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# A Bisociative Design Framework For Knowledge Discovery Across Seemingly Unrelated Product Domains

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# PRESENTATION OVERVIEW

- Research Motivation
  - Introduction to Bisociation
- Methodology
  - The Big Data Challenge in Product Design
  - Design Artifact Decomposition
    - Form Similarity (Reeb Graph)
    - Function Similarity (Latent Semantic Analysis)
    - Behavior Similarity (Latent Semantic Analysis)
  - Data Mining Clustering of Bisociative Designs
- Results
- Path Forward

# RESEARCH MOTIVATION

# Let's start with a joke…

Did you hear about the computer programmer that got stuck in his shower for a week?

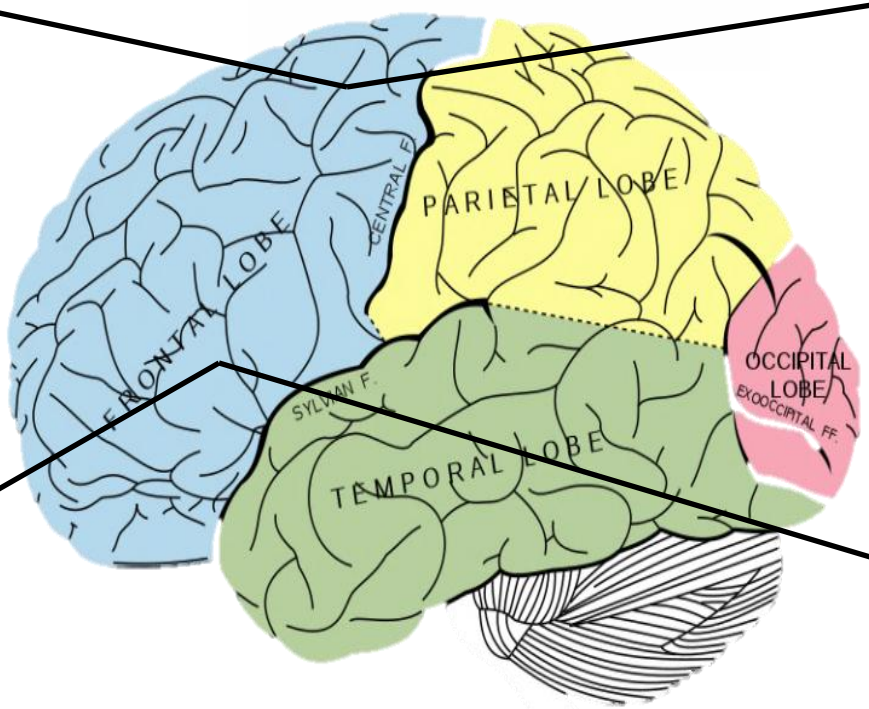

**Shampoo Instructions:**

Lather, Rinse, Repeat…

Source: http://ageekthing.tatadocomo.com/Geek-Sphere.aspx

# Domain: Computer Science

| Code | Endless Loop | Gamer | Programs | Ctrl, Alt Delete | Blue screen of death | Patience |
|---|---|---|---|---|---|---|




| Product Name | Product Jargon | Product Function | Product Behavior | Shower Frequency | Shower Duration | Shower Characteristics |
|---|---|---|---|---|---|---|

# Domain: Personal Hygiene

# Domain: Computer Science

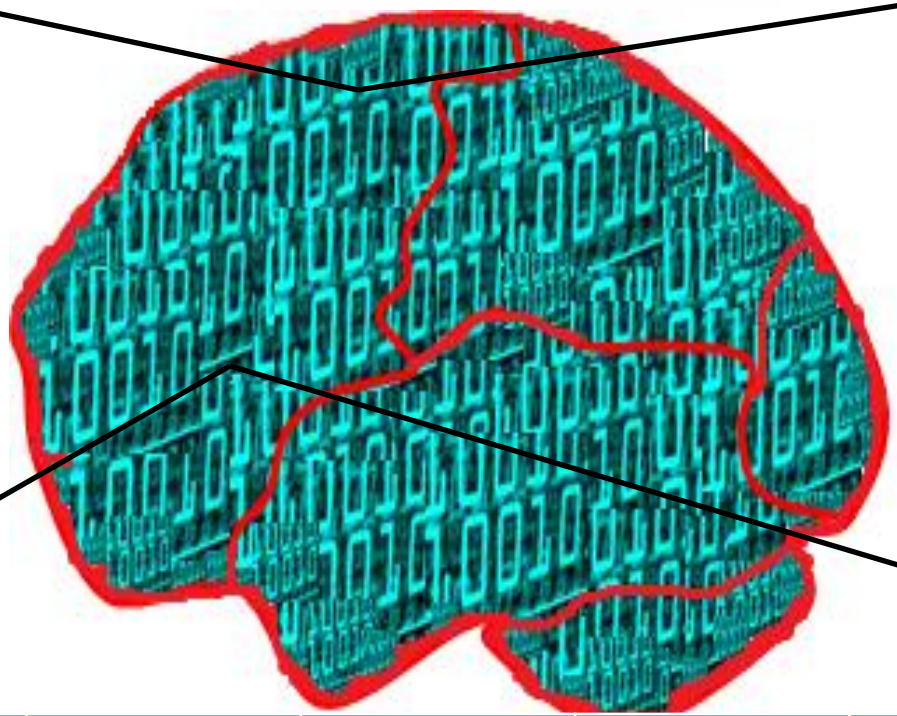
| Code | Endless Loop | Gamer | Programs | Ctrl, Alt Delete | Blue screen of death | Patience |
|---|---|---|---|---|---|---|

**"Bisociation"** – a synthesis of elements drawn from of two previously unrelated matrices of thought into a new matrix of meaning by way of a process involving comparison"- Koestler

| Product Name | Product jargon | Product Function | Shower characteristics | Shower Frequency | Shower Duration | When to call for help |
|---|---|---|---|---|---|---|

# Domain: Personal Hygiene

# Bisociative Design



# Large Scale Product Data Base

| Design | Manufacturer | Display Size | Talk Time | Connectivity | Processor | Price |
|---|---|---|---|---|---|---|

# Large Scale Product Data Base

| | Manufacture | Display Size | Talk Time | Connectivity | Processor | … | … | … | … | … | … | … | … | Price |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
|  | Apple | 3.5 inches | 8 hours | Bluetooth, Wi-Fi, 3G+ | 1 GHz | … | … | … | … | … | … | … | … | $649 |
|  | Samsung | 4.5 inches | 8.5 hours | Bluetooth, Wi-Fi, 3/4G | 1.2 GHz | … | … | … | … | … | … | … | … | $445 |
| | … | … | … | … | … | … | … | … | … | … | … | … | … | … |
| | … | … | … | … | … | … | … | … | … | … | … | … | … | … |
| … | … | … | … | … | … | … | … | … | … | … | … | … | … | … |
| … | … | … | … | … | … | … | … | … | … | … | … | … | … | … |
| … | … | … | … | … | … | … | … | … | … | … | … | … | … | … |
| … | … | … | … | … | … | … | … | … | … | … | … | … | … | … |
| … | … | … | … | … | … | … | … | … | … | … | … | … | … | … |
| … | … | … | … | … | … | … | … | … | … | … | … | … | … | … |
| … | … | … | … | … | … | … | … | … | … | … | … | … | … | … |
| … | … | … | … | … | … | … | … | … | … | … | … | … | … | … |
| … | … | … | … | … | … | … | … | … | … | … | … | … | … | … |
|  | Microsoft/Nokia | 3.7 inches | 9.5 hours | Bluetooth, Wi-Fi, 3G+ | 1.4 GHz | … | … | … | … | … | … | … | … | $364 |

**5.9 Billion Mobile Phones in the World [2]**

[2] ITU Facts and Figures 2011

# Predictive Modeling Techniques in Product Design

## Discrete Choice Analysis

| Attribute 1 | Attribute 2 | .. | Attribute N | Class |
|---|---|---|---|---|
| $A_{1,1}$ | $A_{2,1}$ | | $A_{N,M}$ | $C_{i,1}$ |
| . | . | | . | . |
| . | . | | . | . |
| . | . | | . | . |
| $A_{1,M}$ | $A_{2,M}$ | | $A_{N,M}$ | $C_{i,N}$ |

$$\Pr_n(i:C_m) = \frac{e^{W_{ni}/u}}{\sum_{j=1}^{m} e^{W_{nj}/u}} = \frac{e^{\beta^T z_{ni}/u}}{\sum_{j=1}^{m} e^{\beta^T z_{nj}/u}}$$

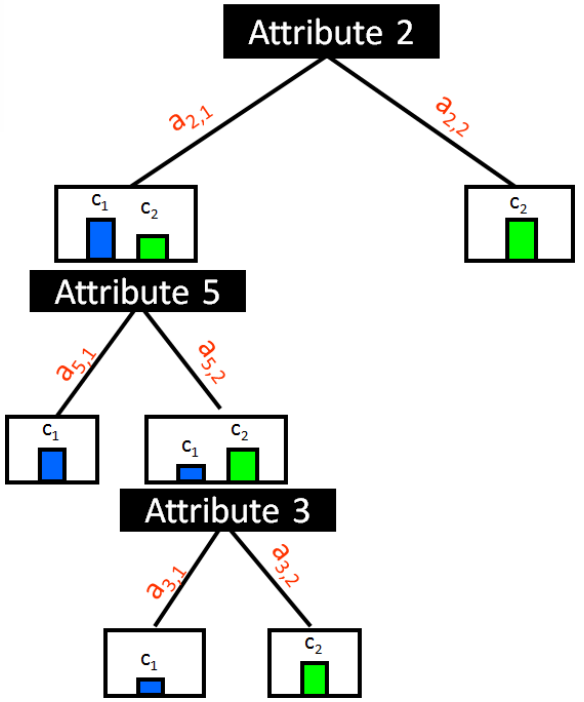
Where,

$$W_{ni} = f(\mathbf{A}_i, P_i, \mathbf{S}_n : \boldsymbol{\beta}_n)$$

β: Unknown parameters estimated using the Maximum Likelihood Estimation (MLE)

$Z_{ni}$: Represents the observable independent variables

## Data Mining




$$Entropy(T) = -\sum_j p(C_j \mid T)\log_2 p(C_j \mid T)$$

$$GAIN_{split} = Entropy(T) - \left(\sum_{i=1}^{k} \frac{T_i}{T} Entropy(T_i)\right)$$

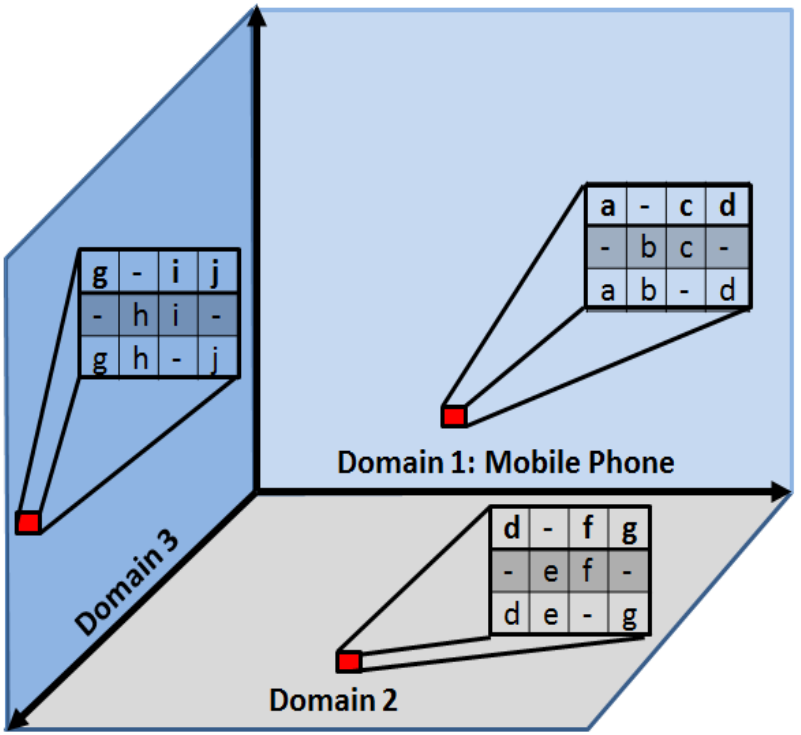
# Predictive Modeling Techniques in Product Design

## Challenges:

**1) Bound by the parameters of the model**

**2) Difficult to quantify *latent* relationships between products**

**3) Next generation product designs are limited to knowledge inherent in the existing domain**

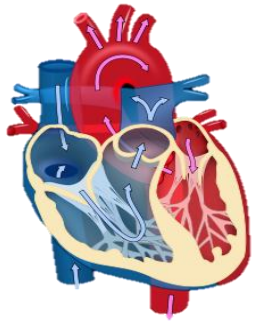


# Research Objectives

- Quantify the characteristics of a "Design Artifact" through a set of proposed *form*, *function* and *behavior* similarity metrics
- Discover latent, previously unknown relationships between products from seemingly unrelated domains
- Enable next generation product platform designs to synthesize design knowledge beyond the existing design domain

# Examples of Bisociative Design

**Domain 1**
Cardiology



**Human Heart**

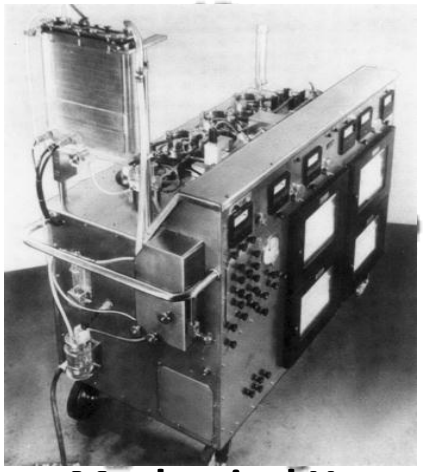
**Function:** a muscular organ that pumps blood to your body

**Domain 2**
Automotive

**Cadillac370A coupeV12-engine**

**Function:** convert gasoline into motion so that your car can move

**Domain 3**
Mechanical Cardiology

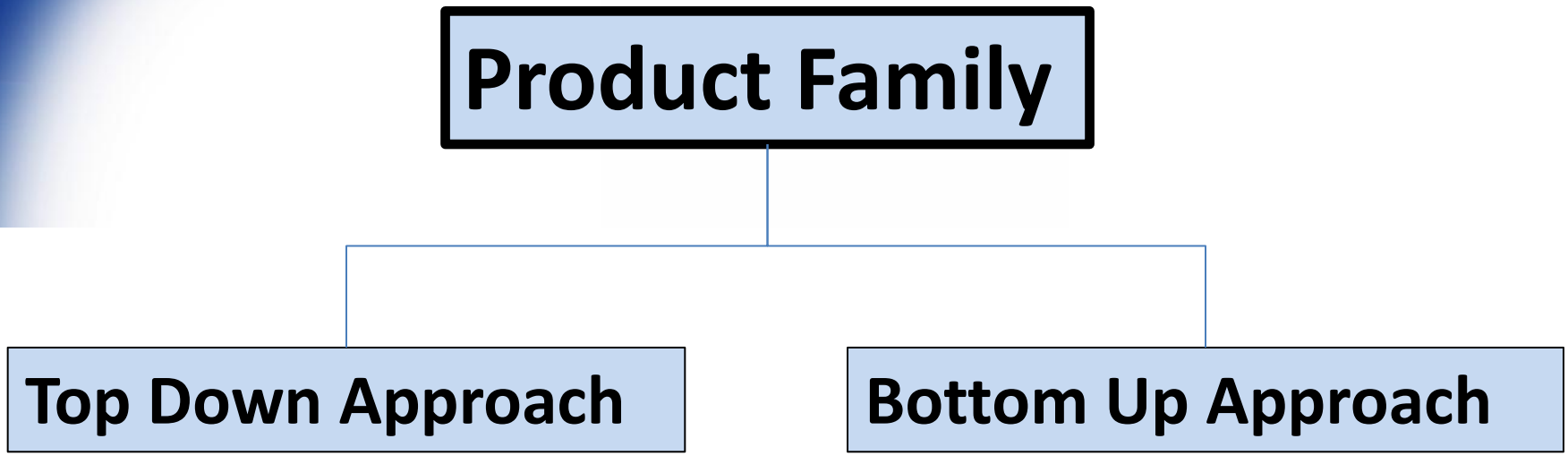


**Mechanical Heart**

**Function:** Maintains the functions of the heart while it is unable to continue to function adequately

# RESEARCH METHODOLOGY

# Research Methodology

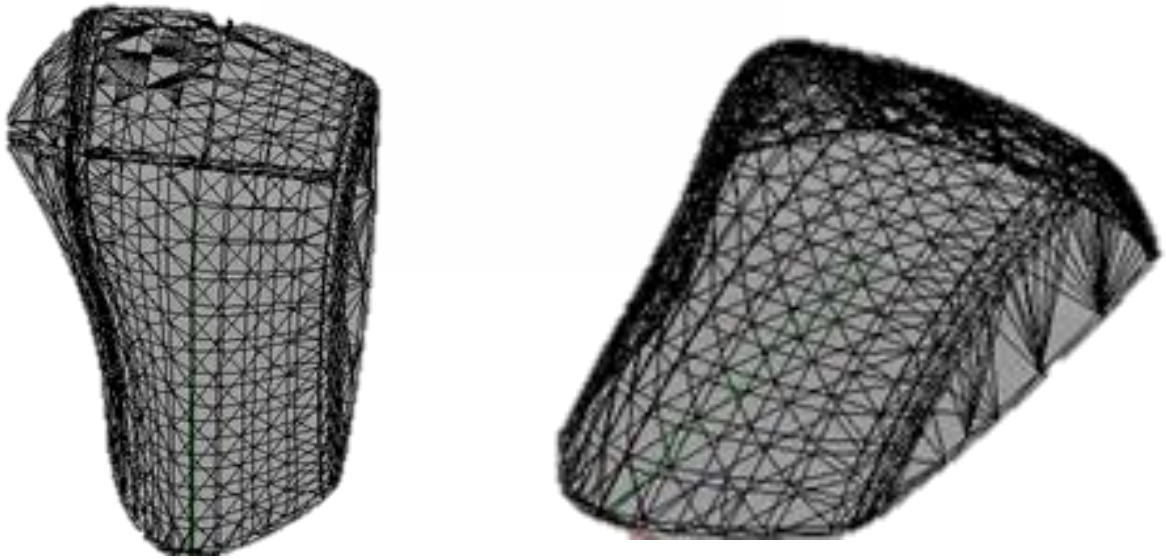



A company strategically manages and develops a family of products based on a **product platform** and its module- and/or scale-based derivatives

A company consolidates a group of distinct products by standardizing components to improve economies of scale and reduce inventory

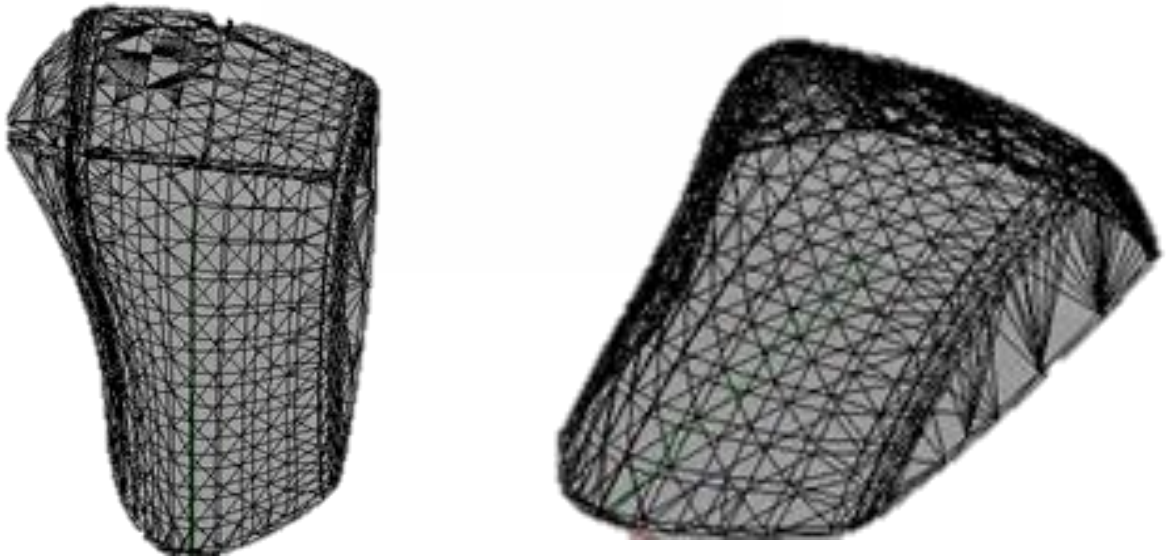
Simpson *et al, 2005*

# Characterization of a *Design Artifact*



A *design artifact* is defined as any tangible, physical entity that is created to satisfy an existing or future objective/need

# Characterization of a *Design Artifact*



**Form**: representing the physical configurations of an artifact (shape, texture, etc.)

**Function**: representing the specific objectives of an artifact

**Behavior**: representing the manner (intentional or unintentional) in which an artifact operates

-O. Benami and Y. Jin., 2002

# Quantifying Form Similarity

**Topology matching[4] for similarity estimation of product forms**

[4] M. Hilaga *et al* 2001

# Large Scale Product Data Base

## Product Features

Product domains

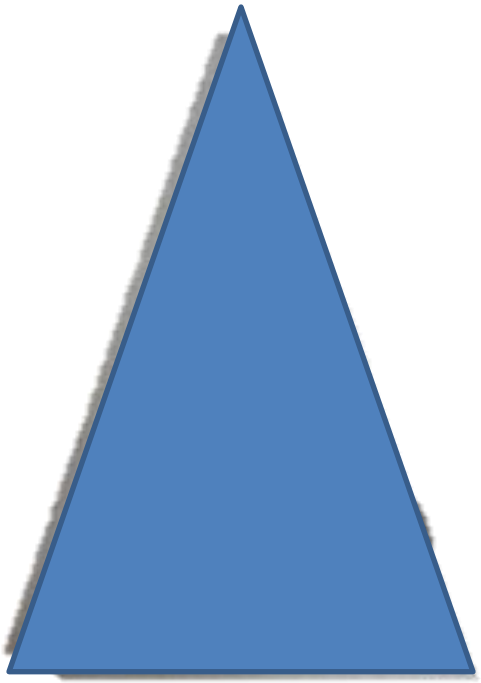
Cell Phone Domain

Sound Speaker Domain

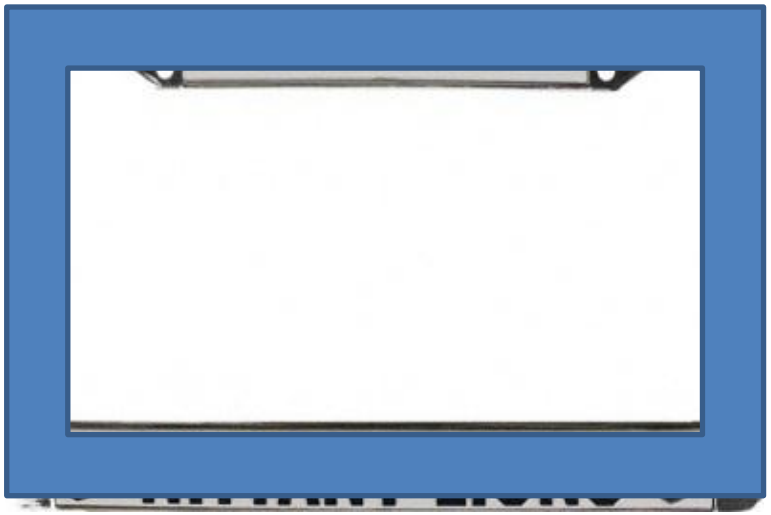
Automotive Domain

| | Product Feature 1 | Product Feature 2 | Product Feature 3 | Product Feature 4 | … | … | … | … | … | … | … | … |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
|  | a | - | c | d | … | … | … | … | … | … | … | … |
|  | - | b | c | - | … | … | … | … | … | … | … | … |
|  | a | b | - | d | … | … | … | … | … | … | … | … |
| … | … | … | … | … | … | … | … | … | … | … | … | … |
| … | … | … | … | … | … | … | … | … | … | … | … | … |
| … | … | … | … | … | … | … | … | … | … | … | … | … |
|  | … | … | … | … | … | … | … | … | … | … | … | … |
| … | … | … | … | … | … | … | … | … | … | … | … | … |
| … | … | … | … | … | … | … | … | … | … | … | … | … |
|  | … | … | … | … | … | … | … | … | … | … | … | … |
| … | … | … | … | … | … | … | … | … | … | … | … | … |
| … | … | … | … | … | … | … | … | … | … | … | … | … |
| … | … | … | … | … | … | … | … | … | … | … | … | … |
| … | … | … | … | … | … | … | … | … | … | … | … | … |

# The Form similarity algorithm



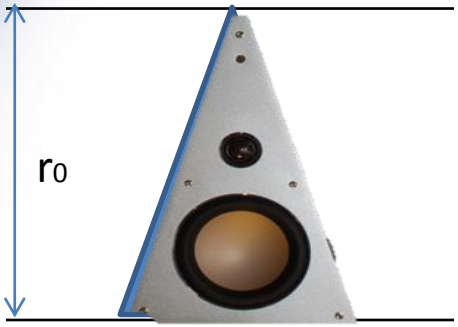
Cone Speaker System

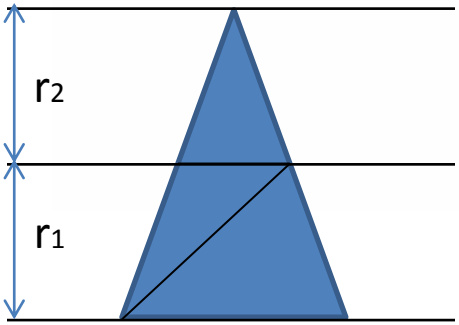


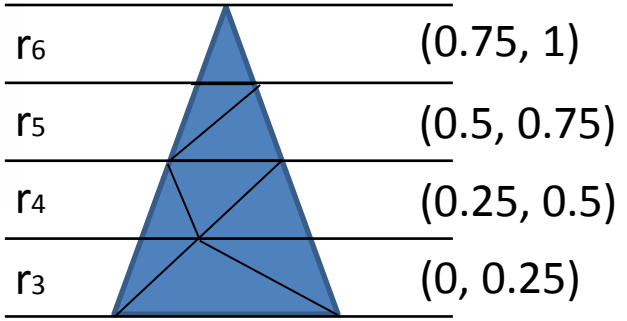
License Plate Cover

# The Form similarity algorithm

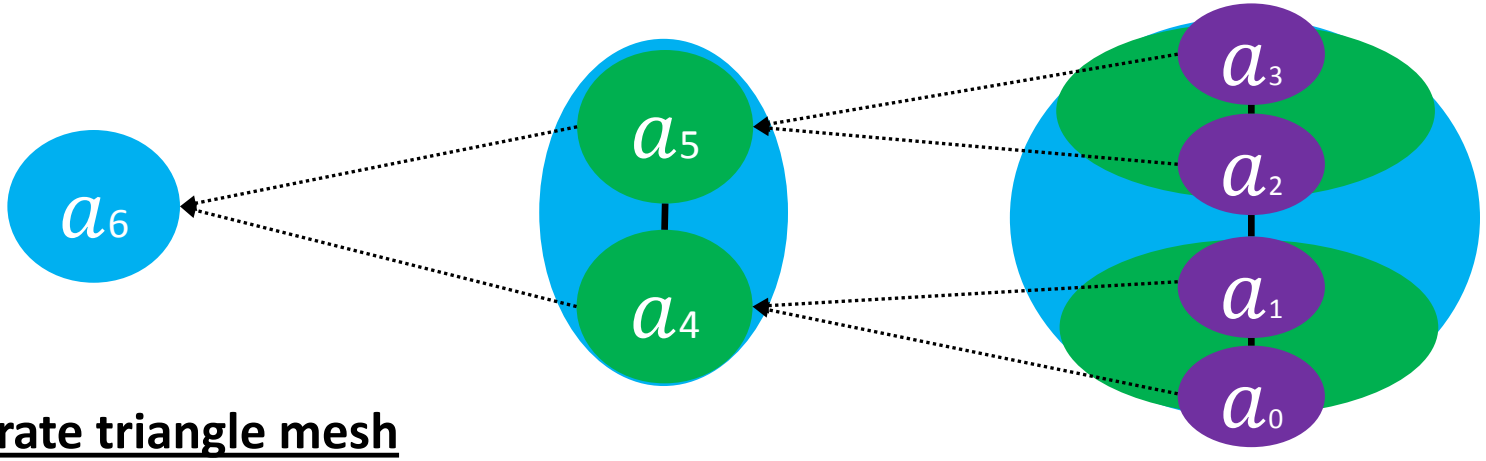
## Generating multi-resolution Reeb graph




A



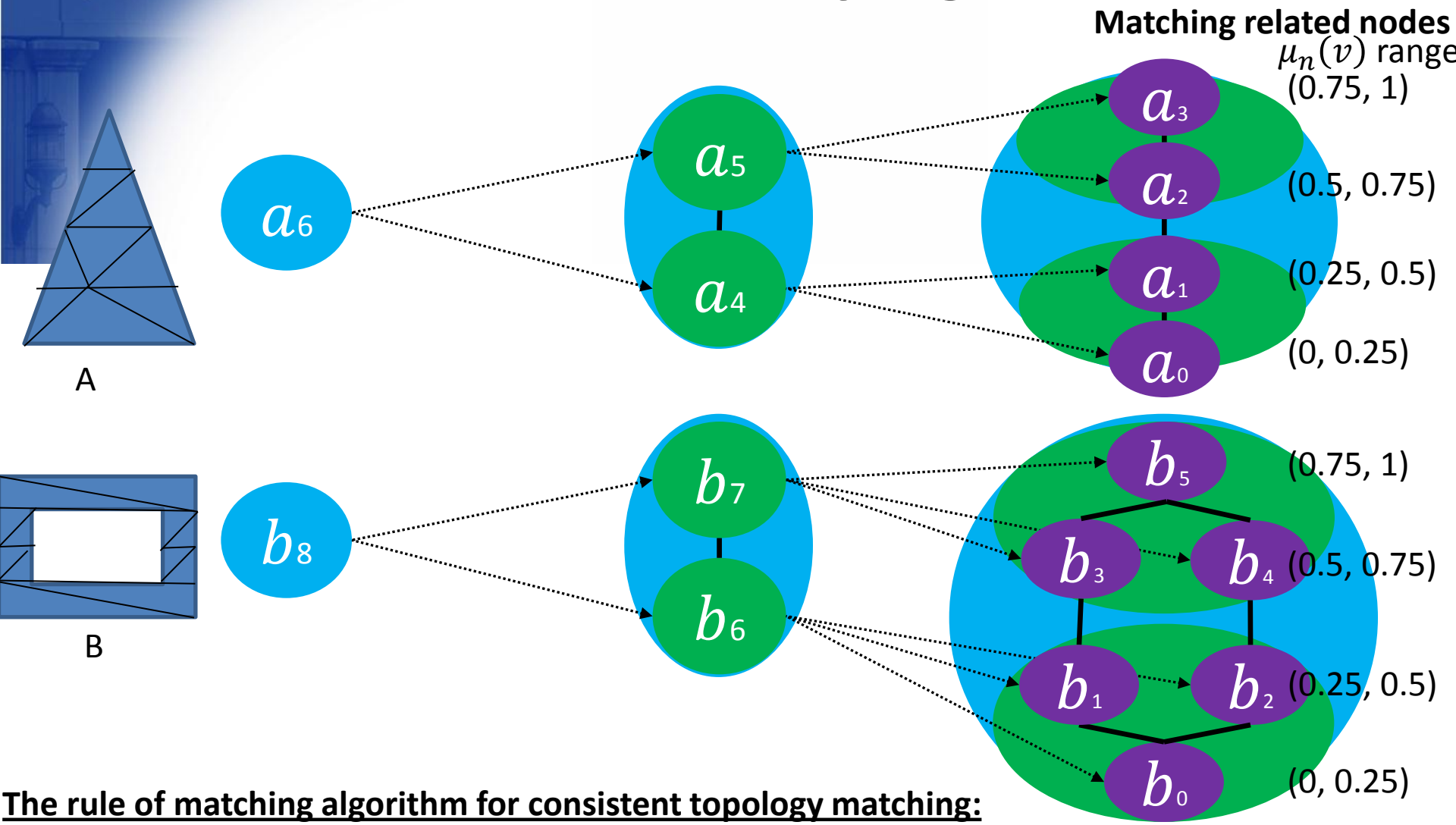

1. **Generate triangle mesh**

2. **Range setting**

$$\mu_n(v) = \frac{\mu(v) - min_{p \in S}\, \mu(p)}{max_{p \in S}\, \mu(p)}$$

3. **Generate the Reeb graph A**

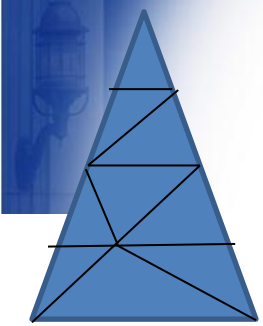
# The Form similarity algorithm



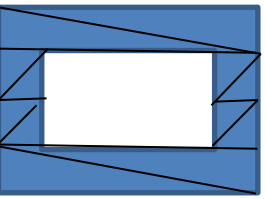

**The rule of matching algorithm for consistent topology matching:**

- Nodes can be matched only of they are on the same $\mu_n$*range* and their parents are matched.

# The Form similarity algorithm

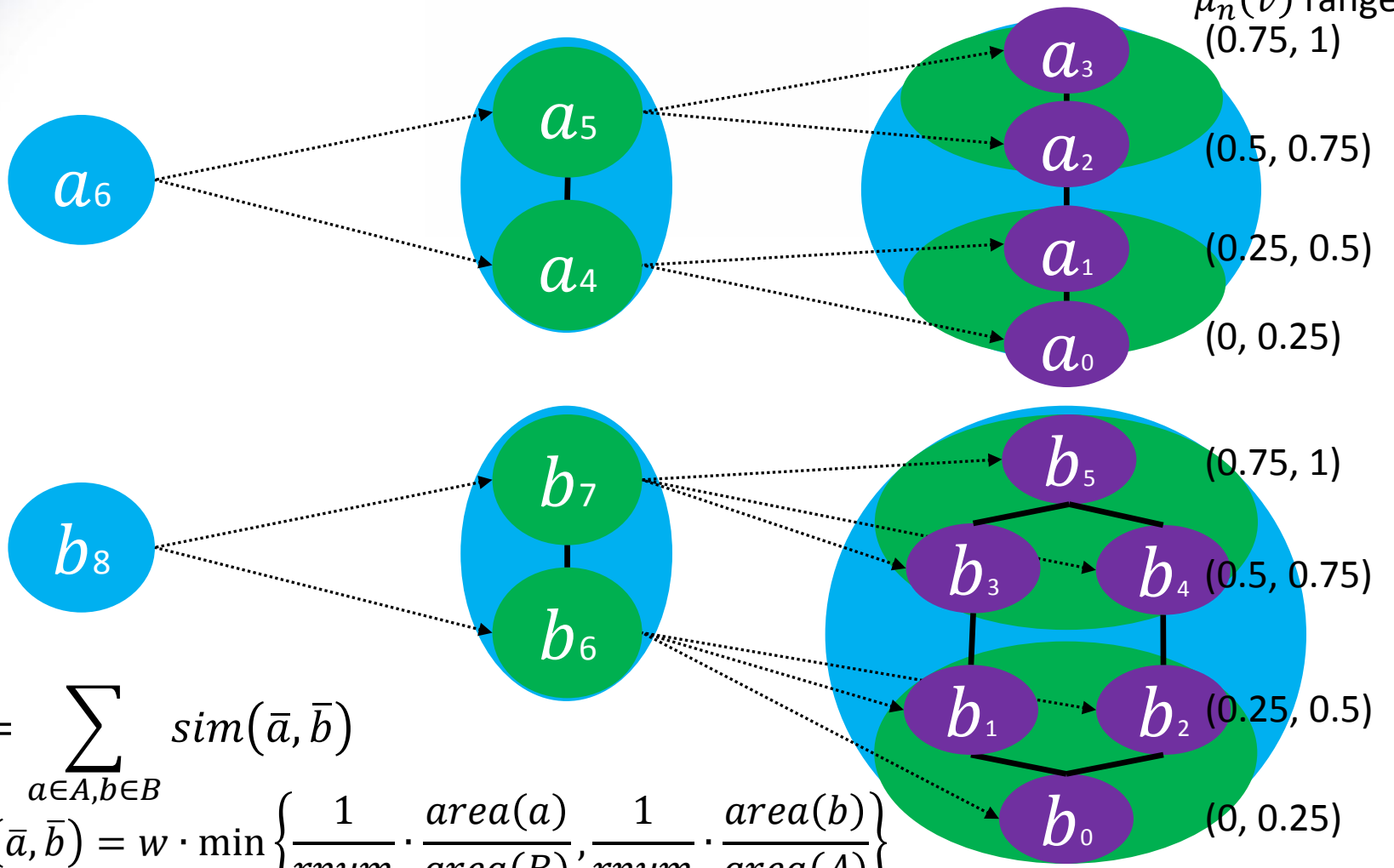


A



B

**Overview of similarity algorithm**

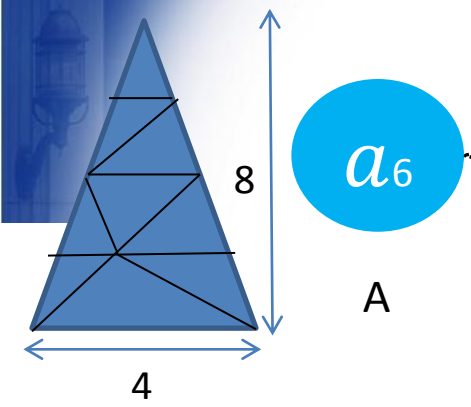



$$SIM(A,B) = \sum_{a \in A, b \in B} sim(\bar{a}, \bar{b})$$

Where, $sim(\bar{a}, \bar{b}) = w \cdot \min\left\{\frac{1}{rnum} \cdot \frac{area(a)}{area(B)}, \frac{1}{rnum} \cdot \frac{area(b)}{area(A)}\right\}$

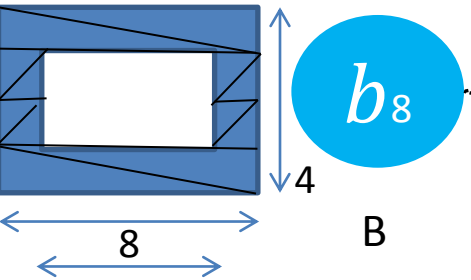
$$+(1-w) \cdot \min\left\{\frac{1}{rnum} \cdot \frac{len(a)}{\sum_b len(b)}, \frac{1}{rnum} \cdot \frac{len(b)}{\sum_a len(a)}\right\}$$

# The Form similarity algorithm



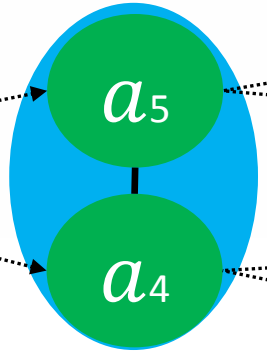

$a_6$

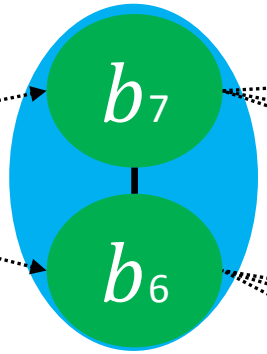
A

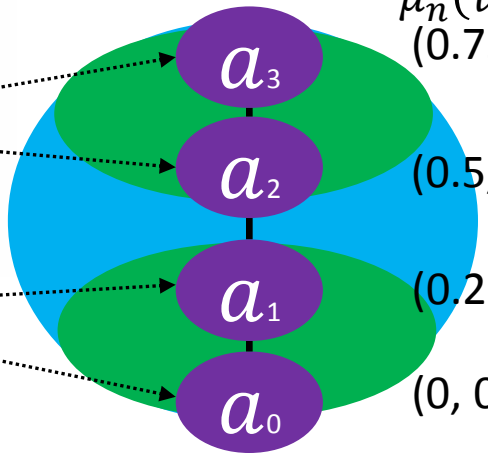


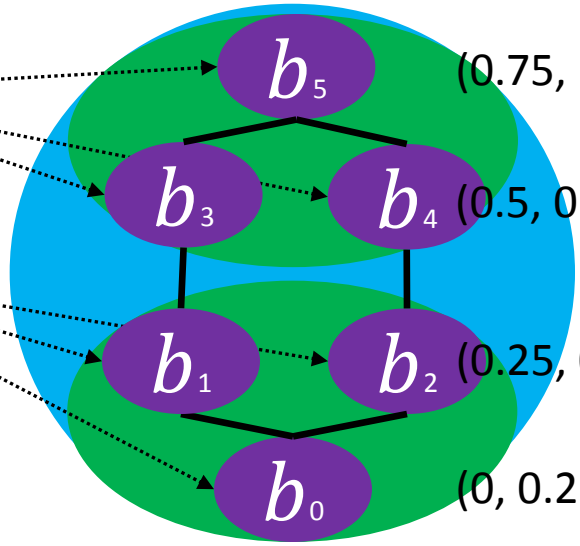

$b_8$

B




**Similarity between nodes**

$\mu_n(v)$ range

(0.75, 1)

(0.5, 0.75)

(0.25, 0.5)

(0, 0.25)

(0.75, 1)

(0.5, 0.75)

(0.25, 0.5)

(0, 0.25)

7.6

| | |
|---|---|
| $sim(\overline{a_0}, \overline{b_0})$ | 0.046743532 |
| $sim(\overline{a_1}, \overline{b_1}), sim(\overline{a_1}, \overline{b_2})$ | 0.019296394 |
| $sim(\overline{a_2}, \overline{b_3}), sim(\overline{a_2}, \overline{b_4})$ | 0.010025745 |
| $sim(\overline{a_3}, \overline{b_5})$ | 0.014972883 |

$SIM(A, B)$ =0.0910

# Form Similarity Metric

## Product domain

Product domain

| | |
|---|---|
| Similarity of Product domain |  |
|  | 0.0910 |

# Form Similarity Matrix

## Product domain

Product domain

| Similarity of Product domain |  |  |  |
|---|---|---|---|
|  | 1 | 0.0910 | … |
|  | 0.0910 | 1 | … |
|  | … | … | 1 |

# Form Similarity Matrix

## Product domain

Product domain

| |  |  |  |  |  |  | ... | ... | ... | ... | ... | ... | ... | ... | ... |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
|  | 1 | 0.0910 | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... |
|  | 0.0910 | 1 | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... |
|  | ... | ... | 1 | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... |
|  | ... | ... | ... | 1 | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... |
|  | ... | ... | ... | ... | 1 | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... |
|  | ... | ... | ... | ... | ... | 1 | ... | ... | ... | ... | ... | ... | ... | ... | ... |
| ... | ... | ... | ... | ... | ... | ... | 1 | ... | ... | ... | ... | ... | ... | ... | ... |
| ... | ... | ... | ... | ... | ... | ... | ... | 1 | ... | ... | ... | ... | ... | ... | ... |
| ... | ... | ... | ... | ... | ... | ... | ... | ... | 1 | ... | ... | ... | ... | ... | ... |
| ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | 1 | ... | ... | ... | ... | ... |
| ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | 1 | ... | ... | ... | ... |
| ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | 1 | ... | ... | ... |
| ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | 1 | ... | ... |
| ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | 1 | ... |
| ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | 1 |

# Quantifying Function and Behavior Similarity

## Function-Behavior Metric based on Latent Semantic Analysis (LSA)[5]

[5] Landauer *et al*, 2007

# The Function similarity algorithm

## Cone Speaker System

**Function**: The T200B is a professional monitor electro-acoustical design for multimedia products. T200B can upgrade your iPhone or computer into a Mini HiFi system and setup your personal PC studio.

## License Plate Cover


**Function:** Showcase your school spirit when you're on the road with this officially licensed NCAA® team laser chrome license plate frame from Rico. The 6-in x 12-in frame is decorated in the team colors and designed with plastic team inserts at the top and bottom.

# Function-Term Matrix

| | | Design Artifact | | | |
|---|---|---|---|---|---|
| | | Design Artifact 1 | Design Artifact 2 | .. | Design Artifact N |
| **Functional Descriptive Terms** | Term 1 | $C_{1,1}$ | $C_{1,2}$ | .. | $C_{1,n}$ |
| | Term 2 | $C_{2,1}$ | $C_{2,2}$ | .. | $C_{2,n}$ |
| | . | . | . | .. | . |
| | . | . | . | .. | . |
| | Term M | $C_{m,1}$ | $C_{m,2}$ | .. | $C_{m,n}$ |

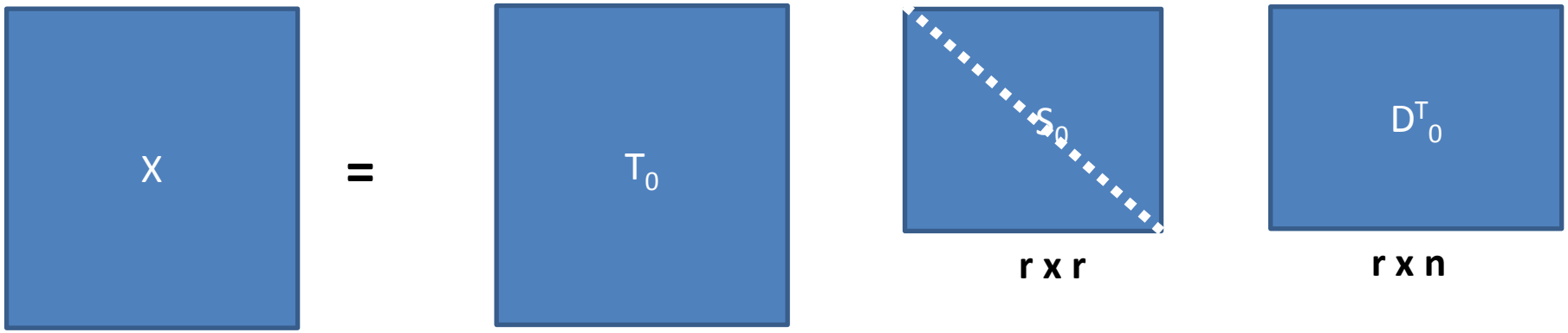
# Function-Term Matrix

**X=**

| | | | |
|---|---|---|---|
| $C_{1,1}$ | $C_{1,2}$ | .. | $C_{1,n}$ |
| $C_{2,1}$ | $C_{2,2}$ | .. | $C_{2,n}$ |
| . | . | .. | . |
| . | . | .. | . |
| $C_{m,1}$ | $C_{m,2}$ | .. | $C_{m,n}$ |

# Singular Value Decomposition

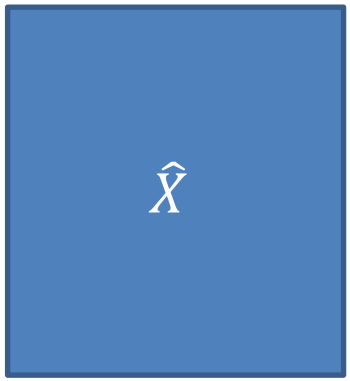
**Product-Term Matrix** | **Term Vectors** | **Diagonal Matrix** | **Product Vectors**




**m x n** **m x r** **r x r** **r x n**

# Singular Value Decomposition

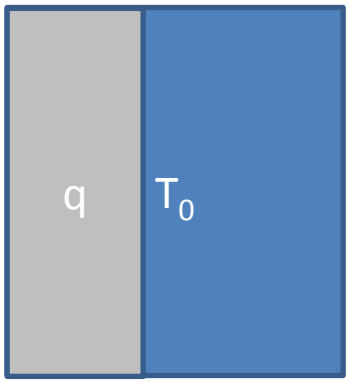
**Lower Dimension Product-Term Matrix**




**m x n**

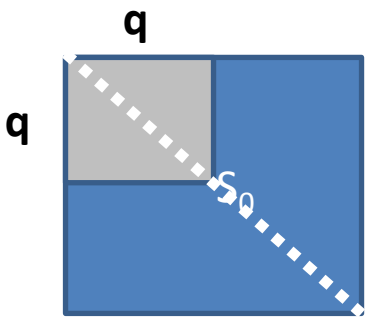
=

**Term Vectors**



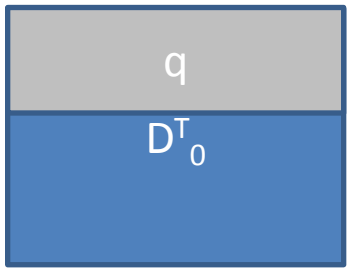

**m x r**

**Diagonal Matrix**




**r x r**

**Product Vectors**




**r x n**

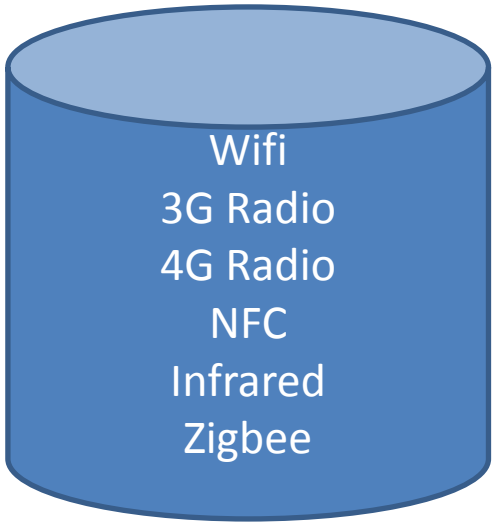
# Latent Semantic Analysis

**Lower Dimension Product-Term Matrix**

| | | | |
|---|---|---|---|
| $v_{1,1}$ | $v_{1,2}$ | .. | $v_{1,n}$ |
| $v_{2,1}$ | $v_{2,2}$ | .. | $v_{2,n}$ |
| . | . | .. | . |
| . | . | .. | . |
| $v_{m,1}$ | $v_{m,2}$ | .. | $v_{m,n}$ |

**m x n**

# Latent Semantic Analysis




**Communication**

| | | Design Artifact | | | |
|---|---|---|---|---|---|
| | | Design Artifact 1 | Design Artifact 2 | .. | Design Artifact N |
| **Functional Descriptive Terms** | Term 1 | $v_{1,1}$ | $v_{1,2}$ | .. | $v_{1,n}$ |
| | Term 2 | $v_{2,1}$ | $v_{2,2}$ | .. | $v_{2,n}$ |
| | . | . | . | .. | . |
| | . | . | . | .. | . |
| | Term M | $v_{m,1}$ | $v_{m,2}$ | .. | $v_{m,n}$ |

$$\text{Cos Similarity}\,(Term\ i, Term\ j) = \frac{\boldsymbol{Term}(i) \cdot \boldsymbol{Term}(j)}{\|\boldsymbol{Term}\,(i)\| \cdot \|\boldsymbol{Term}\,(j)\|}$$

# Latent Semantic Analysis

| | | Design Artifact | | | |
|---|---|---|---|---|---|
| | | Design Artifact 1 | Design Artifact 2 | .. | Design Artifact N |
| **Functional Descriptive Terms** | Term 1 | $v_{1,1}$ | $v_{1,2}$ | .. | $v_{1,n}$ |
| | Term 2 | $v_{2,1}$ | $v_{2,2}$ | .. | $v_{2,n}$ |
| | . | . | . | .. | . |
| | . | . | . | .. | . |
| | Term M | $v_{m,1}$ | $v_{m,2}$ | .. | $v_{m,n}$ |

$$\text{Cos Similarity } (Artifact\ i, Artifact\ j) = \frac{\boldsymbol{Artifact}(i) \cdot \boldsymbol{Artifact}(j)}{\|\boldsymbol{Artifact}\ (i)\| \cdot \|\boldsymbol{Artifact}\ (j)\|}$$

# Function Similarity Metric

## Product domain

Product domain

| | |
|---|---|
| Similarity of Product domain |  |
|  | 0.22 |

# Function Similarity Matrix

## Product domain

Product domain

| Similarity of Product domain |  |  |  |
|---|---|---|---|
|  | 1 | 0.22 | … |
|  | 0.22 | 1 | … |
|  | … | … | 1 |

# Function Similarity Matrix

## Product domain

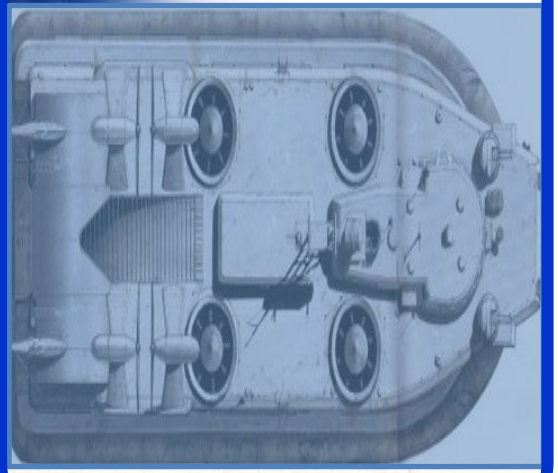
Product domain

| |  |  |  |  |  |  | ... | ... | ... | ... | ... | ... | ... | ... | ... |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
|  | 1 | 0.22 | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... |
|  | 0.22 | 1 | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... |
|  | ... | ... | 1 | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... |
|  | ... | ... | ... | 1 | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... |
|  | ... | ... | ... | ... | 1 | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... |
|  | ... | ... | ... | ... | ... | 1 | ... | ... | ... | ... | ... | ... | ... | ... | ... |
| ... | ... | ... | ... | ... | ... | ... | 1 | ... | ... | ... | ... | ... | ... | ... | ... |
| ... | ... | ... | ... | ... | ... | ... | ... | 1 | ... | ... | ... | ... | ... | ... | ... |
| ... | ... | ... | ... | ... | ... | ... | ... | ... | 1 | ... | ... | ... | ... | ... | ... |
| ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | 1 | ... | ... | ... | ... | ... |
| ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | 1 | ... | ... | ... | ... |
| ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | 1 | ... | ... | ... |
| ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | 1 | ... | ... |
| ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | 1 | ... |
| ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | 1 |

# CASE STUDY

# Next Generation Hybrid Vehicle

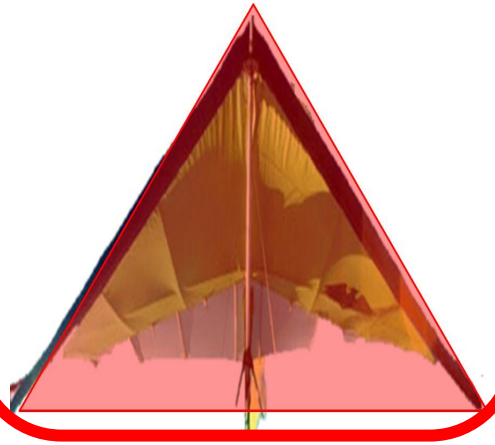
**Domain 1**: Marine



Hovercraft

**Function:** A hovercraft is capable of operation on either a solid surface or a liquid surface

**Domain 2**: Aviation



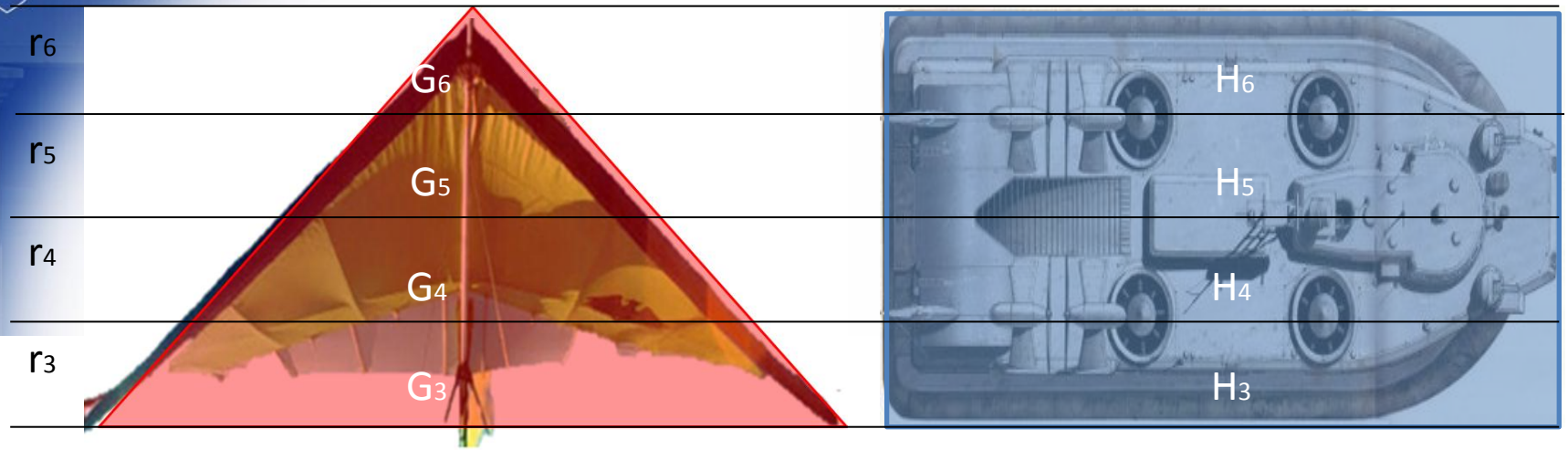
Glider

**Function:** Allow manned flight without the expense or restrictions of powered flight

**Domain 3**: Hybrid Marine

WIG

**Function**: using wings to apply buoyancy and aerodynamics to fly certain height from the surface of water

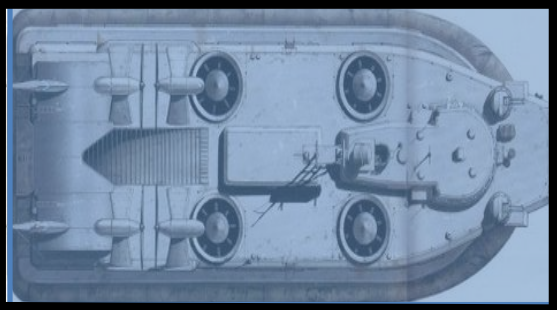


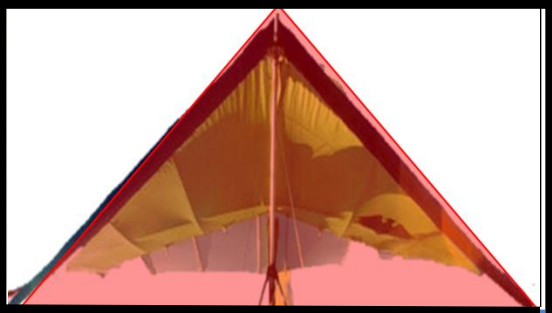

**Domain:** Aviation
**Design Artifact:** Hand Glider

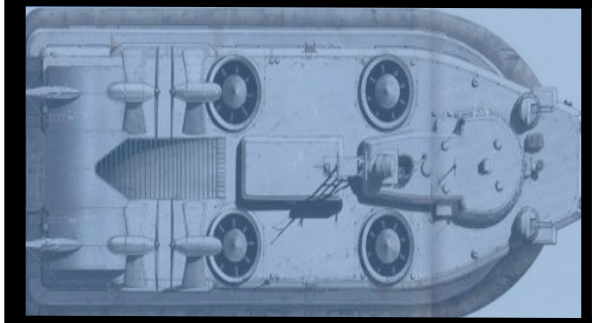
**Domain:** Marine
**Design Artifact:** Hover Craft

| | | |
|---|---|---|
| **Function** | **Allow manned flight without the expense or restrictions of powered flight** | **A hovercraft is capable of operation on either a solid surface or a liquid surface** |
| **Behavior** | Gliders are aerodynamically designed such that their lift-to drag ratio is greater than about 10:1, such that the glider is capable of suspending a flyer for several hours under the proper atmospheric conditions | The hovercraft includes a hull on which is mounted at least one thrust-lift fan assembly for providing an air cushion under the hovercraft and for propelling the hovercraft in a forward or reverse direction |

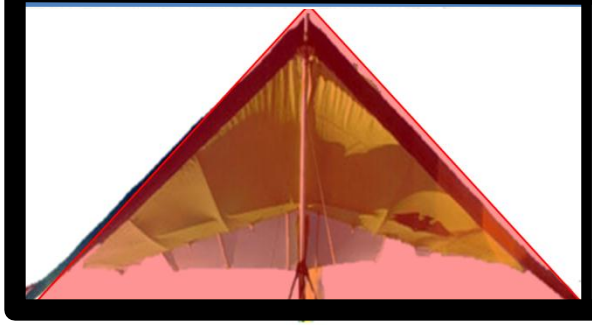
# Bisociative Design Score





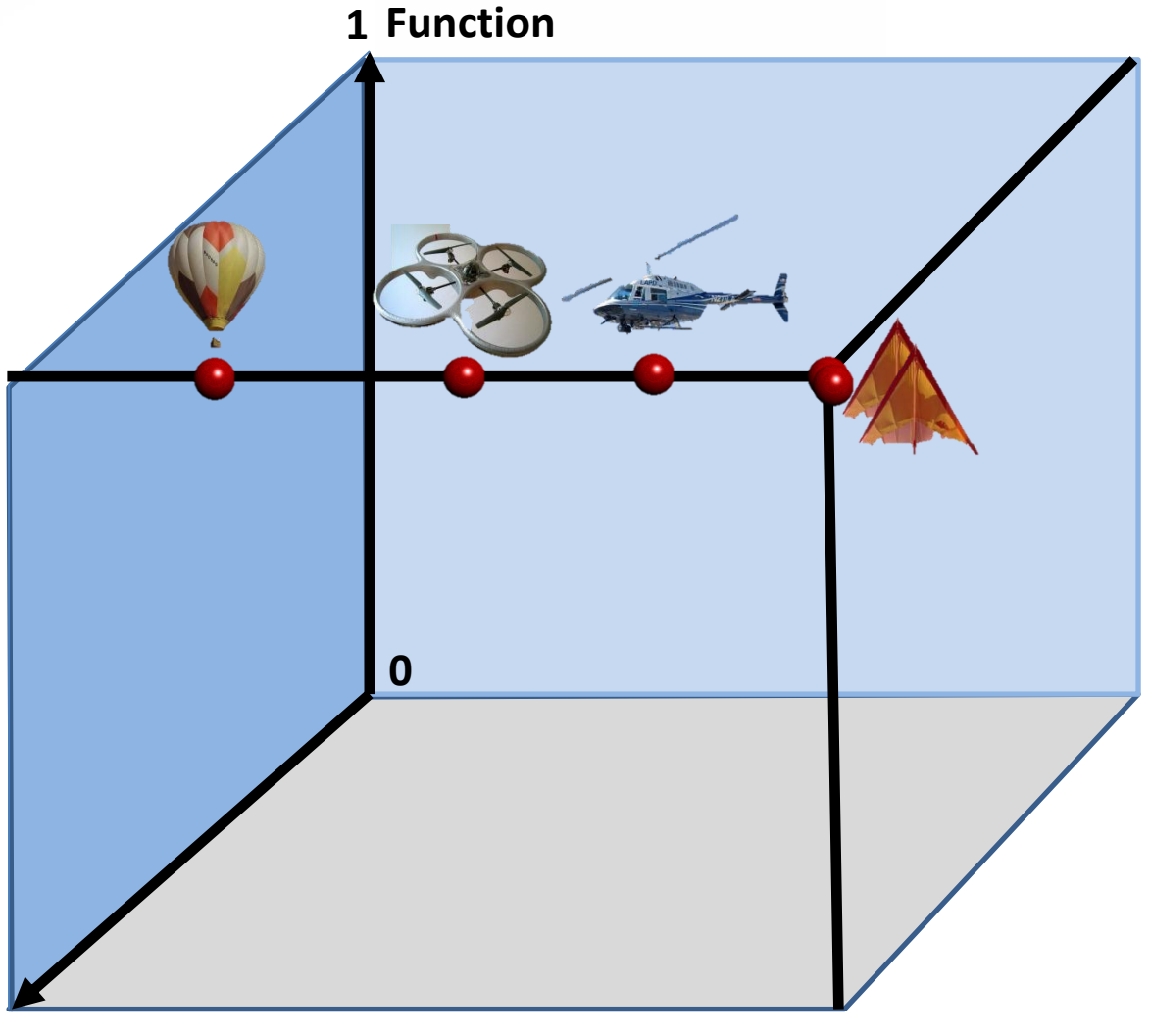


| Form | Function | Behavior | Form | Function | Behavior |
|---|---|---|---|---|---|
| 1.00 | 1.00 | 1.00 | 0.504 | 0.00 | 0.50 |

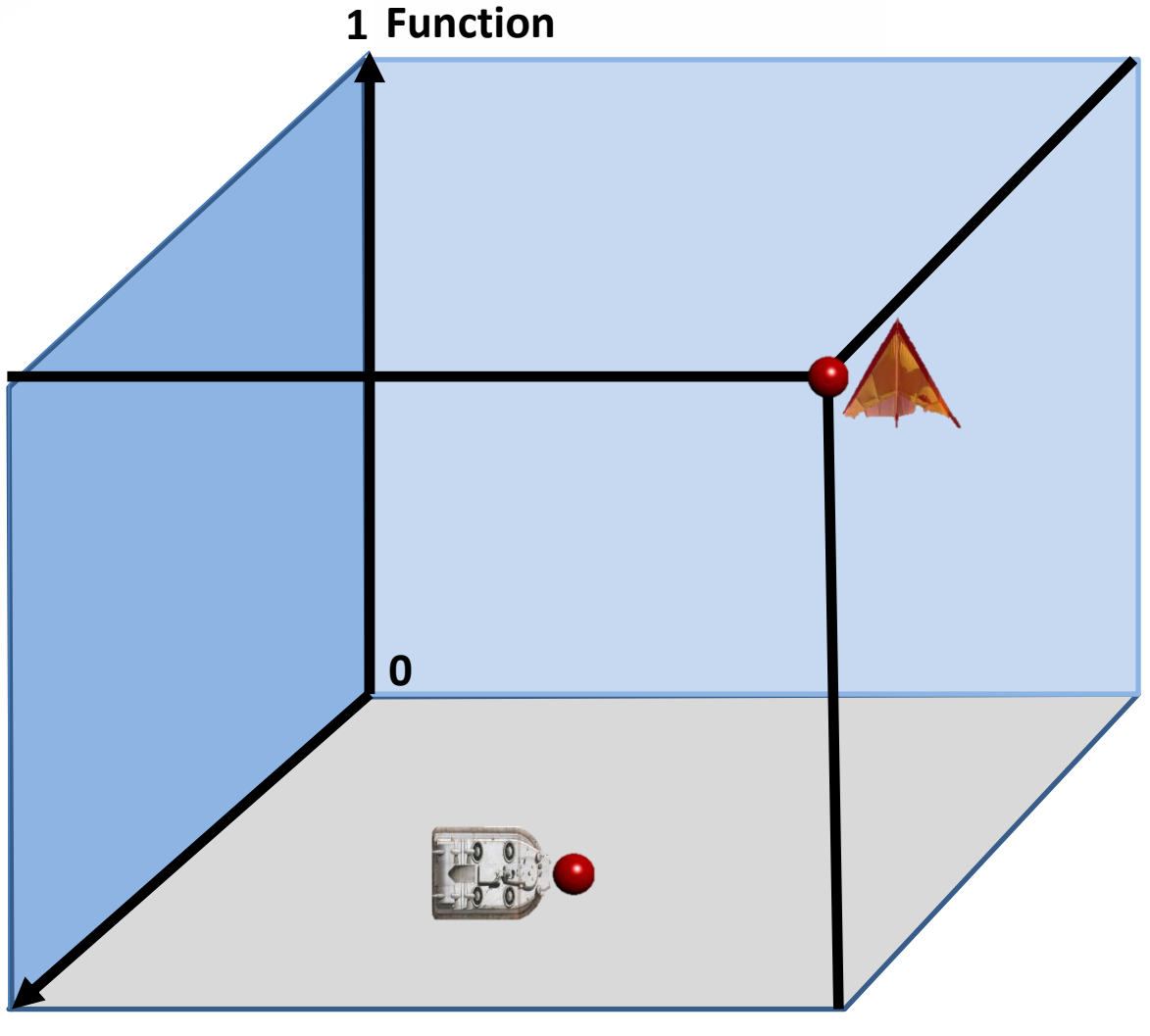


| Form | Function | Behavior | Form | Function | Behavior |
|---|---|---|---|---|---|
| 0.504 | 0.00 | 0.50 | 1.00 | 1.00 | 1.00 |

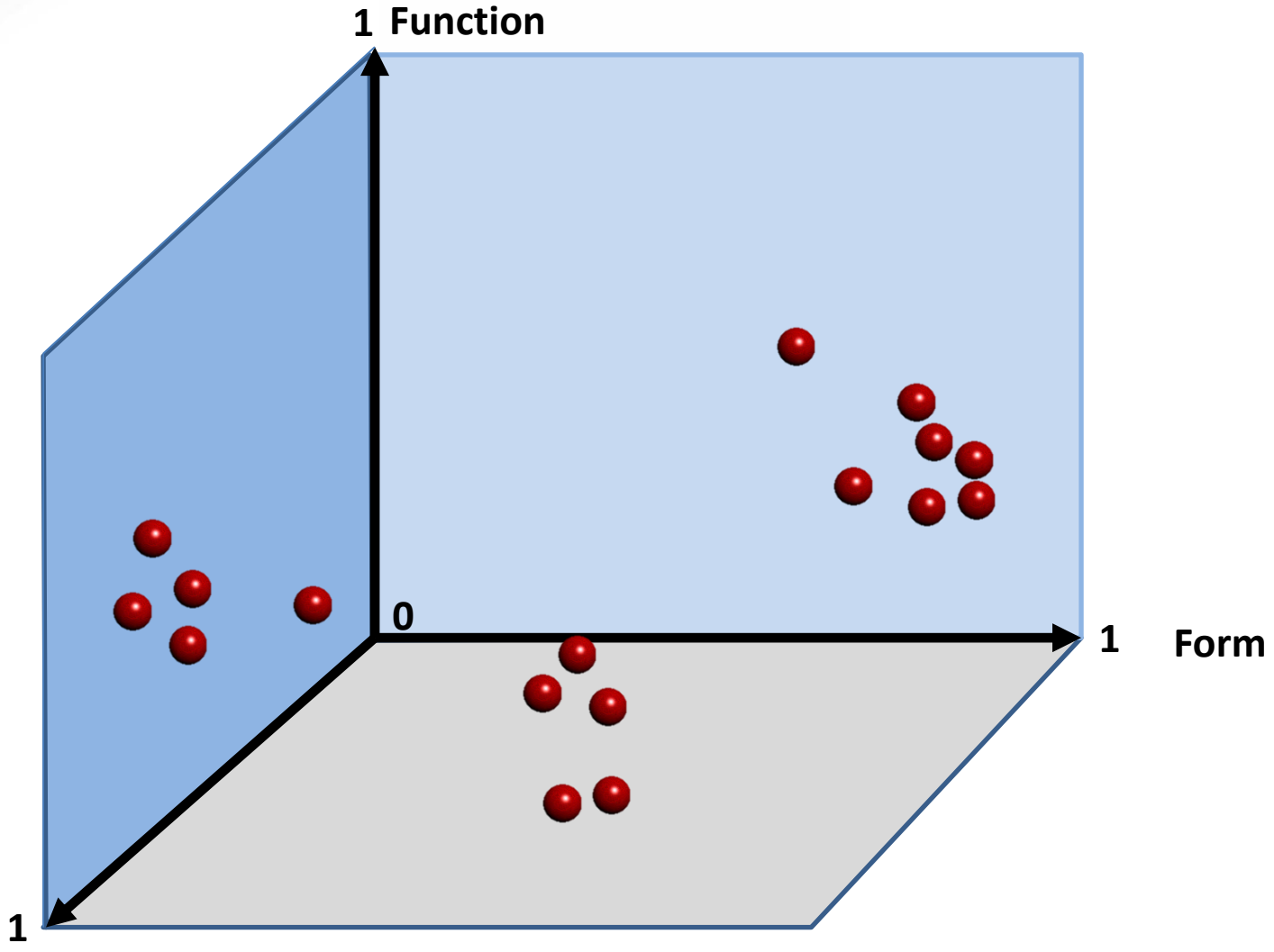
# Bisociative Design Space



# Bisociative Design Space



# Bisociative Design Space




$$E = \Sigma_{i=1}^{k} \Sigma_{p \in C_i} (d(p, c_i))^2$$

# Summary of Research Contributions

- Quantify the characteristics of a "Design Artifact" through a set of proposed *form*, *function* and *behavior* similarity metrics
- Discover latent, previously unknown relationships between products from seemingly unrelated domains
- Enable next generation product platform designs to synthesize design knowledge beyond the existing design domain

# FUTURE WORK

# Future Work

- Graph Theoretical Approach for Product Domain Identification and Classification

- Engineering Feasibility Analysis/Optimization of Bisociative Design Candidates

- Sensitivity Analysis of Function-Form-Behavior Relationships in Bisociative Design

# Acknowledgement & References

## Contributors:

- D.A.T.A. Lab: Conrad S.Tucker, Sung Woo Kang

## References


[1] Arthur Koestler. The Act of Creation. Penguin (Non-Classics), June 1990

[2] H. Bashir and V. Thomson. Estimating design complexity. Journal of Engineering Design, 10(3):247–257, 1999.

[3] O. Benami and Y. Jin. Creative simulation in conceptual design. In Proceedings of ASME Design Engineering Technical Conferences and Computer and Information in EngineeringConference DTM 34023. ASME, 2002.

[4] M. Hilaga, Y. Shinagawa, T. Kohmura, and T.L. Kunii. Topology matching for fully automatic similarity estimation of 3d shapes. In SIGGRAPH '01 Proceedings of the 28th annual conference on Computer graphics and interactive techniques, pages 44–47, 267, Aug 2001

[5] S. K. Moon, S. R. T. Kumara, and T. W. Simpson. Data mining and fuzzy clustering to support product family design. In Proceedings of DETC 06, 2006 ASME

# Design Artifact Data Collection