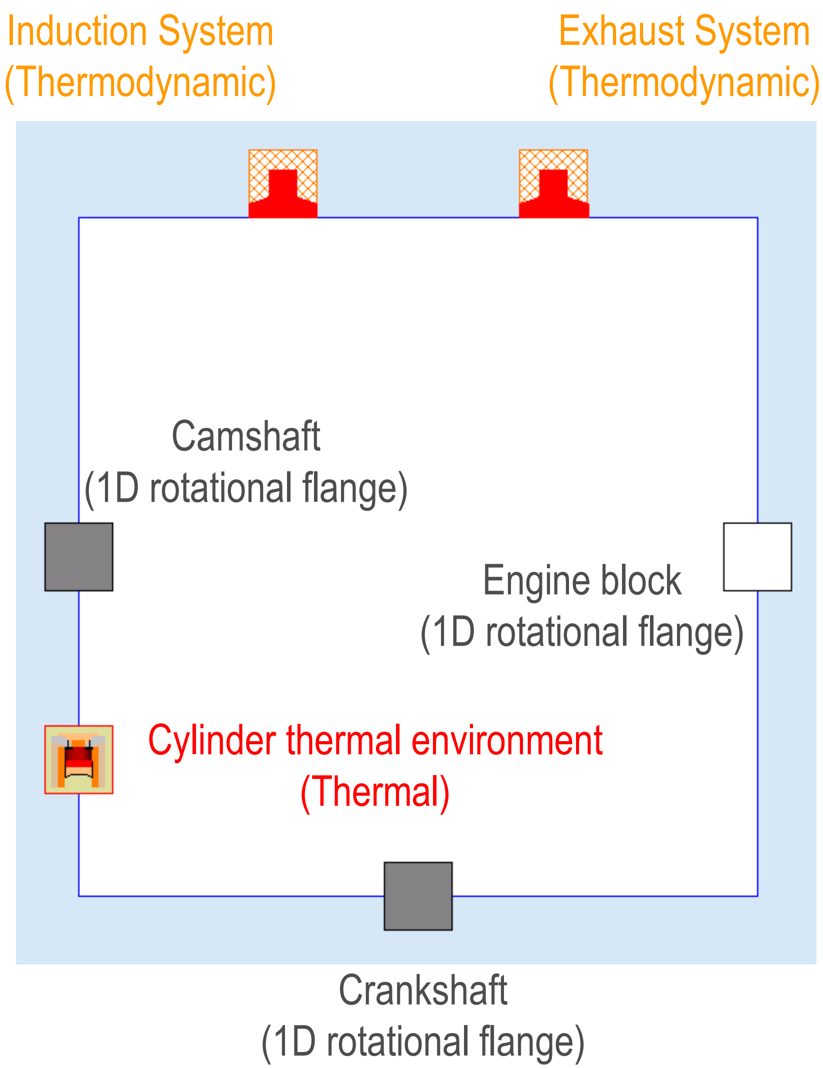
- Introduction
- Interfaces
- Medium Model Concept
- Signal Bus Concept
- Sample Results
- Final Remarks

Interfaces

- **Key to flexibility**
  - Clearly define system interactions
  - Promote orthogonal model development
  - Provide framework for model compatibility
- **Examples**
  - Cylinder interface
  - Engine interface
  - Thermal architecture

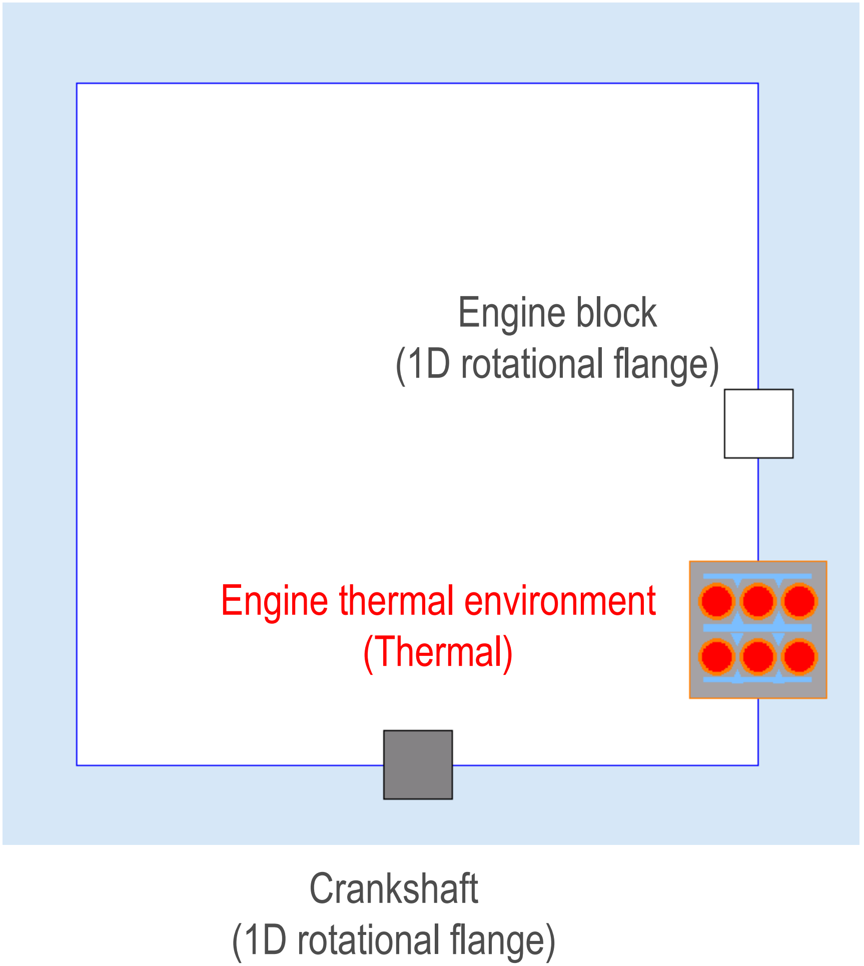
Cylinder Interface

- **Framework for all cylinder models**
  - **Partial model**
- **Defines external connections for cylinder**



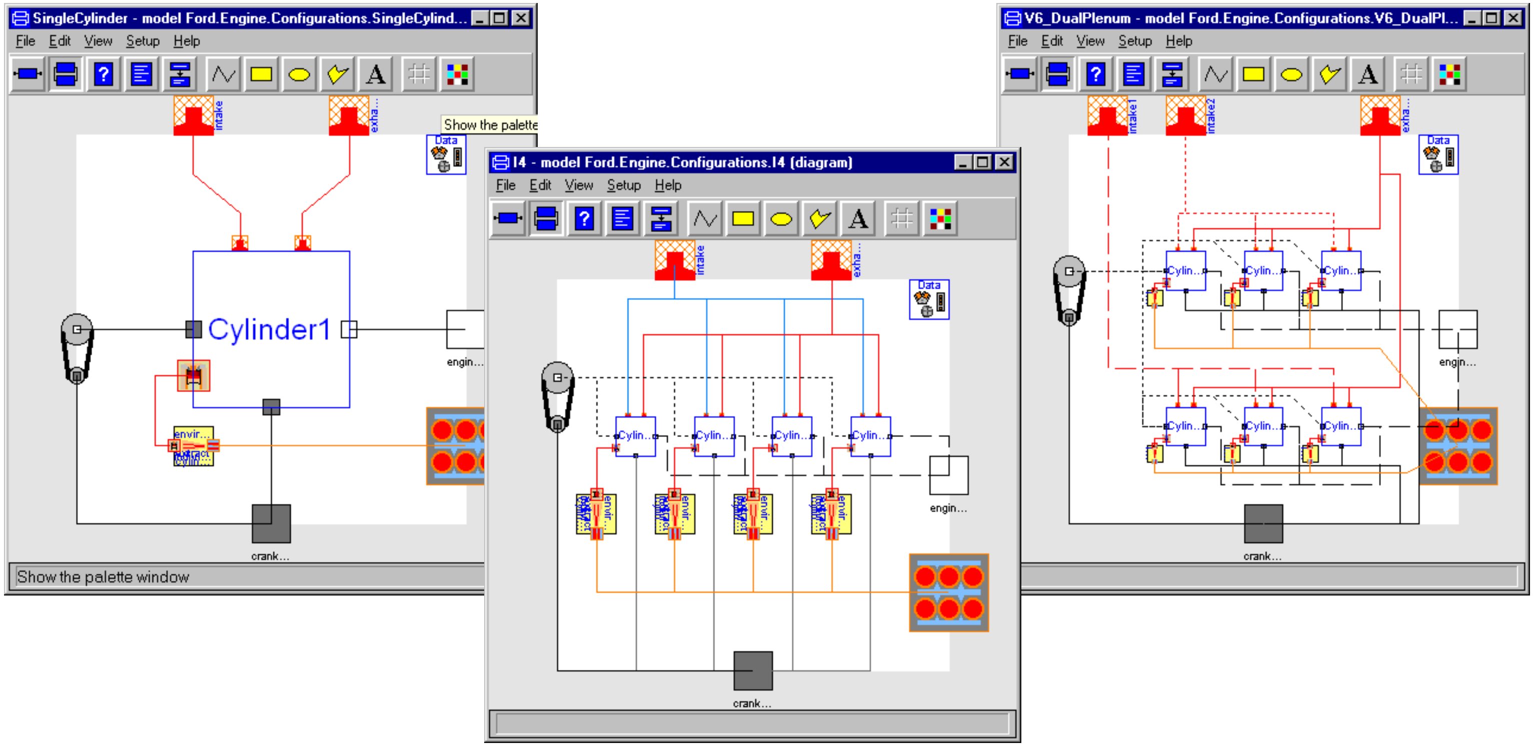
Engine Interface

- **Framework for all engine models**
  - **Partial model**
- **Defines external connections for engine**
- **Extending models define plenum configuration**
  - **Single plenum**
  - **Dual plenum**



Complete Engine

- **Plug-n-Play with a variety of engine configurations**
  - **Replaceable cylinder model fits in all engine configurations**

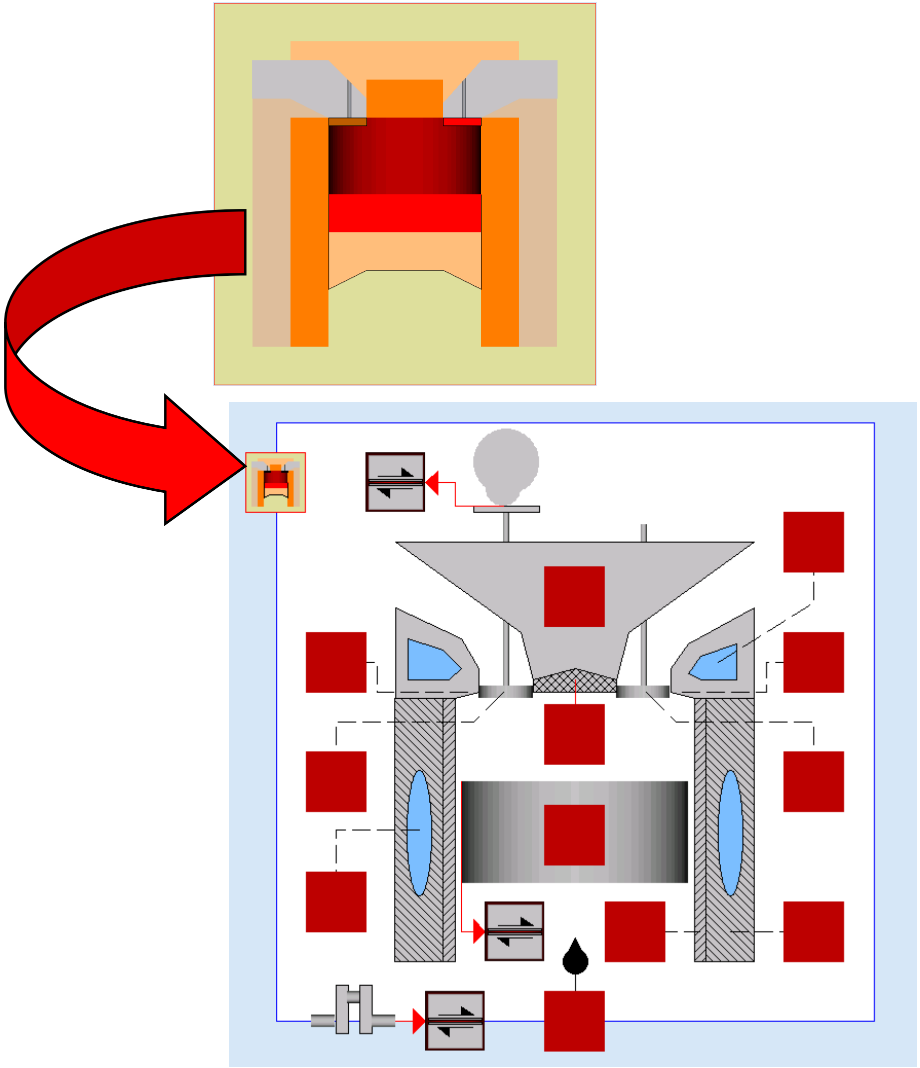


Thermal Architecture

- Provides framework for interaction between cycle simulation and engine temperature models
  - Cycle simulation models
    - Responsible for metal-gas interactions
  - Transient engine temperature models
    - Responsible for metal-fluid interactions
- Allows orthogonal selection of models
  - Cycle simulation
  - Engine temperature

Cylinder Thermal Environment

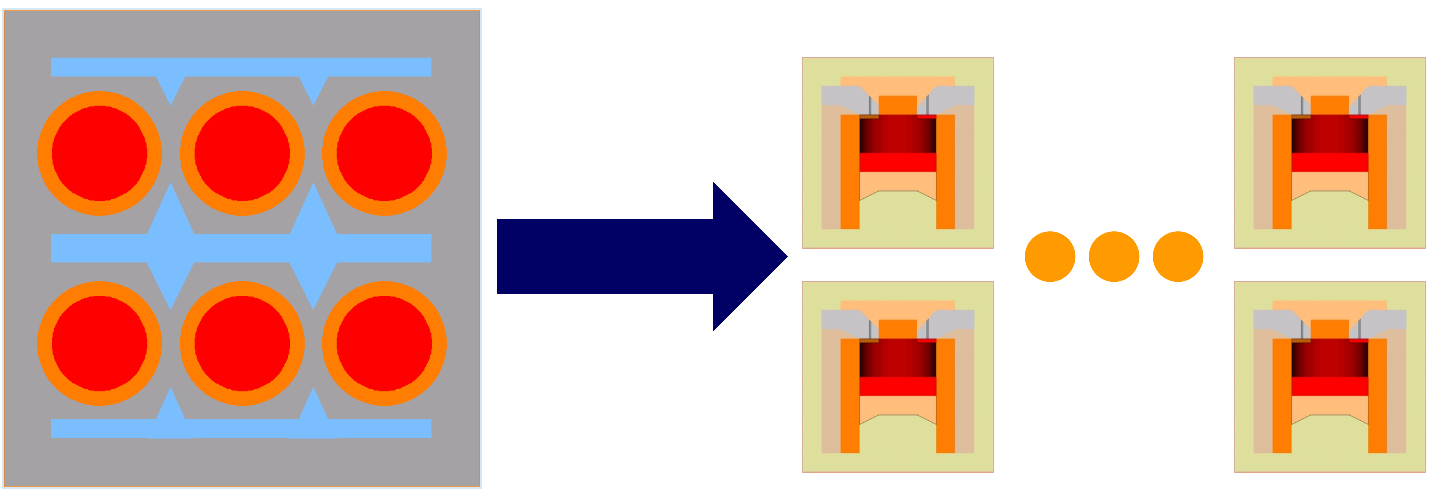
- "Connector of connectors"
- Thermal bus
- Comprised of connectors for standard components which interact with various models
  - Thermal connectors for various engine components (piston, block, head, etc.)
  - Thermal connectors for engine fluids (oil, coolant)
  - Friction connectors
- Used with "break-out box" in low level models



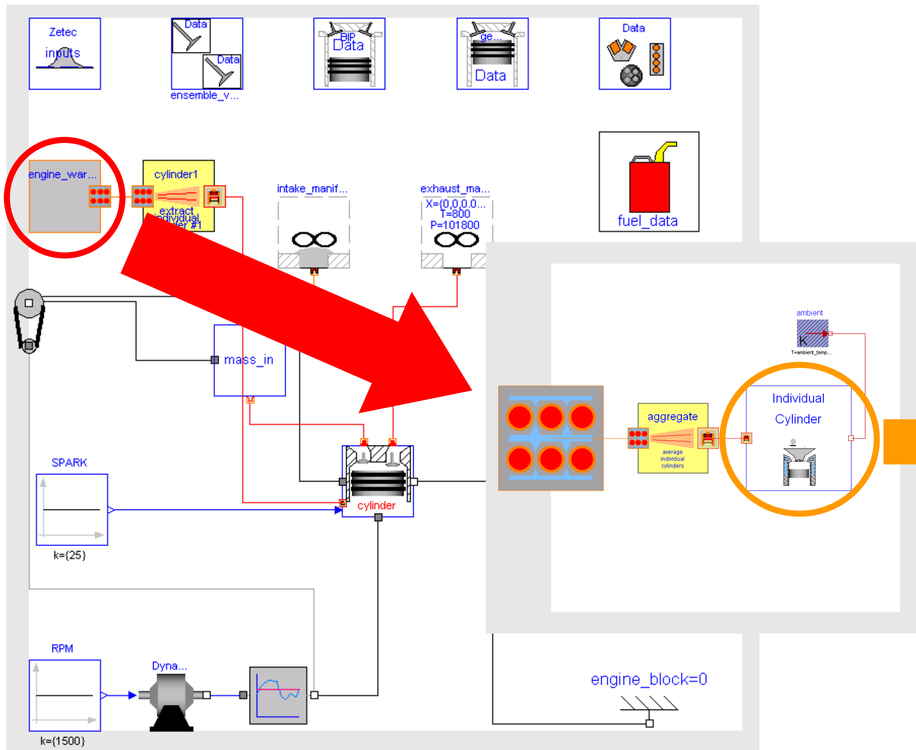
Engine Thermal Environment

- Engine level connector
  - Array of cylinder thermal environment connectors to allow for multiple cylinders

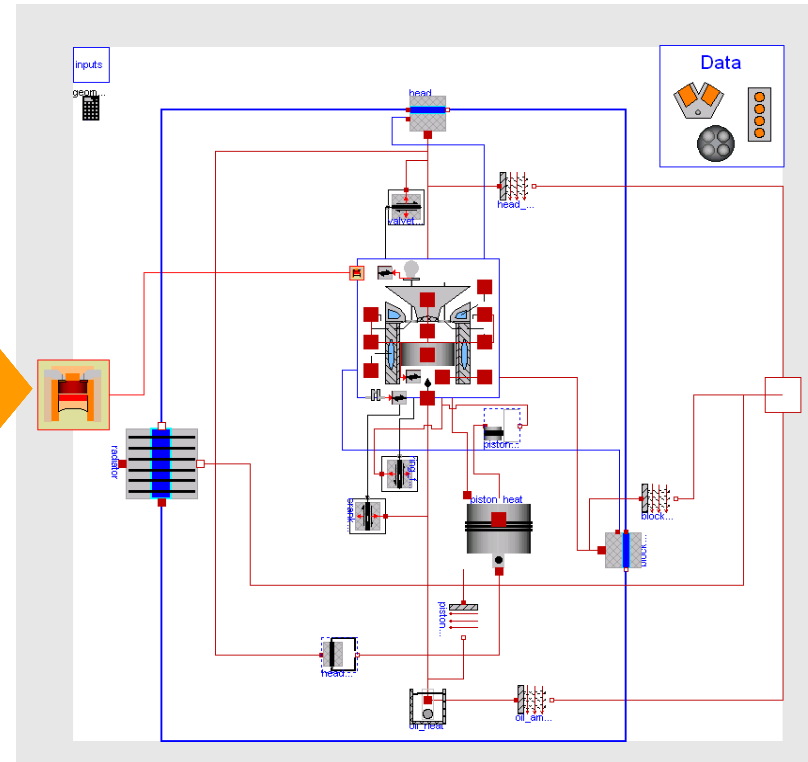
- Features
  - Parametric connector representation for engines with multiple cylinders
  - Consolidates signals to minimize connections
    - Single, engine-level connection



Using the Thermal Architecture



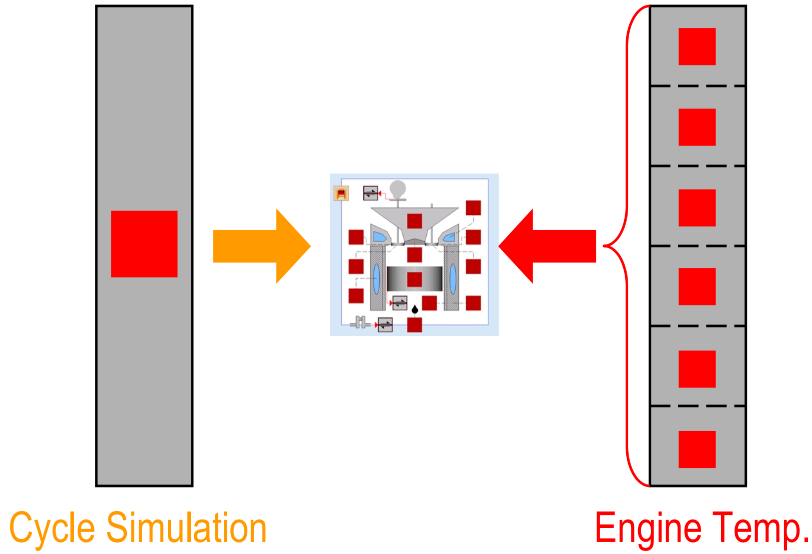
Single-Cylinder Analysis



Engine Temperature Model

Challenges

- **Difficult to connect to connectors within connectors**
  - **Direct connection not possible**
  - **Requires termination of all flow variables before connection (terminator model)**
    - **Signals requiring termination grows exponentially with number of cylinders**
- **Resolving varying level of details in cycle simulation and engine temp. models**



- **Requires:**
  - **Averaging temperature**
  - **Dividing heat transfer rate**

Medium Models

- Define specific working fluid
- Consistent set of models, functions, constants, connectors
  - Material properties (enthalpy, energy, viscosity)
  - Equation of state
  - Chemical representation (# of species)
  - Chemical kinetics of combustion
  - Helper functions (air-fuel ratio, etc.)
- Implemented via replaceable packages

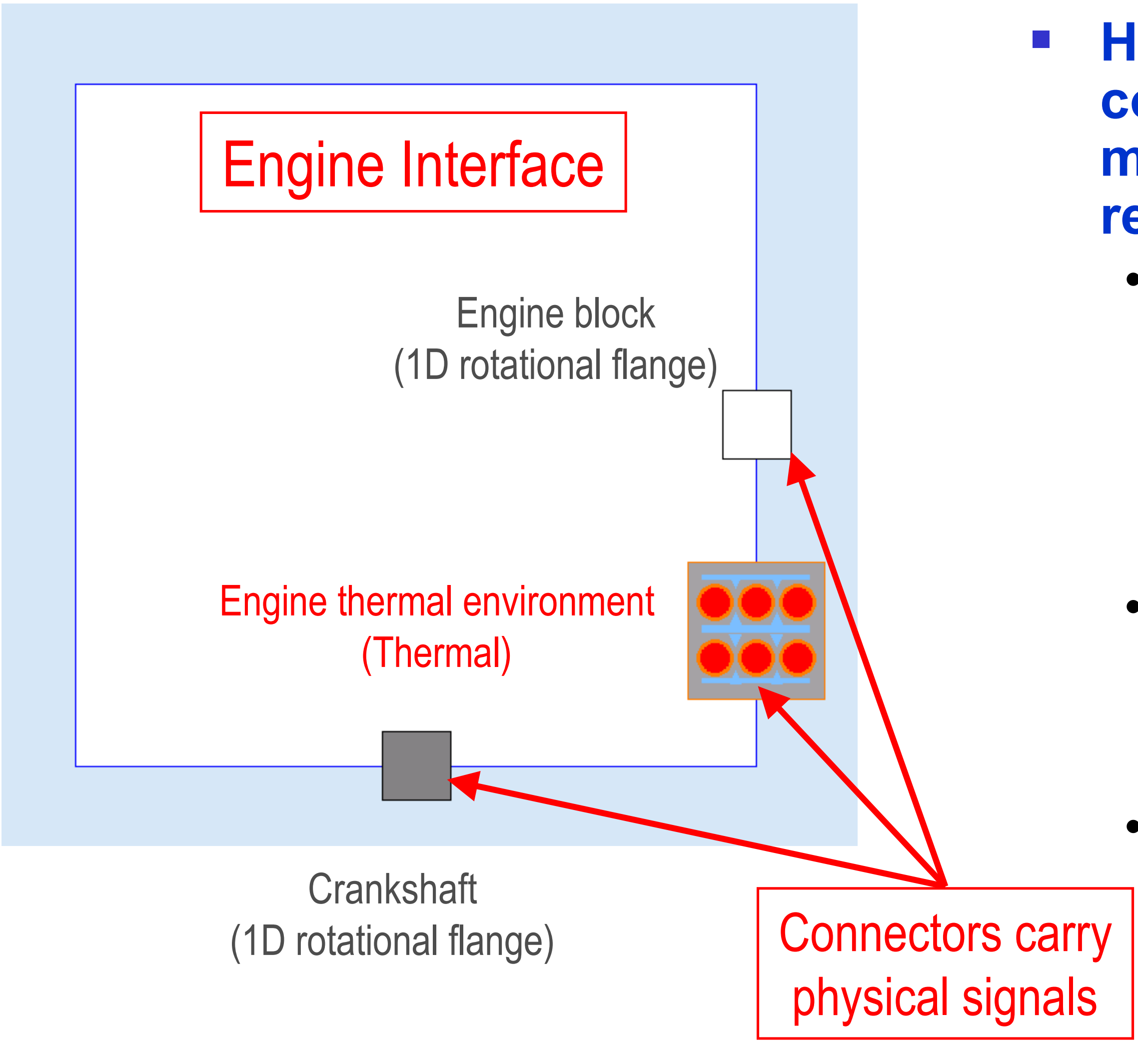
- Features
  - Orthogonal development of property models and the component models which use them
  - Consistent framework for development of medium models with varying levels of detail
  - Consistent application of changes throughout model hierarchy
  - Organized
    - Information entirely contained within medium model package
  - Change working fluid at "flip of switch" at highest level

```
model EngineTest
  Engine engine(redeclare package MediumModel=Air)
end EngineTest;
```

Challenges

- **More fool-proof specification of working fluid**
  - Currently requires redeclaration of medium model in each component
  - Single redeclaration that automatically propagates via connections should be possible
- **Generic implementation?**
  - Applicable in all areas of modeling
    - Working fluids in hydraulics models
    - Fuel composition in wall wetting models
    - Material properties in heat transfer models

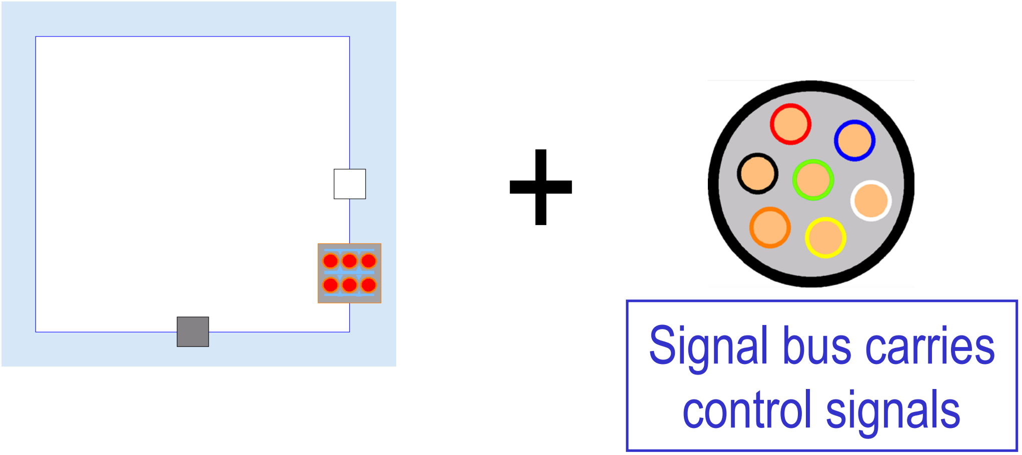
Engine Interface…Revisited



- **How do we propagate control signals for modular hierarchies with replaceable components?**
  - **Redeclaring component model may change information required**
    - **Generic cylinder**
    - **Cylinder with variable cam timing**
  - **Impossible to anticipate all types of signals that might be required by a specific implementation**
  - **Not practical to propagate signals via connectors**

Signal Bus

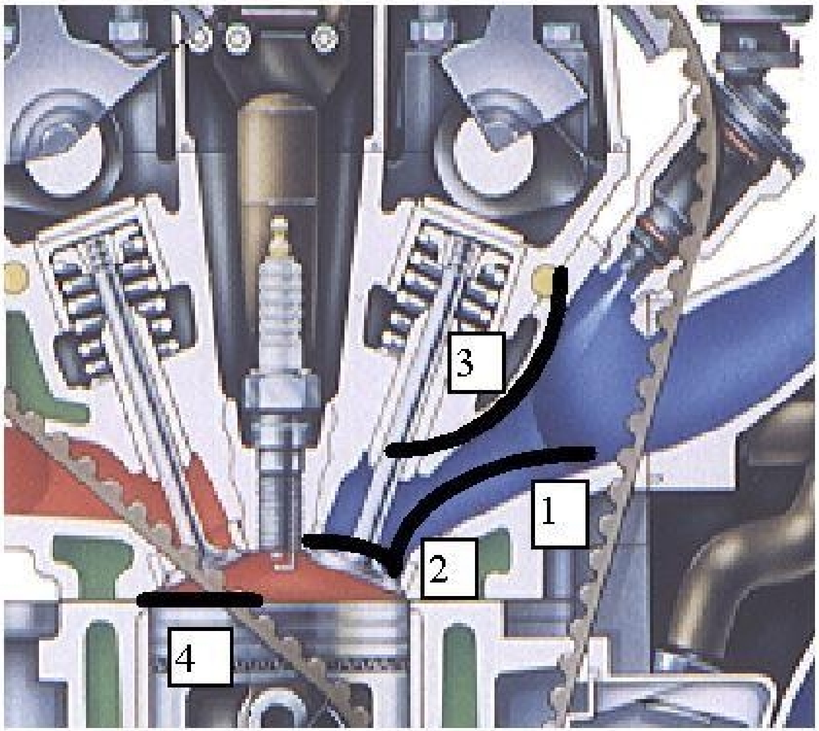
- **Signal bus idiom**
  - Facilitates propagation of control signals for replaceable component models
  - Uses inner/outer semantics
    - Outer required to be subtype of inner
  - Allows top-level definition for union of all control signals
  - Allows selective definition/use of signals at low level



Wall Wetting Model

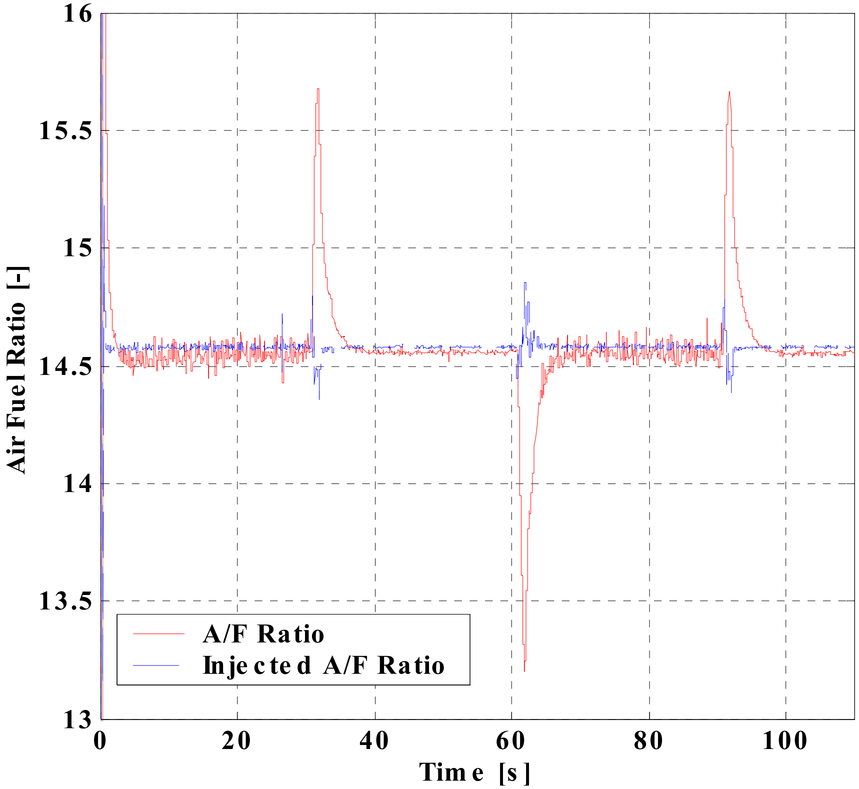
- **Model details**
  - Multiple control volumes
  - Multi-component fuel
  - Evaporation
  - Fluid flow
  - Puddle shattering (backflow)
  - Transient engine cycle simulation
  - Transient engine temperature model

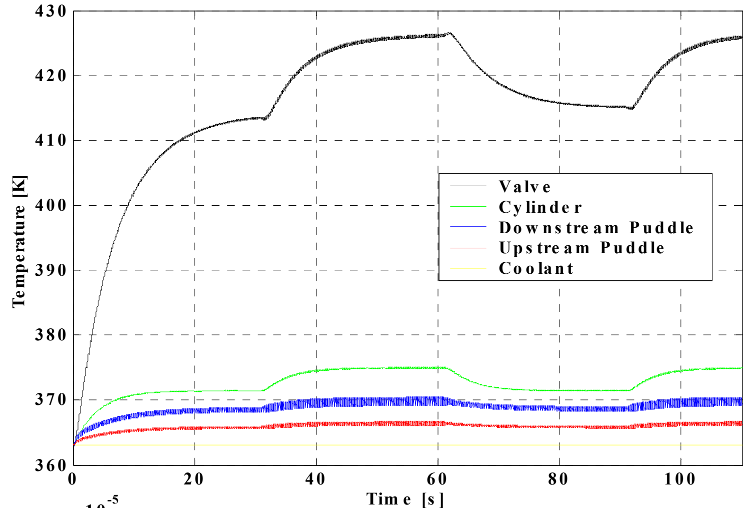
- **Applications**
  - Throttle and speed transients
  - Fuel composition studies
  - Injector targeting studies

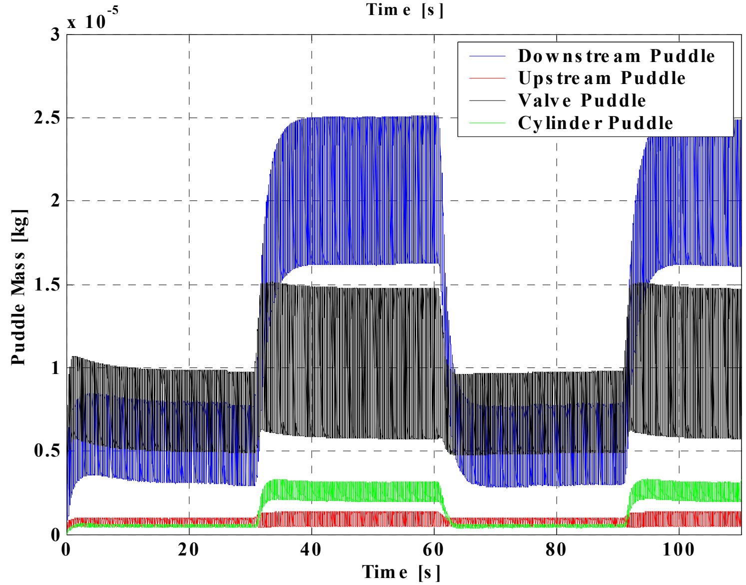


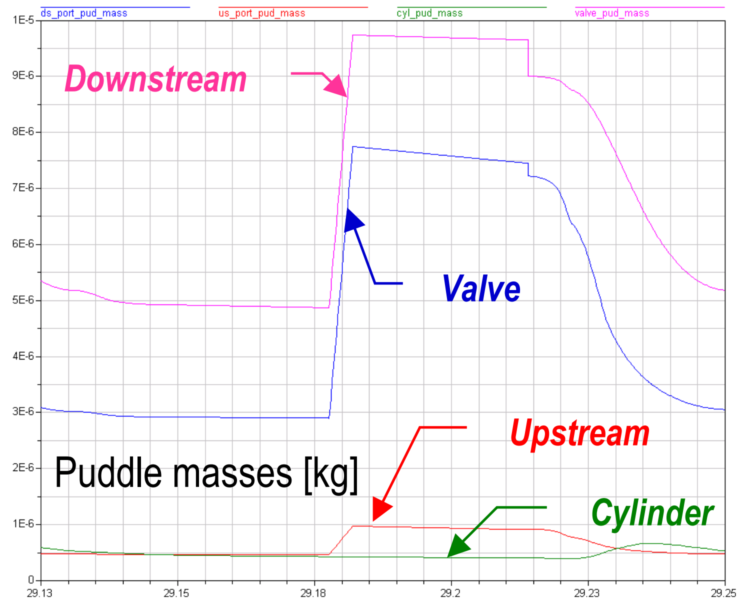
1. Port Film
2. Valve Film
3. Upstream Film
4. In-Cylinder Film

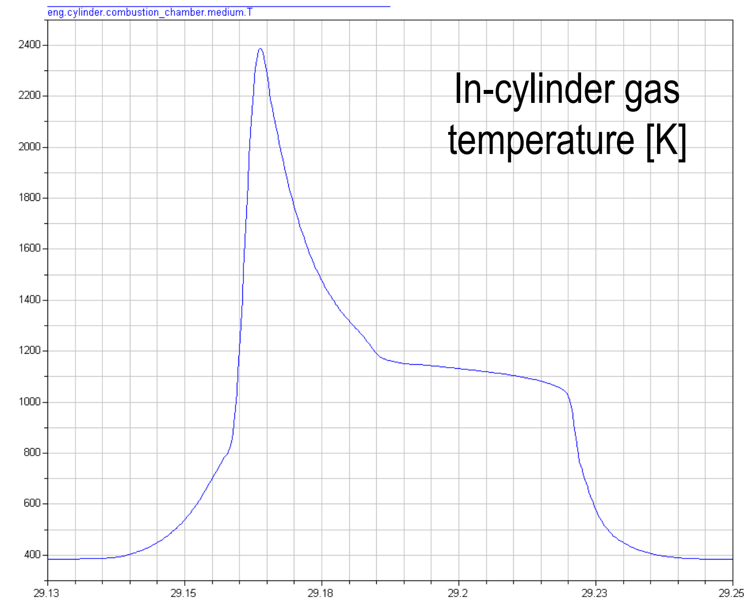
Wall Wetting Results

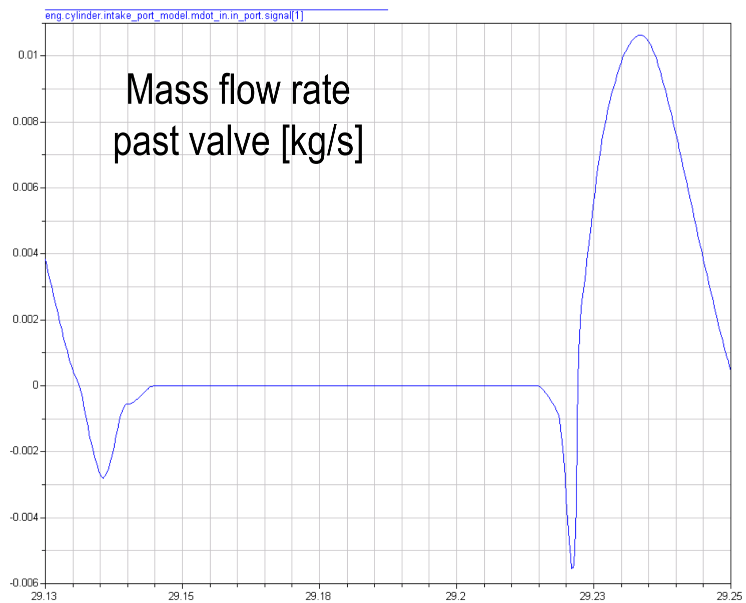


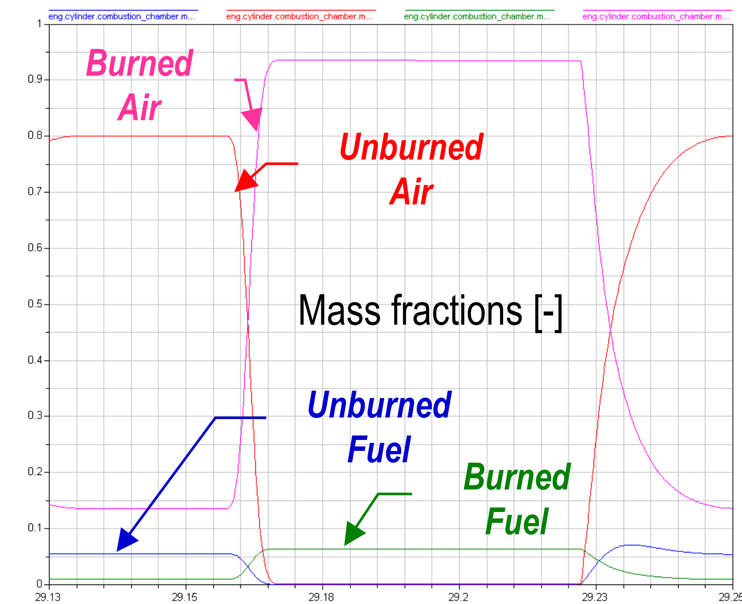





ds_port_pud_mass
us_port_pud_mass
cyl_pud_mass
valve_pud_mass
Downstream
Valve
Upstream
Puddle masses [kg]
Cylinder


eng.cylinder.combustion_chamber.medium.T
In-cylinder gas temperature [K]


eng.cylinder.intake_port_model.mdot_in.in_port.signal[1]
Mass flow rate past valve [kg/s]


Burned Air
Unburned Air
Mass fractions [-]
Unburned Fuel
Burned Fuel

Final Remarks

- **Interfaces provide framework for extensible, flexible engine models by independently choosing:**
  - Combustion models
  - Transient engine temperature models
  - Medium models
  - Engine configurations
- **Modelica language features highly suited to flexible modeling**
  - Extends
  - Replaceable + Redeclare
  - Inner/outer semantics
  - Record semantics
  - Documentation and graphical annotations
- **Looking ahead…**
  - Challenges still exist
    - Zero mass with intensive properties
- **Discussion and new ideas?**