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# Topological Information Content and Expressiveness of Function Models in Mechanical Design

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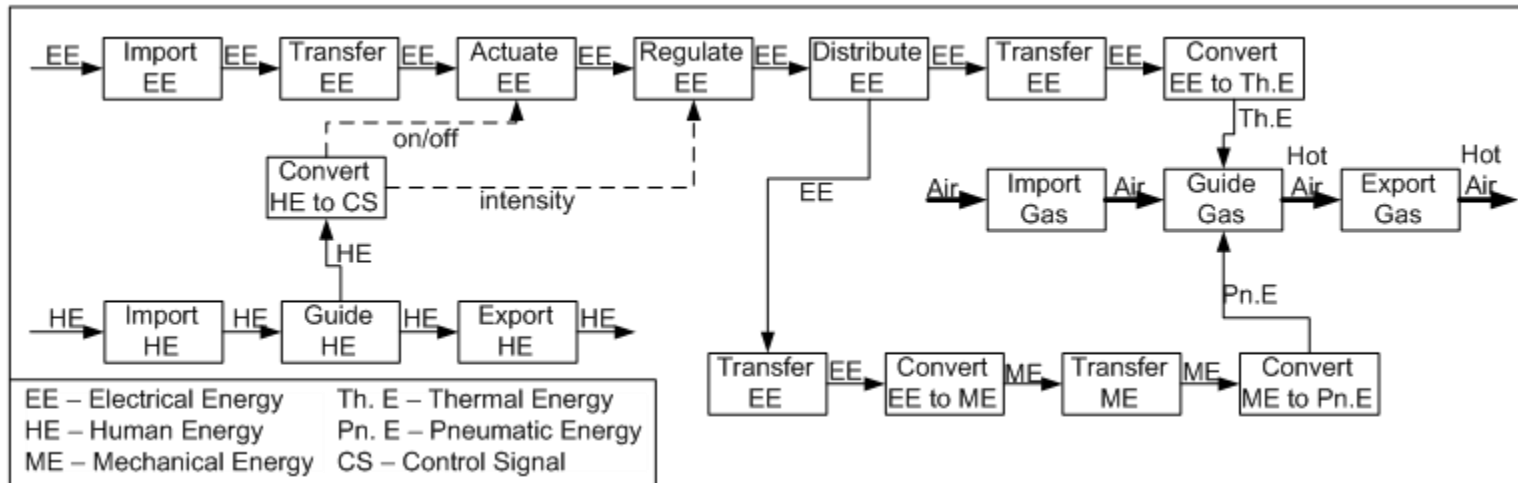
Dr. Georges M. Fadel



- Function
  - “Intended input / output relationship of a system” [Pahl & Beitz, 1996]
- Function models (function structures)
  - Graph based representation of functionality
  - Nodes  $\equiv$  actions, edges  $\equiv$  objects of action
  - Nodes indicate transformative actions of material, energy, and signal



Traditional graphical description of a function [adapted from Pahl & Beitz, 1996]



Function model of a consumer hair dryer

- Improve consistency and objectivity of function description
- First step toward automated reasoning
- Multiple attempts:
  - Collins et al., 1976
  - Kirschman & Fadel, 1998
  - NIST vocabulary [Szykman et al. 1999]
  - Functional Basis [Hirtz et al., 2002]
- UMR/MST Functional Basis
  - 54 functions (verbs)
  - 45 flows (nouns)
  - Three levels of hierarchy (specificity)
  - Developed through reverse engineering (product dissection & cataloging)
  - Component-function mapping – 1:1
  - Reconciled and *frozen* in 2002

(a) Function Set

| Primary           | Secondary  |
|-------------------|------------|
| Branch            | Separate   |
|                   | Distribute |
| Channel           | Import     |
|                   | Export     |
|                   | Transfer   |
|                   | Guide      |
| Connect           | Couple     |
|                   | Mix        |
| Control Magnitude | Actuate    |
|                   | Regulate   |
|                   | Change     |
|                   | Stop       |
| Convert           | Convert    |
| Provide           | Store      |
|                   | Supply     |
| Signal            | Sense      |
|                   | Indicate   |
|                   | Process    |
| Support           | Stabilize  |
|                   | Secure     |

(b) Flow Set

| Primary  | Secondary               |
|----------|-------------------------|
| Material | Human                   |
|          | Gas                     |
|          | Liquid                  |
|          | Solid                   |
|          | Plasma                  |
|          | Mixture                 |
| Signal   | Status                  |
|          | Control                 |
| Energy   | Human                   |
|          | Acoustic                |
|          | Biological              |
|          | Chemical                |
|          | Electrical              |
|          | Electromagnetic         |
|          | Hydraulic               |
|          | Magnetic                |
|          | Mechanical              |
|          | Pneumatic               |
|          | Radioactive/<br>Nuclear |
|          | Thermal                 |

- One of the most popular vocabularies used in design research
  - Design Repository (web-archive of function models)
    - Reverse engineered function models of consumer products
    - 130 products as of January 27, 2009
  - Failure analysis of products [Tumer & Stone, 2001]
  - Concept generation tool [Bryant et al., 2006]
  - Similarity analysis [McAdams et al., 2002]
  - Functional decomposition using empirical rules [Sridharan & Campbell, 2004]
  - Component selection [Kurtoglu & Campbell, 2005]
- Internally validated
  - Applications [Stone & Tumer, 2005]
  - Experiments [Kurfman et al., 2003]
- External critical evaluation – almost none

The usefulness of the Functional Basis vocabulary needs to be examined

- Web-based archive of function models
  - of consumer products (130 as on January 27, 2009)
  - Created using the Functional Basis
  - Reverse engineering approach: dissection and cataloging

**MISSOURI S&T Design Engineering Lab ARTIFACT BROWSE**

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heating coil frame

white wire 2  
spring bracket  
impeller  
cap  
rear housing  
cool shot switch bracket  
debris filter  
plug and cord  
heating coil  
motor housing  
black wire  
brown wire  
cool shot button  
front housing  
blue wire  
switch button  
solder  
motor  
left handle  
spring  
white wire  
bimetallic heat sensor  
handle casing  
insulator  
orange wire  
rivet  
red wire  
right handle  
switch

**System: supermax hair dryer**

**Artifact Name** heating coil frame

**Sub Artifact Of** motor casing assembly

**Quantity** 1

**Description**

**Artifact Color(s)** gray

**Component Naming** support

**Artifact Photo**

click on image for full size

there are no flows defined for this artifact

**Supporting Functions**

|               |       |        |       |        |               |
|---------------|-------|--------|-------|--------|---------------|
| motor housing | solid | secure | solid | active | motor housing |
| heating coil  | solid | couple | solid | active | rivet         |

**Physical Parameters**

|        |      |        |
|--------|------|--------|
| width  | 2.72 | inches |
| length | 4.5  | inches |

**Manufacturing Process**

|                      |             |
|----------------------|-------------|
| material             | [composite] |
| no process specified |             |

**Failure Information**

no failures specified

**Artifact Entry Information:**

|                    |            |
|--------------------|------------|
| release date:      | 2000-01-01 |
| upload date:       | 2008-07-23 |
| modification date: | 2008-06-23 |

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The artifact browser in the Design Repository website

- Function definitions (meanings)
  - Textual expression in natural English
  - Stored in the Design Repository website
  - Not *formally* used in defining or controlling the function models
    - Leads to inconsistencies: contrary to the main purpose of the vocabulary
- Missed opportunity – semantic information of the vocabulary terms

MISSOURI S&T Design Engineering Lab DESIGN METHODOLOGY DICTIONARY

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**Functional Basis Reconciled Function Set**  
(Click on Secondary Level for Definition)

| Class (Primary) | Secondary     |        |
|-----------------|---------------|--------|
| Branch          | Separate      | Divide |
|                 |               | Extra  |
|                 |               | Remc   |
|                 | Distribute    |        |
|                 | <b>Import</b> |        |
|                 | Export        |        |

**Flow Dictionary**  
Select a flow from the Functional Basis web page.

**Channel > Import**

To bring in a flow (material, energy, signal) from outside the system boundary.

*Example: A physical opening at the top of a blender pitcher imports a solid (food) into the system. Also, a handle on the blender pitcher imports a human hand.*

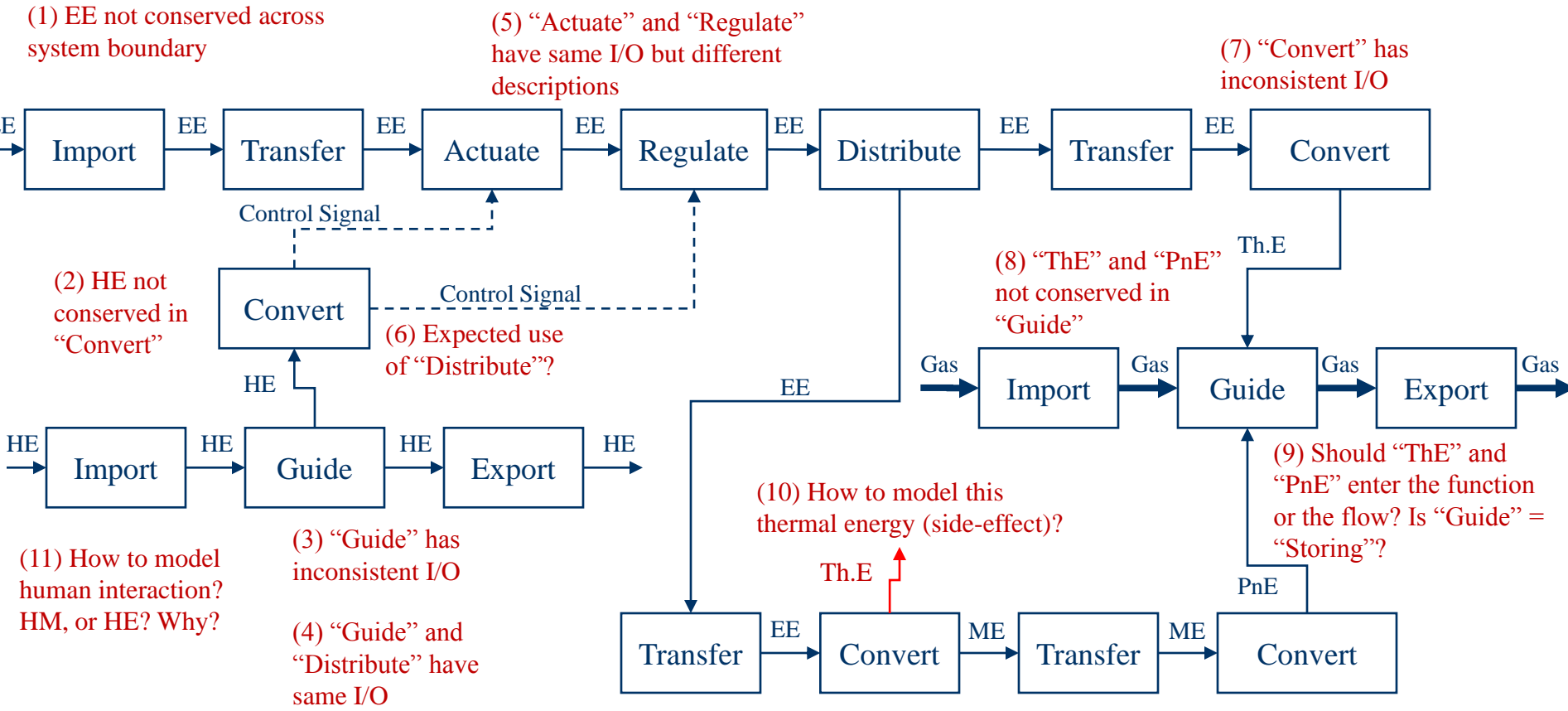


Illustration of modeling inconsistencies in the hair dryer function model

- A measure of quality of representations
  - The expressive power, or the amount of information carried by the representation
  - Consistency and uniqueness
  - Adequacy or coverage
  - Distinction ability (resolution)
  - Extensibility
  - Types - objects, relations, attributes?
  - Succinctness (spatial efficiency / compactness)
  - Mappability with other representations
    - Design Exemplar  $\leftrightarrow$  First order predicate logic
    - Grammars within the Chomsky hierarchy
- Information content of the representation
  - Information metric of function models [AiD/Function/001(2008)]
  - Applied to verbs and nouns within Design Repository models
  - Applied to study the informativeness of the Functional Basis hierarchy
  - Internally validated against Information Theory basics

- Information content of functions (verbs)

$$I_V = y_V \cdot \lceil \log_2 (x_V) \rceil \text{ bits}$$

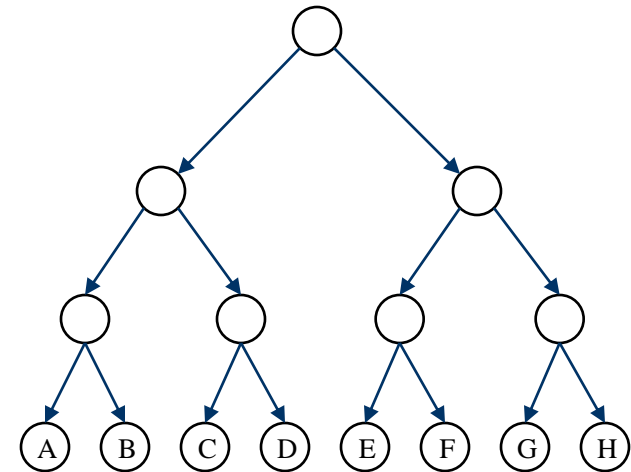
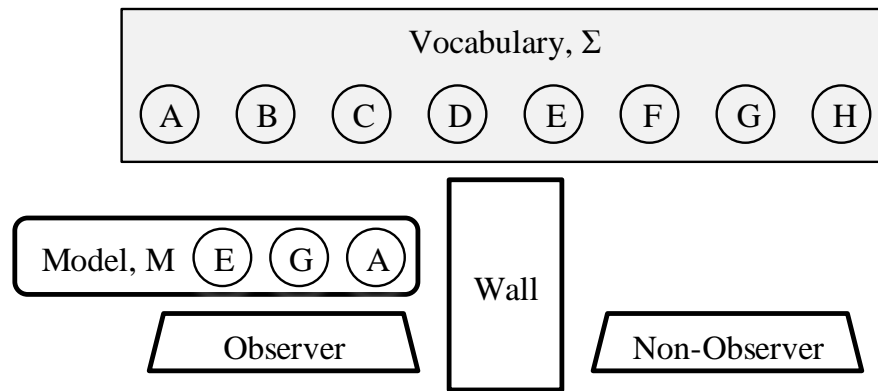
where  $x_V$  is the size of the vocabulary,  $y_V$  is the size of the model – counting only functions (verbs) in both cases

- Information content of flows

$$I_N = y_N \cdot \lceil \log_2 (x_N) \rceil \text{ bits}$$

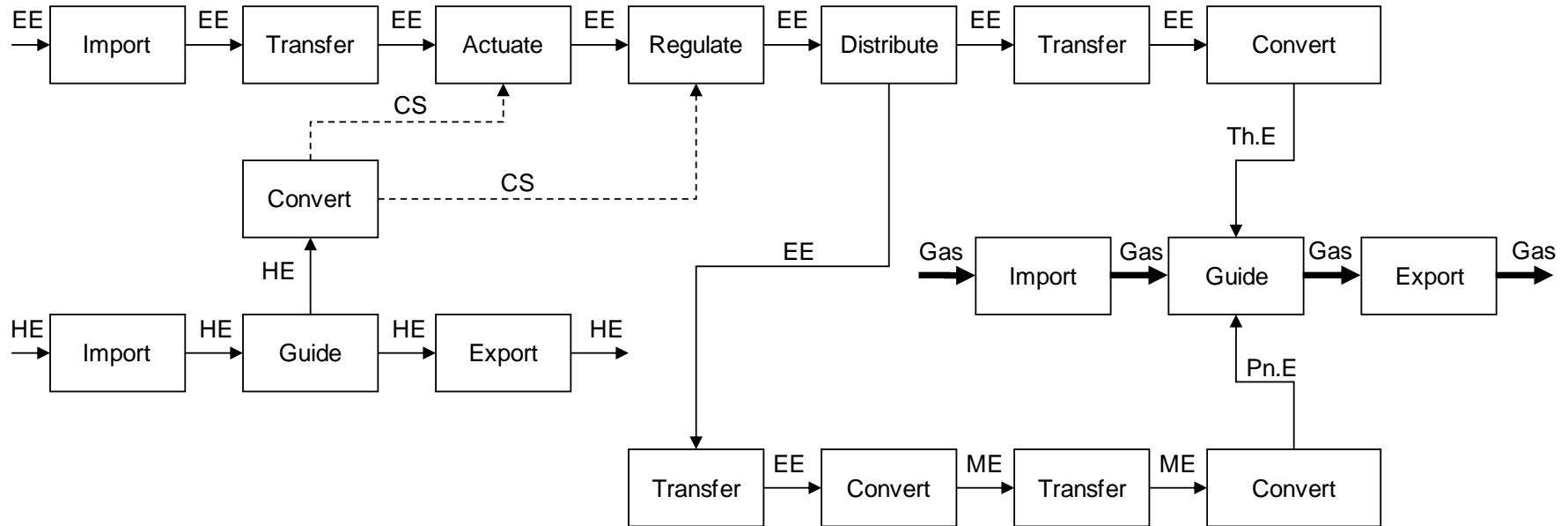
where  $x_N$  is the size of the vocabulary,  $y_N$  is the size of the model – counting only flows (nouns) in both cases

- Number of questions that must be answered about the model so that the model can be reconstructed without directly viewing it



- Uncertainty within the model that need to be resolved in order to fully know the model
- Information or Uncertainty?
  - Between two models on the same representation, the model with the higher information content is more *informative*
  - Between two representations of the same model, the lower the uncertainty of the model, the more *expressive* the representation

- Example function model: Supermax Conair Hair Dryer function model from the Design Repository: cleaned up for non-Functional Basis terms



The hair dryer function model using secondary functions and flows, cleaned up for non-Functional Basis terms

- Information content of functions

|   |           |
|---|-----------|
| Number of functions in the model, $y_V$   | 18        |
| Number of function in the vocabulary, $x_V$   | 21        |
| Information content of functions (bits)<br>$I_V = y_V \cdot \lceil \log_2(x_V) \rceil$ bits | <b>90</b> |

# questions to know all functions

- Information content of flows

|   |            |
|---|------------|
| Number of flows in the model, $y_N$   | 24         |
| Number of flows in the vocabulary, $x_N$  | 20         |
| Information content of flows (bits)<br>$I_N = y_N \cdot \lceil \log_2(x_N) \rceil$ bits | <b>120</b> |

# questions to know all flows

- Information content of the topology

|  |            |
|--|------------|
| Number of functions in the model, $y_V$  | 18         |
| Number of flows in the model, $y_N$  | 24         |
| Topological uncertainty (bits)<br>$I_T = y_N \cdot \lceil \log_2[(y_V + 1) \times y_V] \rceil$ | <b>216</b> |

# questions to know the connections

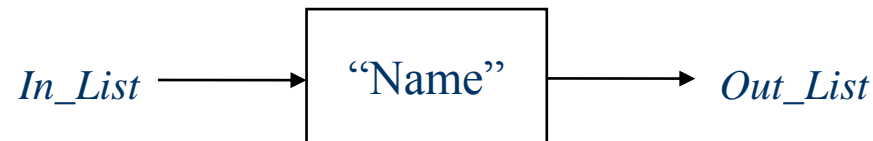
- Information content of the model =  $I_V + I_N + I_T = 90 + 120 + 216 = \mathbf{426}$  bits

- The number of questions required to fully “know” the function model is 426
- Questions required for resolving the topology has largest share: 216 out of 426
  - Unlimited compatibility between functions and flows (no semantics)
  - Unconditional probability of origin and destination functions
  - Large number of combinatory possibilities, large search space
- Reason: Lack of formalism for the function definitions
  - Semantic information of functions and flows are not captured in the model
  - These semantics can impose limits on the topological compatibilities
  - The conditions are implicitly described in the definitions

- Each function is represented as a triple:

$$\{ \text{“Name”}, In\_List, Out\_List \}$$

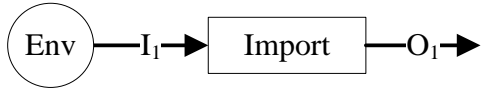
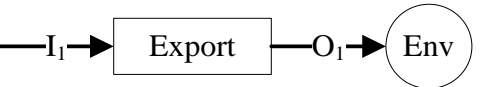

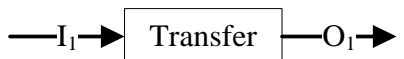
- *Name*: the literal string stored as the name of the function in the Functional Basis
  - *In\_List*: the list of all incoming flows to a function
  - *Out\_List*: the list of all outgoing flow from a function
- Each triple has a graphical counterpart, tentatively called a *template*



- Each triple is supported by a set of rules
  - Compatibility rules: control which flows are *valid* input and output for a function
  - Connection rules: control which functions are *valid* origin and destination for a flow
- These rules are implicitly stated in the function definitions

- Consider the function “Import”
  - Definition: “To bring in a flow (material, energy, signal) from outside the system boundary (*to inside the system*).”

| Implicit knowledge within definition  | Formal representation   |
|---|---|
| <i>The function operates on one flow at a time</i>  | $\text{In\_List} = \{I_1\}$   |
| <i>The incoming flow does not undergo any change within the scope of the function, other than being imported to the system, indicating that the incoming and outgoing flows are identical</i> | $\text{Out\_List} = \{O_1\}$<br>$I_1 = O_1$   |
| <i>The flows (incoming or outgoing) can be of any one type within the classes Material (M), Energy (E), and Signal (S)</i>  | $I_1 = O_1 \in \{M \cup E \cup S\}$   |
| <i>The incoming flow always originates in the environment, and the outgoing flow goes to another function within the model, but does not go back to the environment</i>                       | $\text{Origin}(I_1) = \text{Env} \in V$<br>$\text{Destination}(O_1) \in V - \{\text{Env}\}$ |
| <i>Additionally, it is assumed that a flow cannot terminate back to the same function from which it originated</i>  | $\text{Destination}(O_1) \neq \text{Origin}(O_1)$   |

| Function name | Definition  | Compatibility Rules  | Connection Rules  | Triple Notation and Template  |
|---------------|---|--|---|---|
| Import        | To bring in a flow (material, energy, signal) from outside the system boundary.   | $In\_List = \{I_1\}$<br>$Out\_List = \{O_1\}$<br>$I_1 = O_1 \in \{M \cup E \cup S\}$ | $Origin(I_1) = Env \in V$<br>$Destination(O_1) \in V - \{Env\}$<br>$Destination(O_1) \neq Origin(O_1)$  | $\{Import, \{I_1\}, \{O_1\}\}$<br>   |
| Export        | To send a flow (material, energy, signal) outside the system boundary.            | $In\_List = \{I_1\}$<br>$Out\_List = \{O_1\}$<br>$I_1 = O_1 \in \{M \cup E \cup S\}$ | $Origin(I_1) \in V - \{Env\}$<br>$Destination(O_1) = Env \in V$   | $\{Export, \{I_1\}, \{O_1\}\}$<br>   |
| Guide         | To direct the course of a flow (material, energy, signal) along a specific path.  | $In\_List = \{I_1\}$<br>$Out\_List = \{O_1\}$<br>$I_1 = O_1 \in \{M \cup E \cup S\}$ | $Origin(I_1) \in V - \{Env\}$<br>$Destination(O_1) \in V - \{Env\}$<br>$Origin(I_1) \neq Destination(O_1)$<br>$Destination(O_1) \neq Origin(O_1)$ | $\{Guide, \{I_1\}, \{O_1\}\}$<br>    |
| Transfer      | To shift, or convey, a flow (material, energy, signal) from one place to another. | $In\_List = \{I_1\}$<br>$Out\_List = \{O_1\}$<br>$I_1 = O_1 \in \{M \cup E \cup S\}$ | $Origin(I_1) \in V - \{Env\}$<br>$Destination(O_1) \in V - \{Env\}$<br>$Origin(I_1) \neq Destination(O_1)$<br>$Destination(O_1) \neq Origin(O_1)$ | $\{Transfer, \{I_1\}, \{O_1\}\}$<br> |

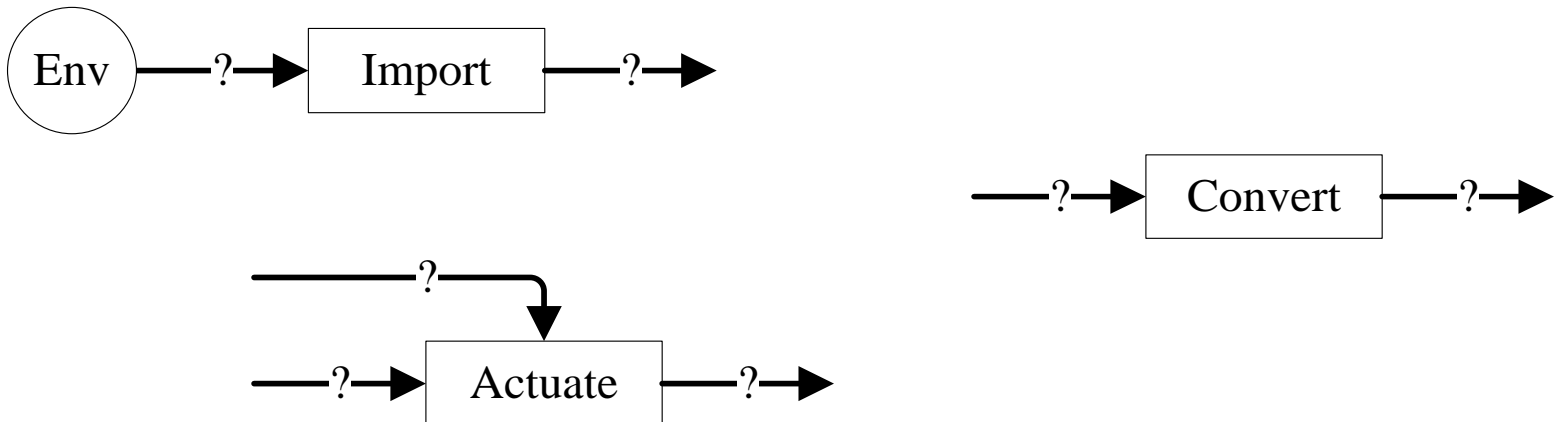
| Function name | Definition  | Compatibility Rules   | Connection Rules  | Triple Notation and Template   |
|---------------|---|---|---|--|
| Distribute    | To cause a flow (material, energy, signal) to break up. The individual bits are similar to each other and the undistributed flow. | $In\_List = \{I_1\}$<br>$Out\_List = \{O_1, O_1, O_1, O_1, \dots\}$<br>$I_1 = O_1 \in \{M \cup E \cup S\}$<br>$ Out\_List  = n > 1$<br>$n$ is a positive integers | $Origin(I_1) \in V - \{Env\}$<br>$Destination(O_1) \in V - \{Env\}$<br>$Destination(O_1) \neq Origin(O_1)$                                  | $\{Distribute, \{I_1\}, \{O_1, O_1, \dots, n \text{ terms}\}\}; n = 2$<br> |
| Actuate       | To commence the flow of energy, signal, or material in response to an imported control signal.                                    | $In\_List = \{I_1, I_2\}$<br>$Out\_List = \{O_1\}$<br>$I_1 = O_1 \in \{M \cup E \cup S\}$<br>$I_2 = CS \in S$   | $Origin(I_1) \in V - \{Env\}$<br>$Origin(I_2) \in V - \{Env\}$<br>$Destination(O_1) \in V - \{Env\}$<br>$Destination(O_1) \neq Origin(O_1)$ | $\{Actuate, \{I_1, I_2\}, \{O_1\}\}$<br>                                   |
| Regulate      | To adjust the flow of energy, signal, or material in response to a control signal, such as a characteristic of a flow.            | $In\_List = \{I_1, I_2\}$<br>$Out\_List = \{O_1\}$<br>$I_1 = O_1 \in \{M \cup E \cup S\}$<br>$I_2 = CS \in S$   | $Origin(I_1) \in V - \{Env\}$<br>$Origin(I_2) \in V - \{Env\}$<br>$Destination(O_1) \in V - \{Env\}$<br>$Destination(O_1) \neq Origin(O_1)$ | $\{Regulate, \{I_1, I_2\}, \{O_1\}\}$<br>                                  |
| Convert       | To change from one form of a flow (material, energy, signal) to another.  | $In\_List = \{I_1\}$<br>$Out\_List = \{O_1\}$<br>$I_1, O_1 \in \{M \cup E \cup S\}$<br>$I_1 \neq O_1$   | $Origin(I_1) \in V - \{Env\}$<br>$Destination(O_1) \in V - \{Env\}$<br>$Destination(O_1) \neq Origin(O_1)$                                  | $\{Convert, \{I_1\}, \{O_1\}\}$<br>  |

- More information is now stored within each vocabulary element
  - Textual description (“*Name*”)
  - Compatibility rules (extra)
  - Connection rules (extra)
- Additional knowledge available to designer before constructing the model
  - Should reduce the information *required* to describe each model
- The information content of the model is measured in three parts
  - Part I: Function names
  - Part II: Flows connected to the templates (compatibility rules)
  - Part III: Connection information between templates (connection rules)

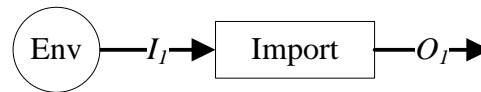
|   |           |
|---|-----------|
| Number of functions in the model, $y_V$   | 18        |
| Number of function in the vocabulary, $x_V$   | 21        |
| Information content of functions (bits)<br>$I_V = y_V \cdot \lceil \log_2(x_V) \rceil$ bits | <b>90</b> |

# questions to know  
all functions

- 90 questions reveal only the function *names* – nothing about the flows



• Example: *Import*



| Compatibility rule   | Information content   |
|--|---|
| $In\_List = \{I_1\}$<br>$I_1 = O_1 \in \{M \cup E \cup S\}$                            | $Info_{I_1} = \lceil \log_2(20) \rceil = \lceil 4.32 \rceil = 5 \text{ bits}$ |
| $Out\_List = \{O_1\}$<br>$I_1 = O_1 \in \{M \cup E \cup S\}$                           | $Info_{O_1} = 0$  |
| $I_{Import} = \lceil \log_2(20) \rceil = \lceil 4.32 \rceil = 5 \text{ bits/instance}$ |   |

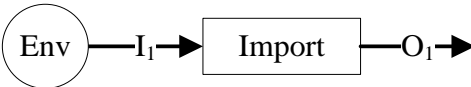

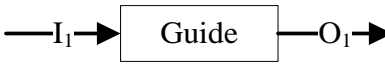
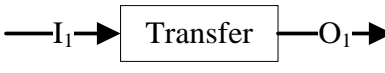
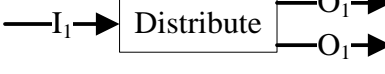
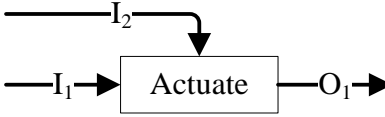
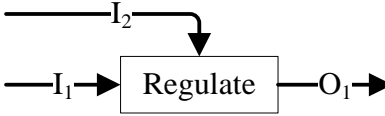
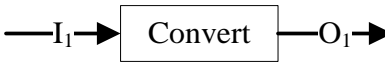
• Example: *Convert*



| Compatibility rule   | Information content   |
|--|---|
| $In\_List = \{I_1\}$<br>$I_1 \in \{M \cup E \cup S\}$                                      | $Info_{I_1} = \lceil \log_2(20) \rceil = \lceil 4.32 \rceil = 5 \text{ bit}$  |
| $Out\_List = \{O_1\}$<br>$O_1 \in \{M \cup E \cup S\}$<br>$I_1 \neq O_1$                   | $Info_{O_1} = \lceil \log_2(19) \rceil = \lceil 4.25 \rceil = 5 \text{ bits}$ |
| $I_{Convert} = \lceil \log_2(20) \rceil + \lceil \log_2(19) \rceil = 10 \text{ bits/inst}$ |   |

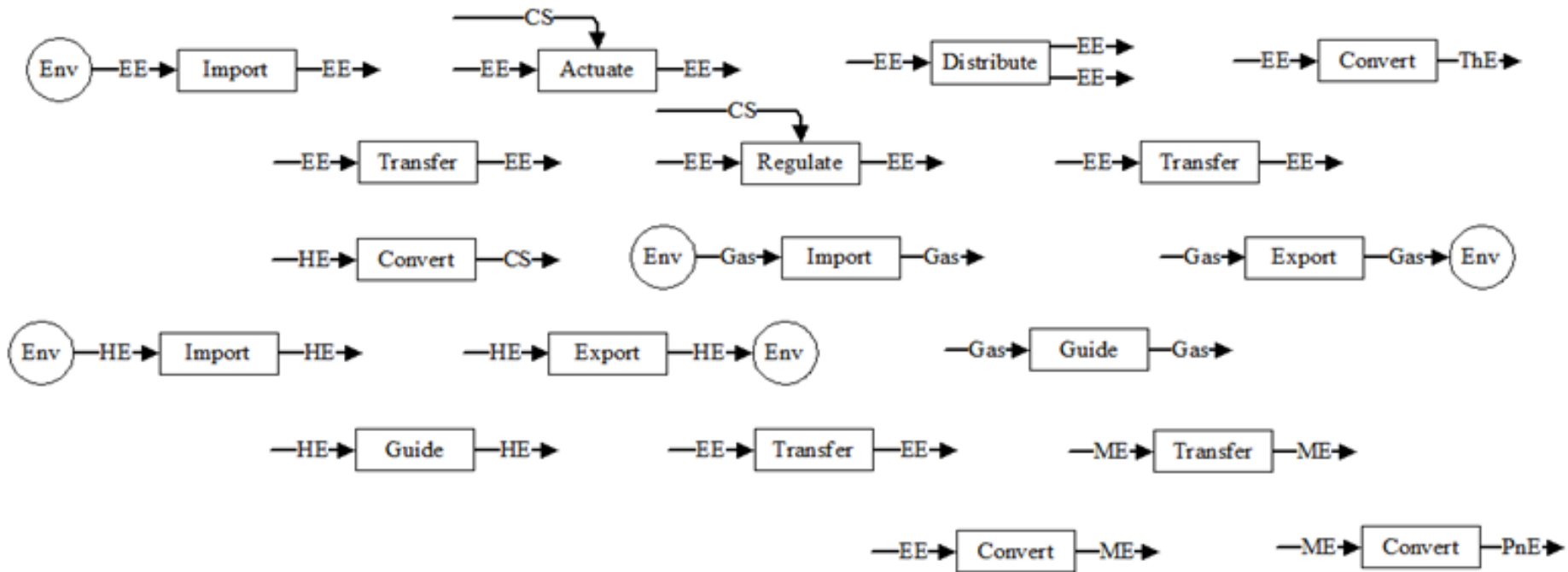
(b) Flow Set

| Primary  | Secondary               |
|----------|-------------------------|
| Material | Human                   |
|          | Gas                     |
|          | Liquid                  |
|          | Solid                   |
|          | Plasma                  |
|          | Mixture                 |
| Signal   | Status                  |
|          | Control                 |
| Energy   | Human                   |
|          | Acoustic                |
|          | Biological              |
|          | Chemical                |
|          | Electrical              |
|          | Electromagnetic         |
|          | Hydraulic               |
|          | Magnetic                |
|          | Mechanical              |
|          | Pneumatic               |
|          | Radioactive/<br>Nuclear |
| Thermal  |                         |

| Template  | Information content  |
|---|--|
|    | $I_{\text{Import}} = \lceil \log_2(20) \rceil = \lceil 4.32 \rceil = 5 \text{ bits/instance}$                                      |
|    | $I_{\text{Export}} = I_{\text{Guide}} = I_{\text{Transfer}} = I_{\text{Distribute}} = I_{\text{Import}} = 5 \text{ bits/instance}$ |
|    |  |
|    |  |
|    |  |
|    |  |
|  | $I_{\text{Regulate}} = \lceil \log_2(20) \rceil = \lceil 4.32 \rceil = 5 \text{ bits/instance}$                                    |
|  | $I_{\text{Convert}} = \lceil \log_2(20) \rceil + \lceil \log_2(19) \rceil = 10 \text{ bits/inst}$                                  |

| Function                        | Uncertainty<br>(bits/instance) | Number of<br>instances | Total<br>uncertainty<br>(bits) |
|---------------------------------|--------------------------------|------------------------|--------------------------------|
| Import                          | 5                              | 3                      | 15                             |
| Export                          | 5                              | 2                      | 10                             |
| Guide                           | 5                              | 2                      | 10                             |
| Transfer                        | 5                              | 4                      | 20                             |
| Distribute                      | 5                              | 1                      | 5                              |
| Actuate                         | 5                              | 1                      | 5                              |
| Regulate                        | 5                              | 1                      | 5                              |
| Convert                         | 10                             | 4                      | 40                             |
| <b>TOTAL (<math>I_F</math>)</b> |                                | <b>18</b>              | <b>110</b>                     |

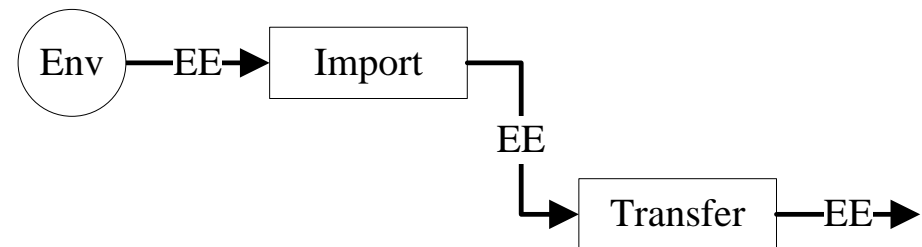
- By asking 110 questions, the flows connected to the templates can be known



- After asking  $90 + 110 = 200$  questions, the function model can be reconstructed using disconnected templates
  - All function names are known
  - All flows connected to the templates are known
  - The connections are still not known (Part III)

- The connection possibilities are now less than exhaustive
- Example: Consider the outgoing *EE* flow coming out of *Import*
  - It can terminate into only those functions that receive *EE* as an input (known)
  - Nine such templates in the model
  - Ignore identical templates (indistinguishable)
  - Six unique templates

- {Actuate, {EE, CS}, {EE}}
- {Distribute, {EE}, {EE, EE}}
- {Convert, {EE}, {ThE}}
- {Convert, {EE}, {ME}}
- {Transfer, {EE}, {EE}}
- {Regulate, {EE, CS}, {EE}}



- # questions to determine the destination of *EE*:  $\lceil \log_2(6) \rceil = \lceil 2.58 \rceil = 3$

# Part III: Uncertainty of the Connection between Templates

| Sl. No. | Template in Triple Notation     | Out Flow | Destination Options   | No. of Options | Connection Uncertainty<br>$\lceil \log_2(n) \rceil$ |
|---------|---------------------------------|----------|---|----------------|---|
| 1       | {“Import”, {EE}, {EE}}          | EE       | {Transfer, Actuate, Regulate, Distribute, Convert, Convert} | 6              | 3   |
| 2       | {“Transfer”, {EE}, {EE}}        | EE       | {Actuate, Regulate, Distribute, Transfer, Convert, Convert} | 6              | 3   |
| 3       | {“Actuate”, {EE, CS}, {EE}}     | EE       | {Transfer, Regulate, Distribute, Convert, Convert}          | 5              | 3   |
| 4       | {“Regulate”, {EE, CS}, {EE}}    | EE       | {Transfer, Actuate, Distribute, Convert, Convert}           | 5              | 3   |
| 5       | {“Distribute”, {EE}, {EE, EE}}  | EE       | {Transfer, Actuate, Regulate, Convert, Convert}             | 5              | 3   |
| 6       |                                 | EE       | {Transfer, Actuate, Regulate, Convert, Convert}             | 5              | 3   |
| 7       | {“Transfer”, {EE}, {EE}}        | EE       | {Actuate, Regulate, Distribute, Transfer, Convert, Convert} | 6              | 3   |
| 8       | {“Convert”, {EE}, {ThE}}        | ThE      | {}  | 1              | 0   |
| 9       | {“Convert”, {HE}, {CS}}         | CS       | {Actuate, Regulate}   | 2              | 1   |
| 10      | {“Import”, {HE}, {HE}}          | HE       | {Guide, Export, Convert}                                    | 3              | 2   |
| 11      | {“Guide”, {HE}, {HE}}           | HE       | {Export, Convert}   | 2              | 1   |
| 12      | {“Export”, {HE}, {HE}}          | HE       | {Env}   | 1              | 0   |
| 13      | {“Import”, {Gas}, {Gas}}        | Gas      | {Guide, Export}   | 2              | 1   |
| 14      | {“Import”, {Gas}, {Gas}}        | Gas      | {Export}  | 1              | 0   |
| 15      | {“Export”, {Gas}, {Gas}}        | Gas      | {Env}   | 1              | 0   |
| 16      | {“Transfer”, {EE}, {EE}}        | EE       | {Actuate, Regulate, Distribute, Transfer, Convert, Convert} | 6              | 3   |
| 17      | {“Convert”, {EE}, {ME}}         | ME       | {Transfer}  | 1              | 0   |
| 18      | {“Transfer”, {ME}, {ME}}        | ME       | {Convert}   | 1              | 0   |
| 19      | {“Convert”, {ME}, {PnE}}        | PnE      | {}  | 1              | 0   |
|         | <b>TOTAL (<math>I_c</math>)</b> |          |   |                | <b>29</b>   |

# Total Uncertainty in the model using the Enhanced Vocabulary

| Uncertainty Components   | Uncertainty (bits) |
|--|--------------------|
| Uncertainty from functions ( $I_V$ )                               | 90                 |
| Uncertainty from template Flows ( $I_F$ )                          | 110                |
| Uncertainty from connections ( $I_C$ )                             | 29                 |
| <b>Total in the Function Model</b><br>$(I_{EM} = I_V + I_F + I_C)$ | <b>229</b>         |

- After asking 229 questions, the function model can be completely reconstructed, as nothing more needs to be known about it

| Uncertainty Components | Notation and magnitude of uncertainty (bits) |                                       |
|------------------------|--|---------------------------------------|
|                        | Using the Functional Basis                   | Using the Triple-based Representation |
| Functions              | $I_V = 90$                                   | $I_V = 90$                            |
| Flows                  | $I_N = 120$                                  | $I_F = 110$                           |
| Connections            | $I_T = 216$                                  | $I_C = 29$                            |
| Total                  | <b>426</b>                                   | <b>229</b>                            |

- Total uncertainty in the model reduces by 46%
  - The number of questions required to resolve the functions are identical
  - The number of questions required to resolve the flows are closely comparable
  - The number of questions to resolve the topology are significantly different

The formalization of semantic information made the vocabulary more expressive

- The topology contributes significantly to the model's expressive power
  - Compare topological arrangement vs. flat list of functions and flows
- By capturing the definitions (semantics) of the terms, the vocabulary can be made significantly more expressive
  - More knowledge captured in the static representation (vocabulary)
  - Less knowledge *required* to resolve a specific model – lightweight models
- The enhanced vocabulary provides all the power of the Functional Basis, PLUS MORE
  - Entities: functions, flows (present in the Functional Basis)
  - Relations: compatibility and connection rules (NEW)
  - Constraints on relations (NEW)
- More stringent formalism → improves consistency, potential for automation
  - On the verge of a formal function representation to support automated reasoning

# Questions?