The General Systems Problem Solver

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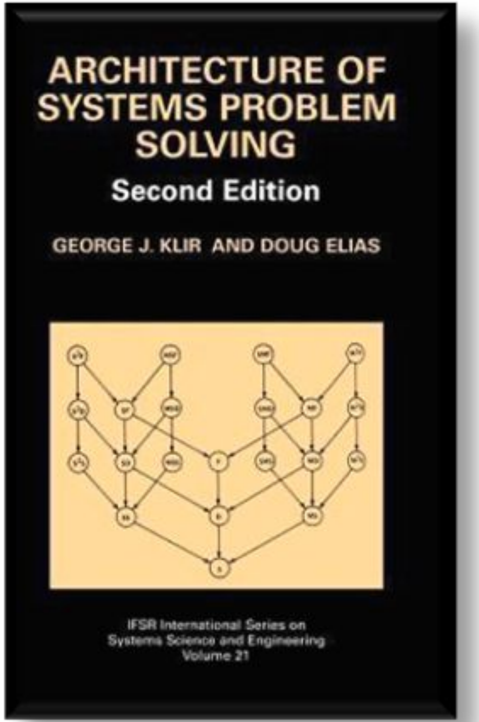
Lecture for SSIE501
24 October 2024

Overview

Goals

George Klir



Discussing key themes about the General Systems Problem Solver, including concerns and implications

Quick Intro to GSPS

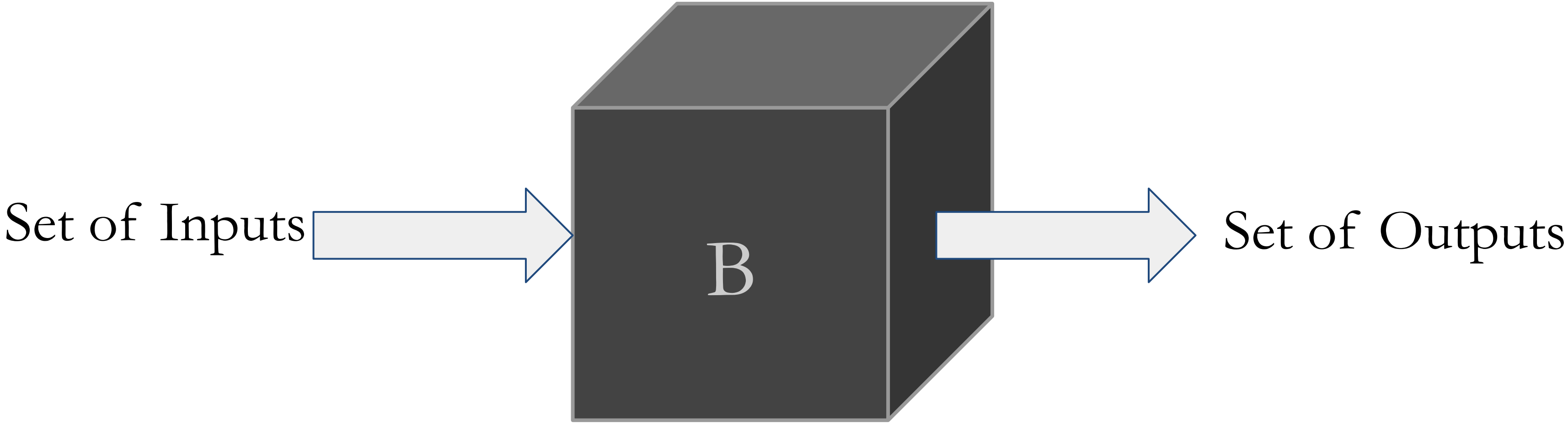
The General Systems Problem Solver (GSPS) is a conceptual framework for systems problems, and methodological tools for solving them.

Quick Intro to GSPS

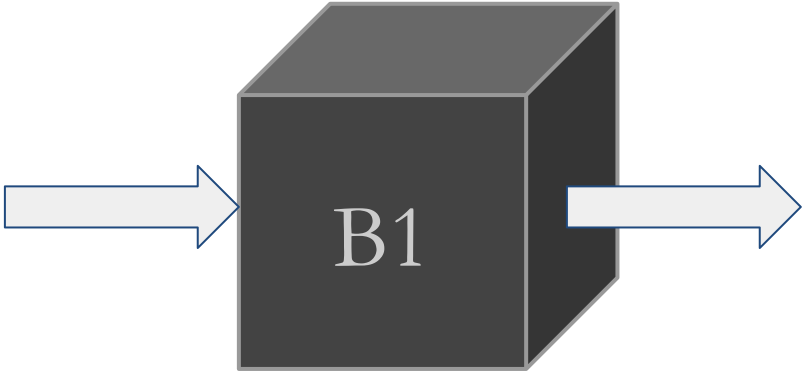
Let's start with a motivating example

The Black Box

What is a Black Box?

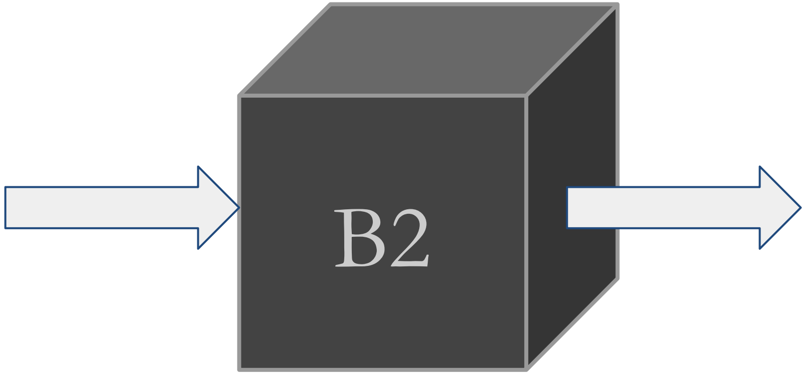


Black Box Example



Inputs and corresponding outputs are equivalent

Question: Are B1 and B2 equivalent?



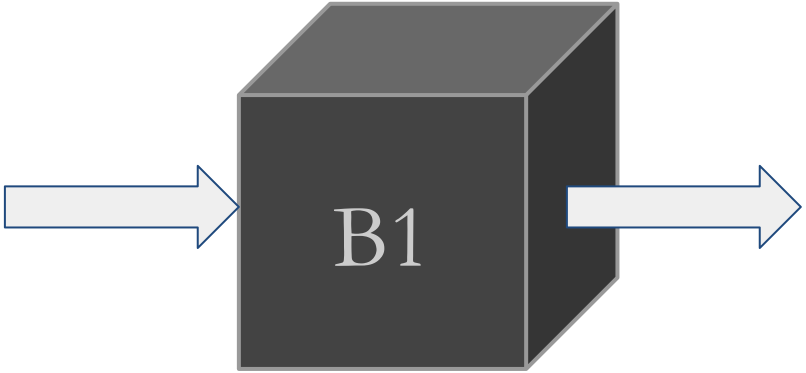
Black Box Example

Answer: Not necessarily

We can say they are isomorphic

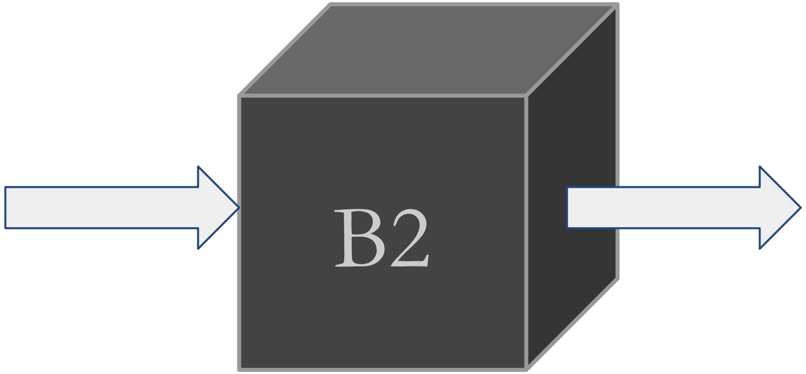
An isomorphism is a function that is *bijective, and relation-preserving*

Black Box Example



Contains data on gravitational attraction

Contains data on charged particle attraction



Black Box Example

$$F = G\frac{m_1 m_2}{r^2}$$

$$F = k_e \frac{|q_1||q_2|}{r^2}$$

$$G \leftrightarrow k_e$$

$$m_1 \leftrightarrow q_1$$

$$m_2 \leftrightarrow q_2$$

$$r \leftrightarrow r$$

B1

B2

Isomorphic Systems

Other examples:

Damped Mass-Spring ↔ RLC Circuit

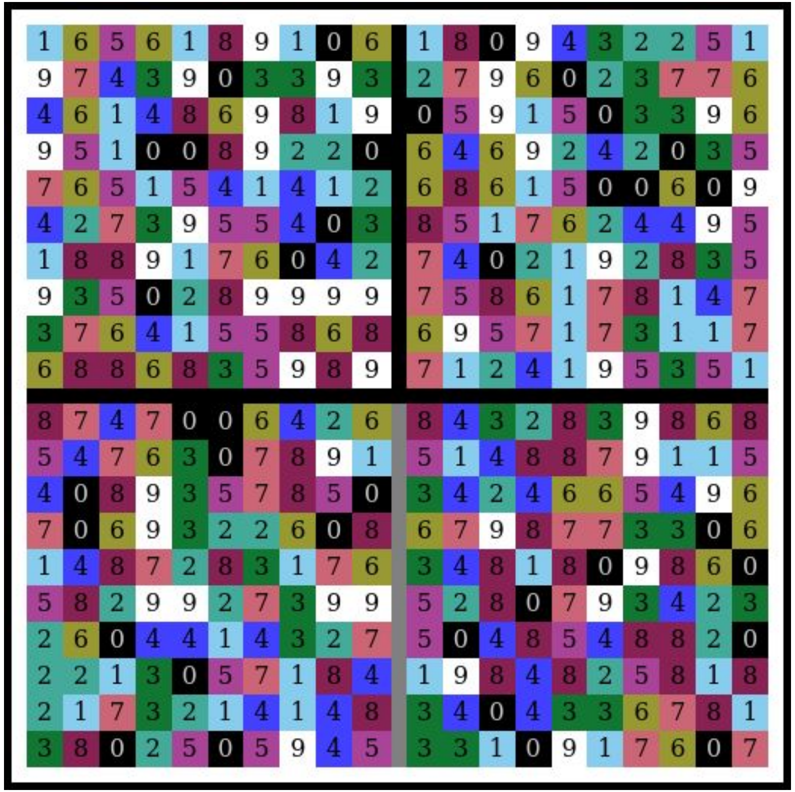
Circular Motion ↔ Charged particle through a magnetic field

Some physical system ↔ Computer program

Any others?

* All of the above assume correctly tuned parameters

A More Complex Black Box



How can we gain information about black boxes?

We can look at general tools to study black boxes, and related ideas to get a better conceptual understanding of systems

We will now be moving on to some formalisms in defining systems

A system
is a big
black box

of which we
can't unlock
the doors

and all we
can find
out about

is what goes
in and what
comes out

-Kenneth L.
Boudling

Epistemological Hierarchy of Systems

Source Systems (E)

Variables and Supports

$$v_i \in V_i$$

Interpretations of both above

Source System
Level 0

E

Source Systems (E)

v_1 is ambient air temperature outside in degrees Celsius

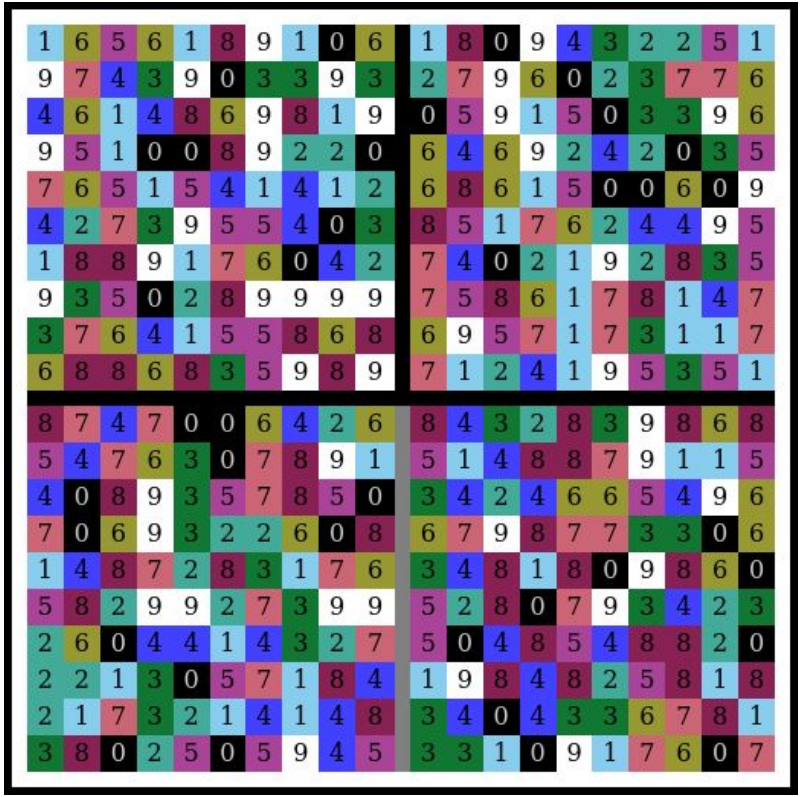
$$v_1 \in V_1 = [-25, 40]$$

t is the time of measurement (UTC timestamp? Date + time?)

Source System
Level 0

E

Source Systems (E)



Each cell is a variable that takes a value {0, 1, 2, …, 9}.

Any evidence of a variable with a different value?

Any variables that can only take on a subset of the above values?

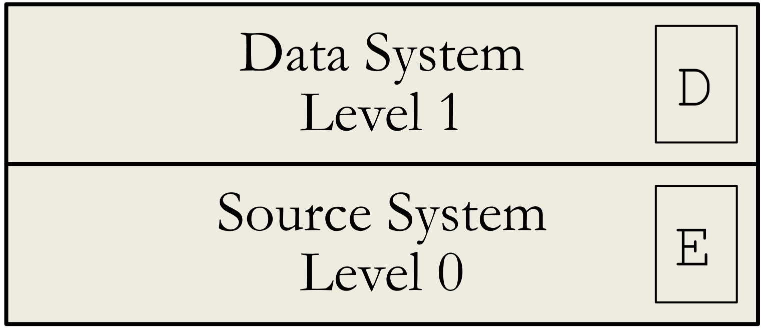
Source System
Level 0

E

Data Systems (D)

E + Data

Gather data through harvesting, experimentation, observations

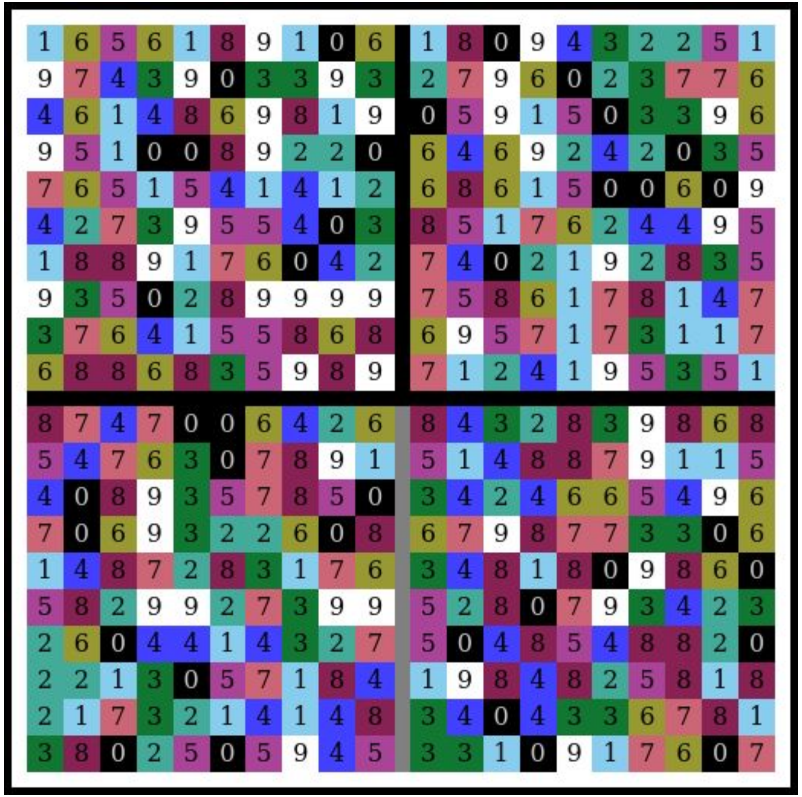


Data Systems (D)

t=	0	1	2	3	4	5	6	7	8	9	10
v_1=	1	1	2	3	5	8	13	21	34	55	89
v_2=	1	1	0	1	1	2	3	5	8	3	11

Data System Level 1	D
Source System Level 0	E

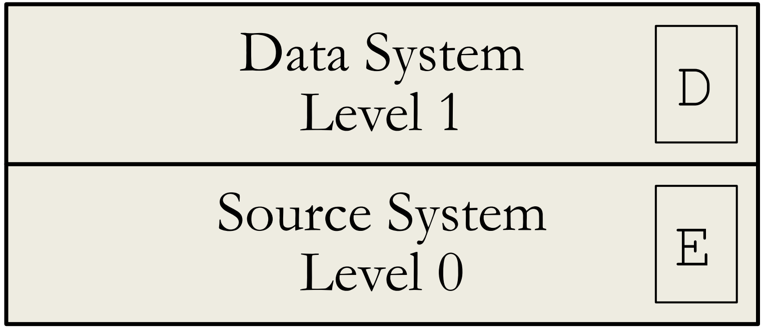
Data Systems (D)



Collecting data from here?

Web scraper to harvest data from the webpage

How much data is enough?



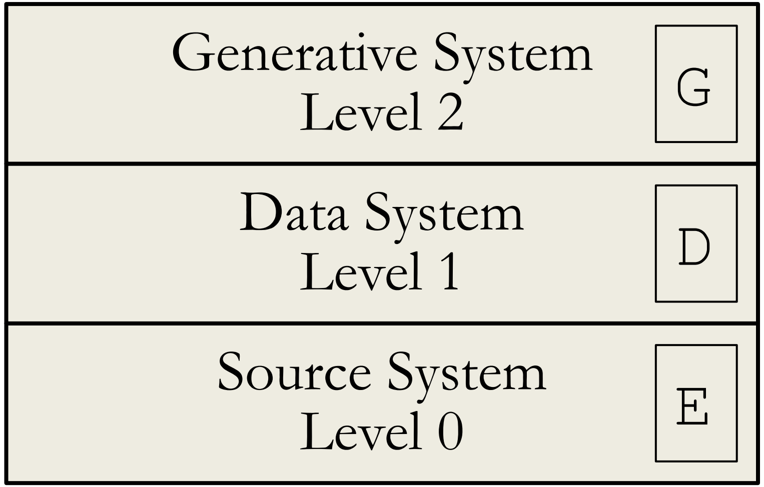
Generative Systems (G)

E + Relation

Data is optional

The relation must be consistent with the data, if included (masking)

Sampling variables



Generative Systems (G)

t=	0	1	2	3	4	5	6	7	8	9	10
v_1=	1	1	2	3	5	8	13	21	34	55	89
v_2=	1	1	0	1	1	2	3	5	8	3	11

S_1	S_2	S_3
		S_4

Rules:

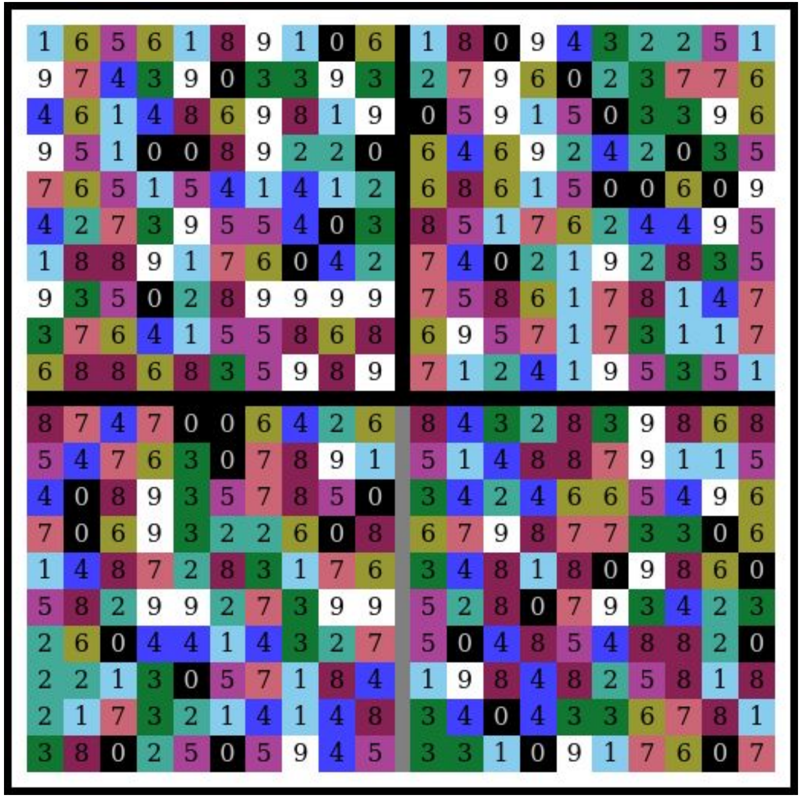
$S_3 = S_1 + S_2$

$S_4 = S_2 - S_1$ if $S_2 - S_1 < 10$

$S_4 = S_2 - S_1 - 10$ if $S_2 - S_1 \geq 10$

Generative System Level 2	G
Data System Level 1	D
Source System Level 0	E

Generative Systems (G)



What mask would you use?

We will revisit this…

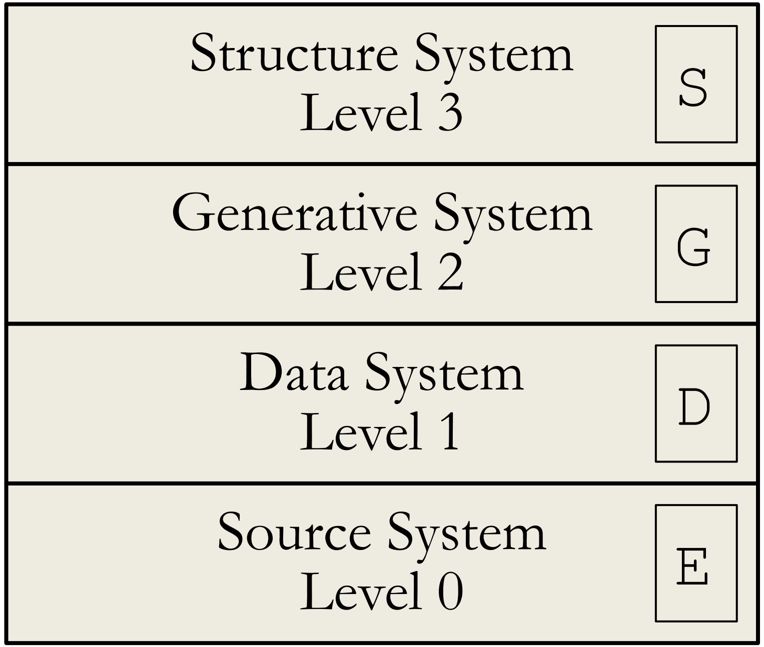
Generative System Level 2	G
Data System Level 1	D
Source System Level 0	E

Structure Systems (S)

Collection of Subsystems (G, D, E) and how they relate

Compatibility requirement

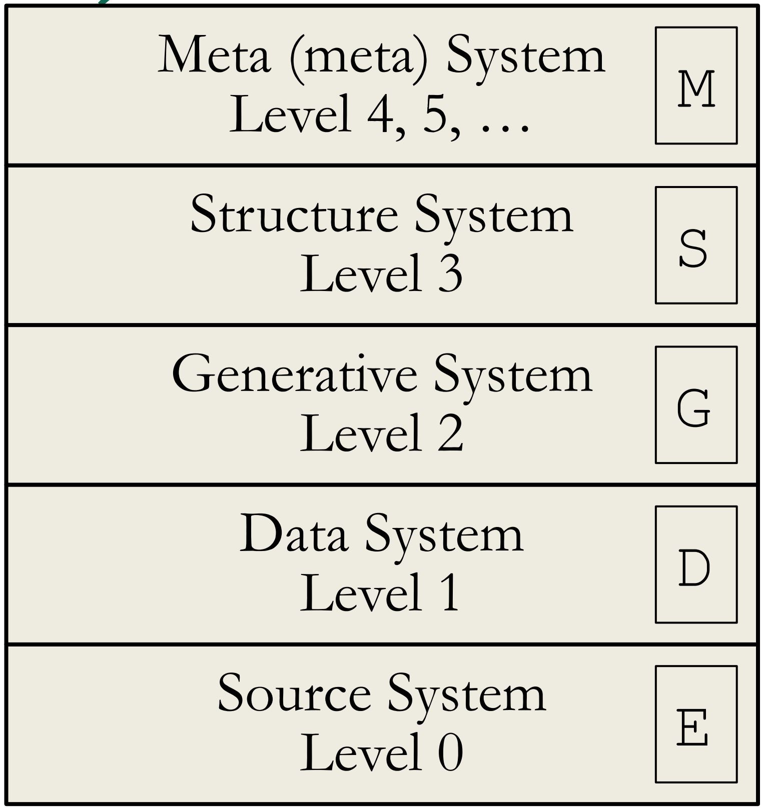
G, D, and E are all called "low-level" subsystems



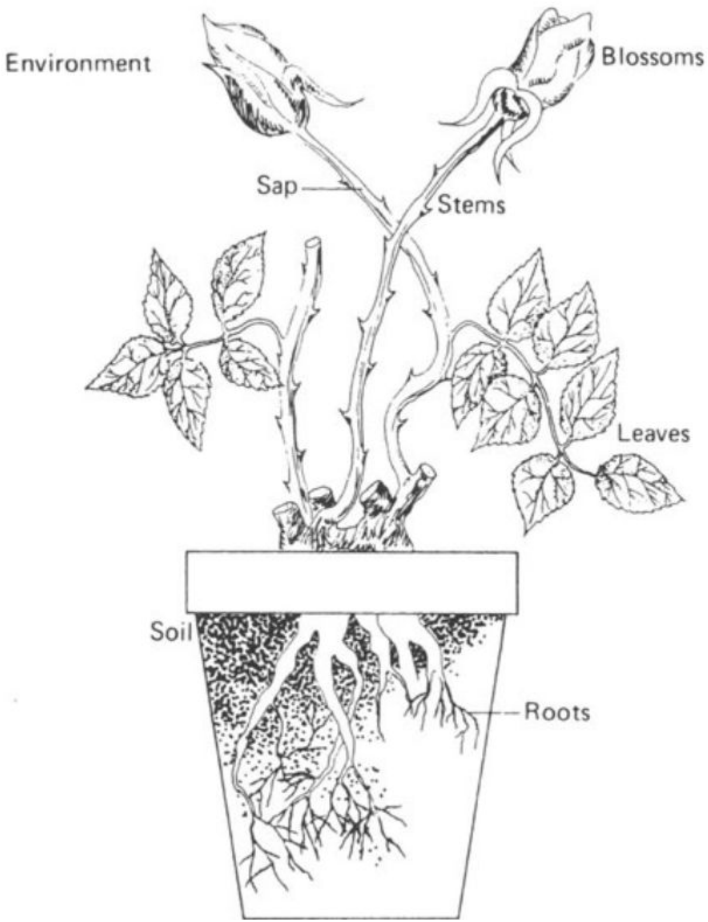
Meta Systems (M)

Set of Systems

Meta-characterization of the lower-level subsystems



Identifying Systems

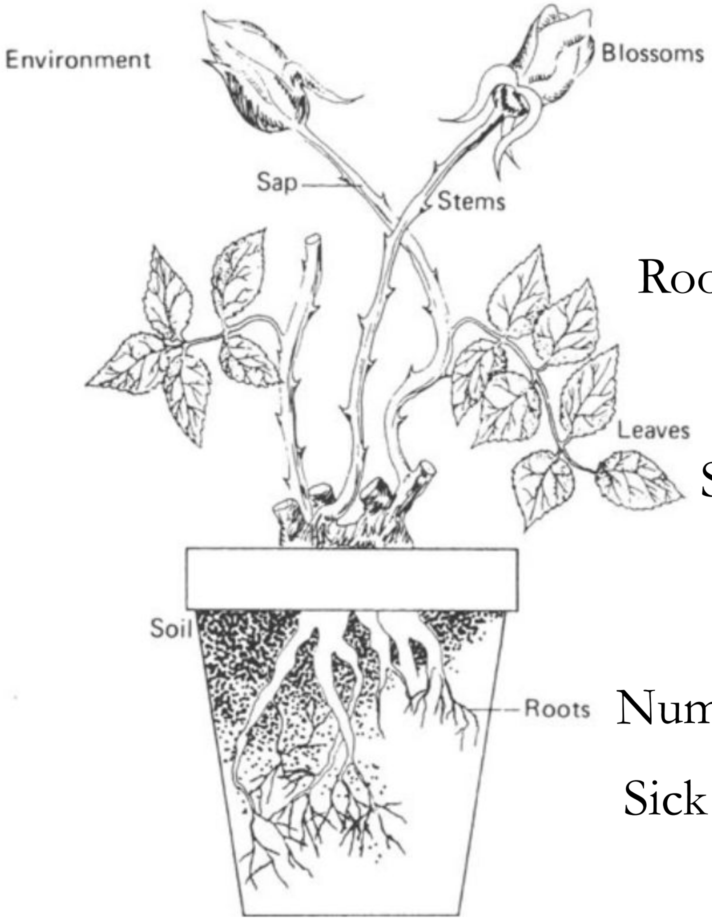


Architecture of Systems Problem Solving, 2002

Consider the system of a flower growing

We can call the whole potted plant a system

What subsystems can we define?



Architecture of Systems Problem Solving, 2002

We can begin by defining variables:

Root water absorption

Root mineral absorption

Stem sap-carrying ability

Soil moisture

Stem blossom density

Stem leaf density

Sap color substances

Sap odor substances

Sap growth substances

Leaf color

Number of leaves

Blossom color

Sick leaves

Blossom size

Number of blossoms

Air temperature

Rainfall

Average sunlight

We can group variables:

Sap
- Water absorption
- Mineral absorption
- Sap carrying
- Temperature
- Sunlight
- Sap color
- Sap growth
- Sap odor

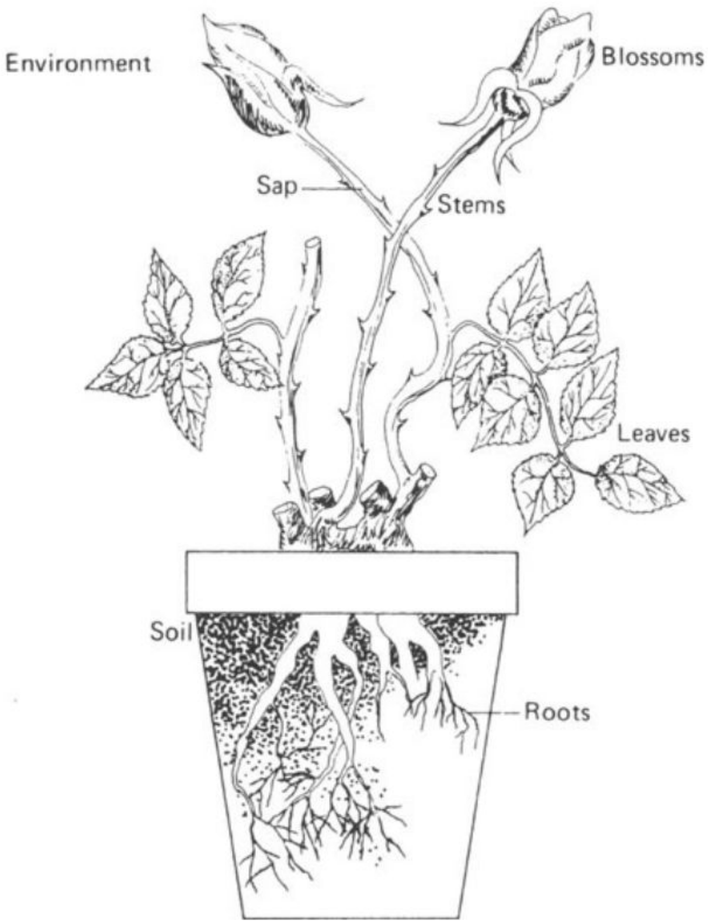
Roots
- Water absorption
- Soil moisture
- Mineral absorption

Soil
- Temperature
- Soil moisture
- Sunlight
- Rainfall

Leaves
- Leaf density
- Sick Leaves
- Leaf Color
- Sunlight
- Temperature
- Rainfall
- Num. Leaves

Stems
- Temperature
- Sunlight
- Mineral absorption
- Sap carrying
- Leaf density
- Blossom density
- Water absorption

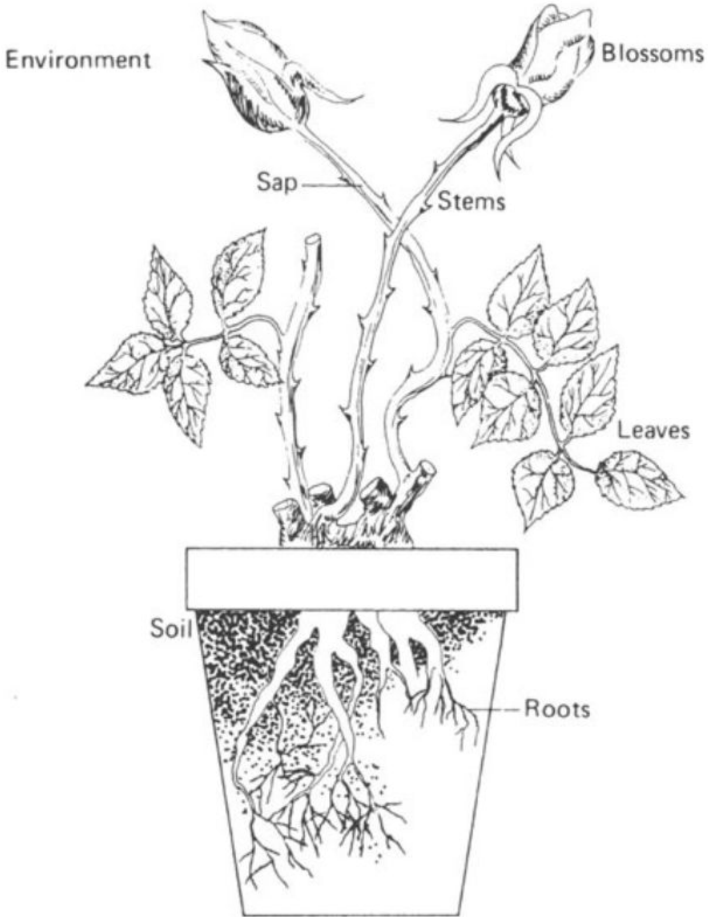
Blossoms
- Temperature
- Sunlight
- Blossom density
- Blossom odor
- Num. Blossoms
- Blossom color
- Blossom size
- Rainfall



Architecture of Systems Problem Solving, 2002

Our groupings create subsystems that are related:

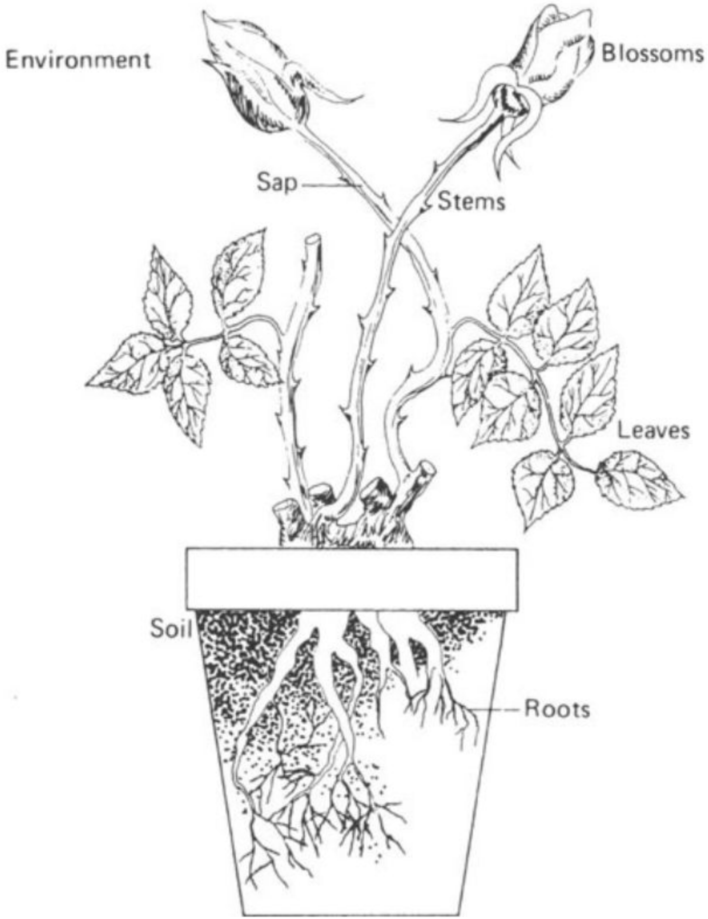
- Soil
- Roots
- Sap
- Stems
- Leaves
- Blossoms



Architecture of Systems Problem Solving, 2002

We see related groupings through shared variables (coupled variables)

- Sap, Roots
- Sap, Soil
- Sap, Leaves
- Sap, Stems
- Sap, Blossoms
- Roots, Soil
- Roots, Stems
- Soil, Leaves
- Soil, Stems
- Soil, Blossoms
- Leaves, Stems
- Leaves, Blossoms
- Stems, Blossoms



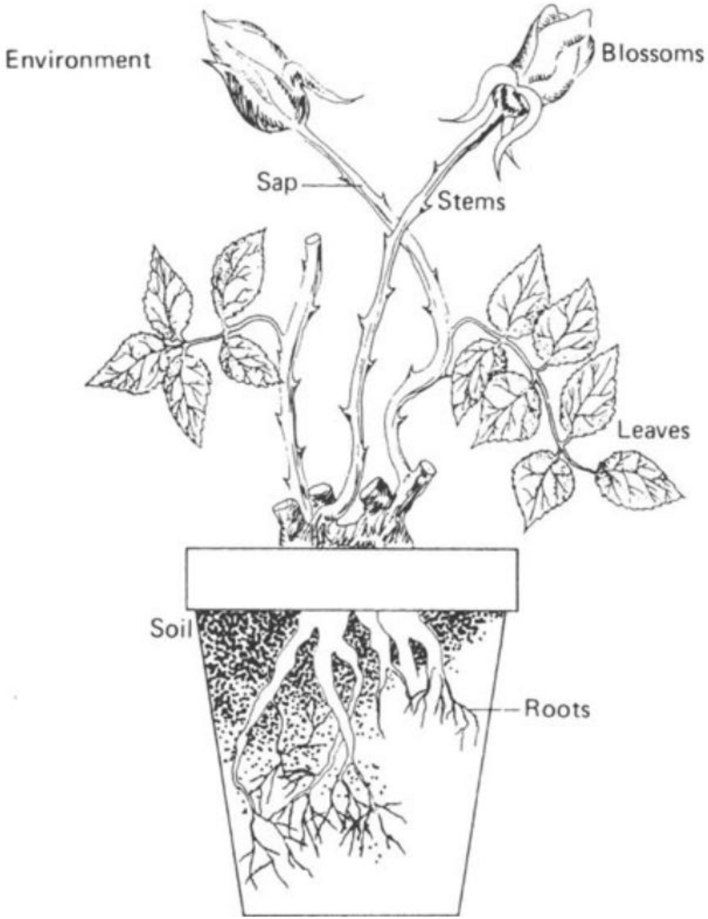
Architecture of Systems Problem Solving, 2002

Each group is a subsystem, and their relations now define a structure system

We could have grouped subsystems, like stems and roots

We can define other subsystems too, such as environment (temperature, rainfall, sunlight)

Or define more variables and repeat (humidity, stem length, etc)



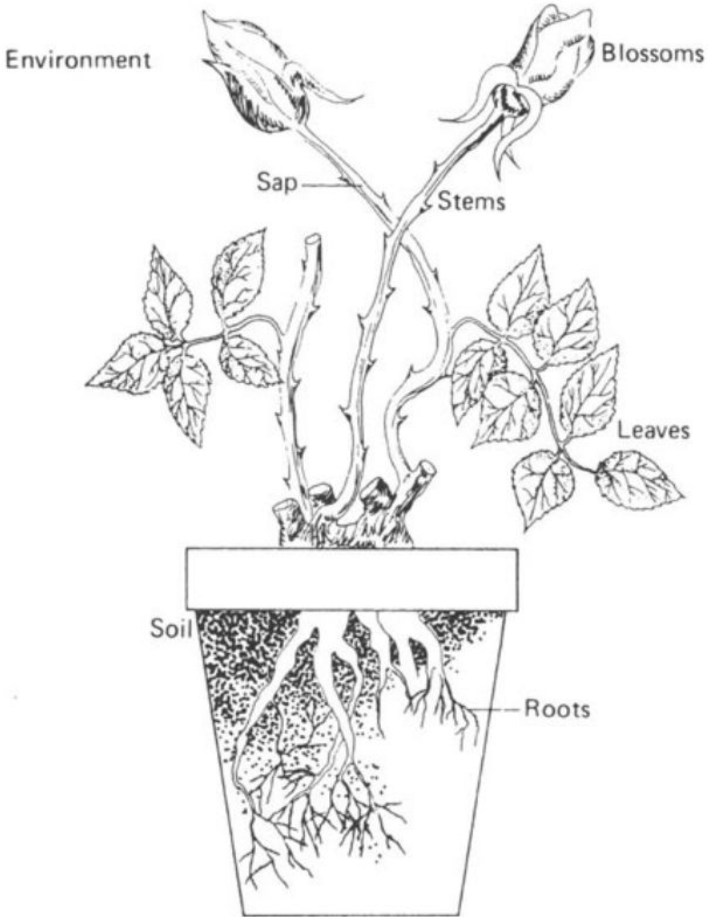
Architecture of Systems Problem Solving, 2002

We can also get more granular:

Define petals as a subsystem

Pollen? Thorns?

Look at the genetic level



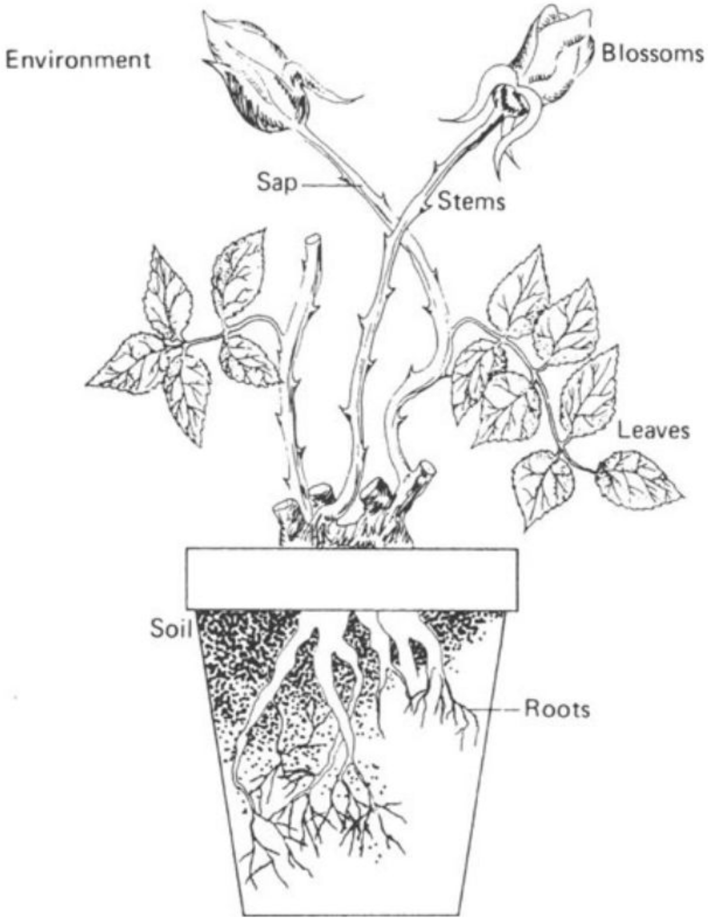
Architecture of Systems Problem Solving, 2002

Were the subsystems defined sufficiently?

Were any other ideas about defining subsystems good?

It depends…

What is your research question? What relationships are you studying? Your hypothesis?



Architecture of Systems Problem Solving, 2002

An elementary schooler at a science fair might only care about number of blossoms and rainfall

A florist might be interested in variables that affect blossom color and size

A botanist might look at genetic and environmental interactions on overall growth

Once the whole is divided,
the parts need names.

There are already enough names.
One must know when to stop.

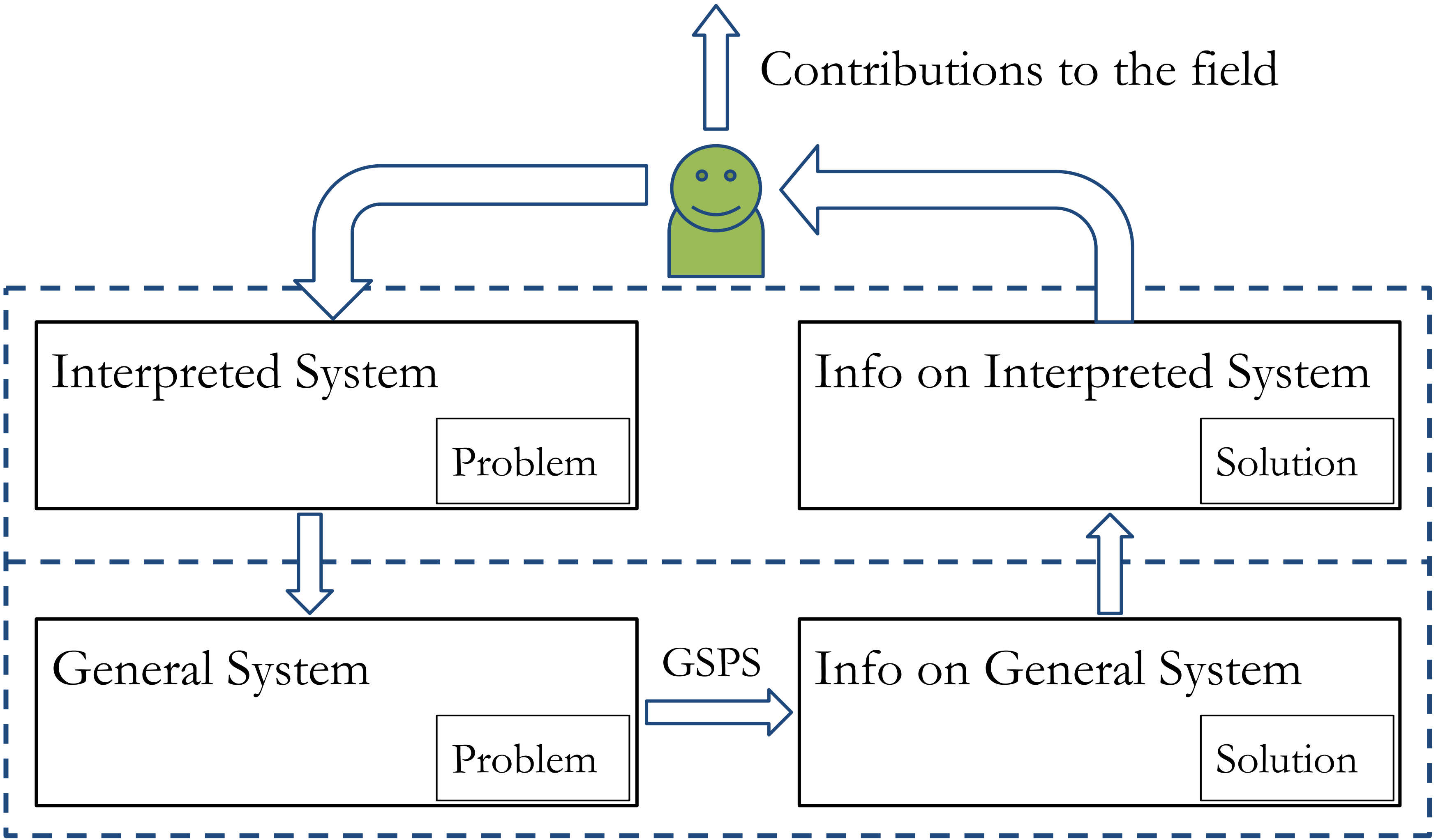
Knowing when to stop averts trouble.

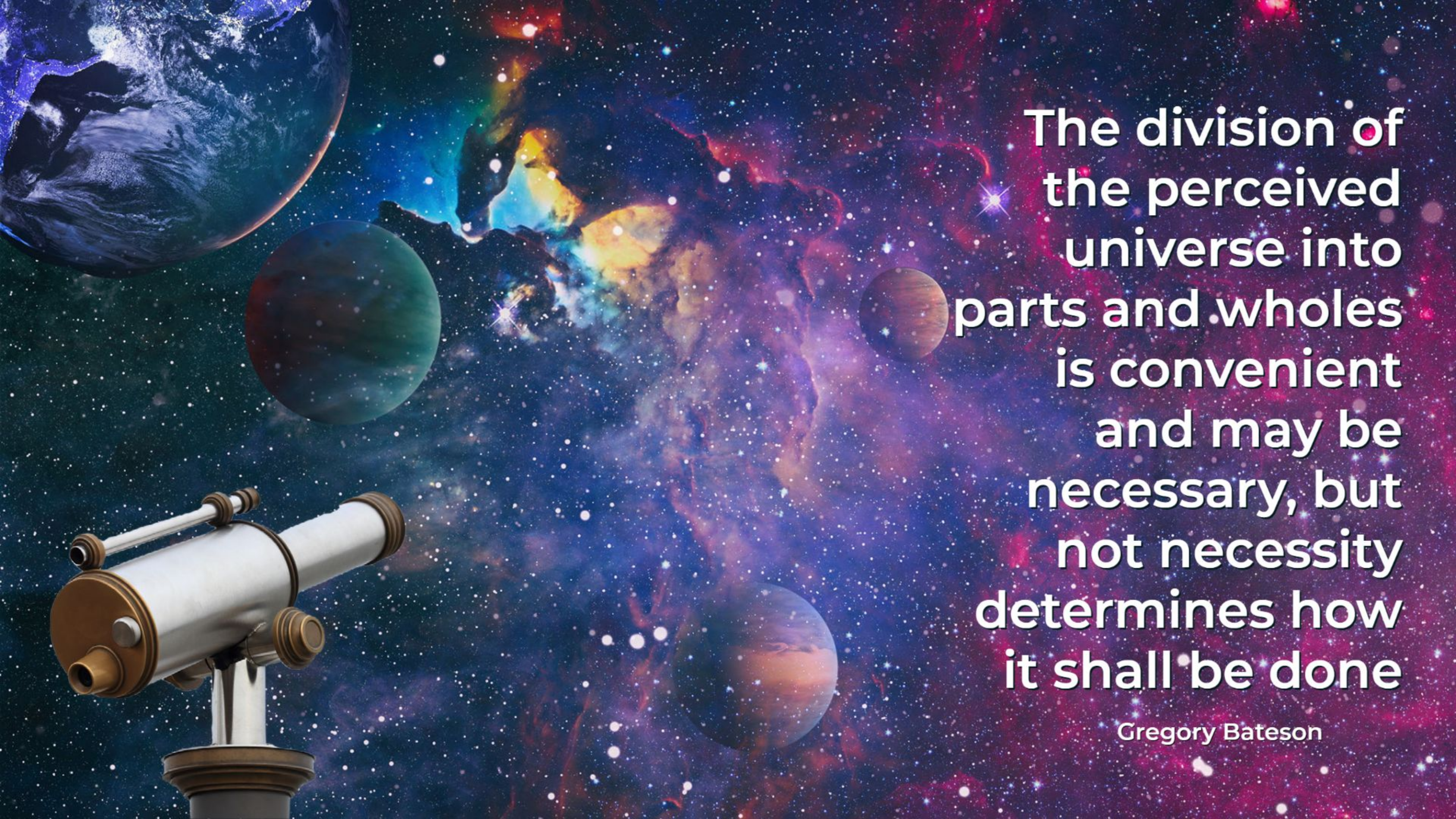
-LAO TSU

Architecture of the General Systems Problem Solver

GSPS

Recall GSPS is a framework that groups systems problems, and tools for solving them.


Contributions to the field
Interpreted System
Problem
Info on Interpreted System
Solution
General System
Problem
GSPS
Info on General System
Solution


The division of the perceived universe into parts and wholes is convenient and may be necessary, but not necessity determines how it shall be done
Gregory Bateson

GSPS Methods

Once Abstracted…

Depending on the model used, tools may already be developed

Here we will go over some tools

Networks

Sometimes features can be meaningfully extracted in a network

The field of study only cares about network properties, not what the nodes and edges represent

Computer Simulations

Represent the system to the best of your abilities

Collect more data, validation, prediction, etc

Information Theory

A key concept from information theory is *mutual information*.

It measures the dependence between two variables.

We can use this to aid in the mask analysis.

Information Theory

Say we want to check if two variables are "sharing information"

We treat both as random variables.

Random variables must contain:

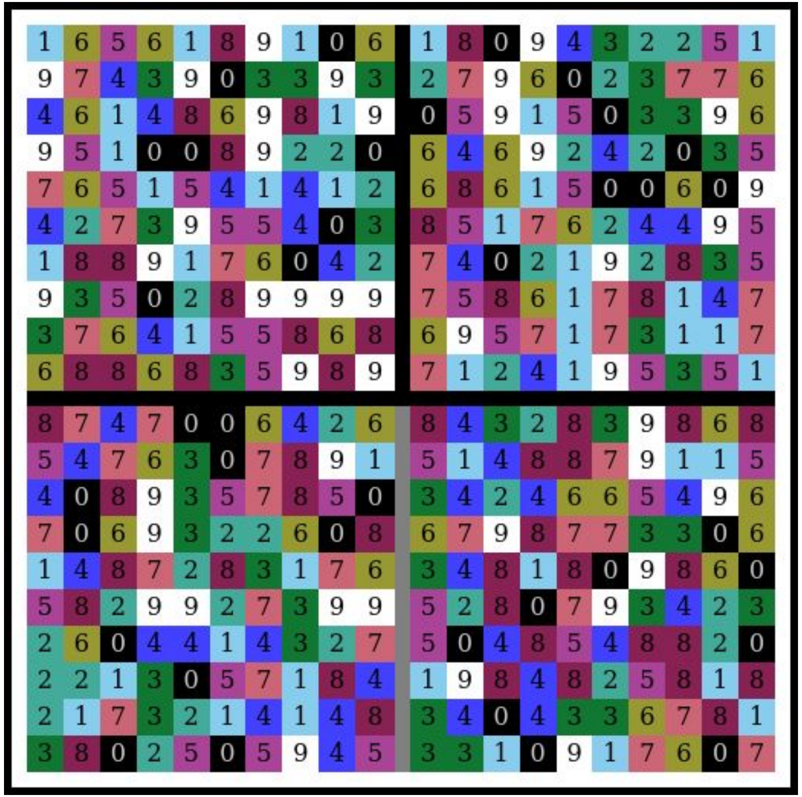
1. A set of outcomes
2. A probability for each outcome (that collectively sum to 1)

Information Theory

Our set of outcomes is defined in the source system.

To get the probabilities associated with each outcome, we have to collect some data.

Information Theory



We do not know the underlying mechanisms, so we have to sample.

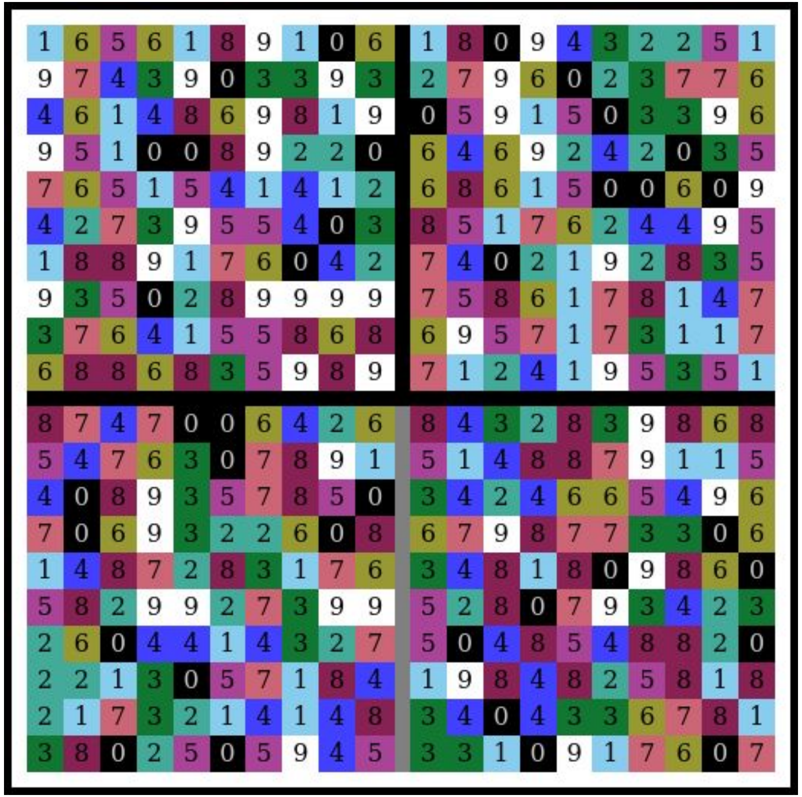
For any two cells, we collect data:

Value of cell 1 at time *t*

Value of cell 2 at time *t*

Values of (cell 1, cell 2) at time *t*

Information Theory



In our example, this gives us a probability of each value (0-9) occurring in cell 1 and 2.

We also have a *joint probability* of those two values occurring at the same time step.

Information Theory

We then go through the formula:

$$\sum_{a=0}^{9} \sum_{b=0}^{9} P(a,\ b) \cdot \log\left(\frac{P(a,b)}{P_1(a) \cdot P_2(b)}\right)$$

Where P(a, b) is the joint probability of cell 1 and cell 2 taking on those values

$P_1(a)$ is the probability of cell 1 having the value of a

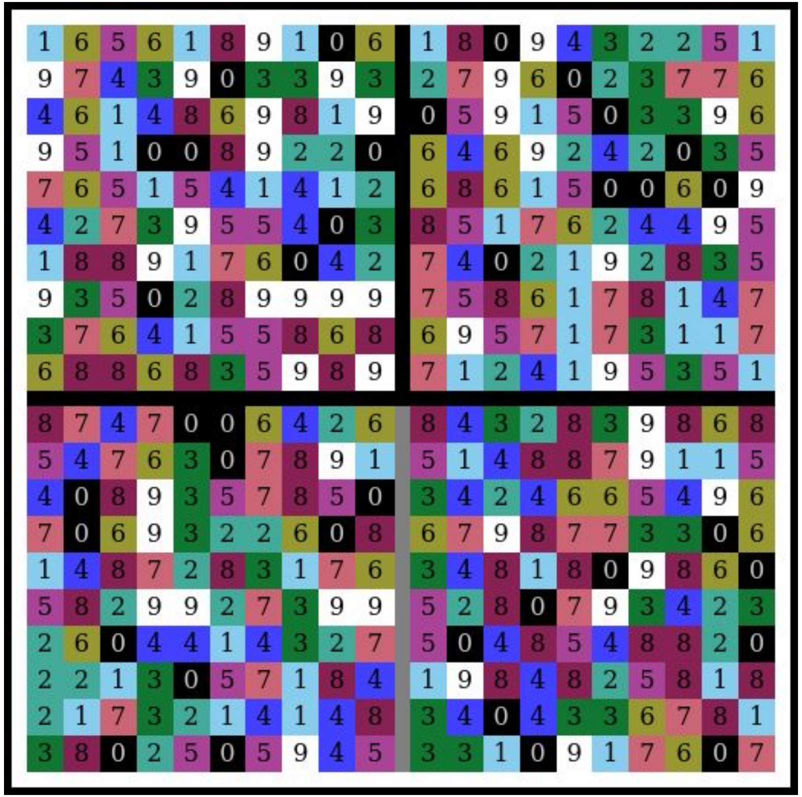
$P_2(b)$ is the probability of cell 2 having the value of b

Information Theory

What values are we looking for?

$$\sum_{a=0}^{9} \sum_{b=0}^{9} P(a,\ b) \cdot \log\left(\frac{P(a, b)}{P_1(a) \cdot P_2(b)}\right)$$

Information Theory



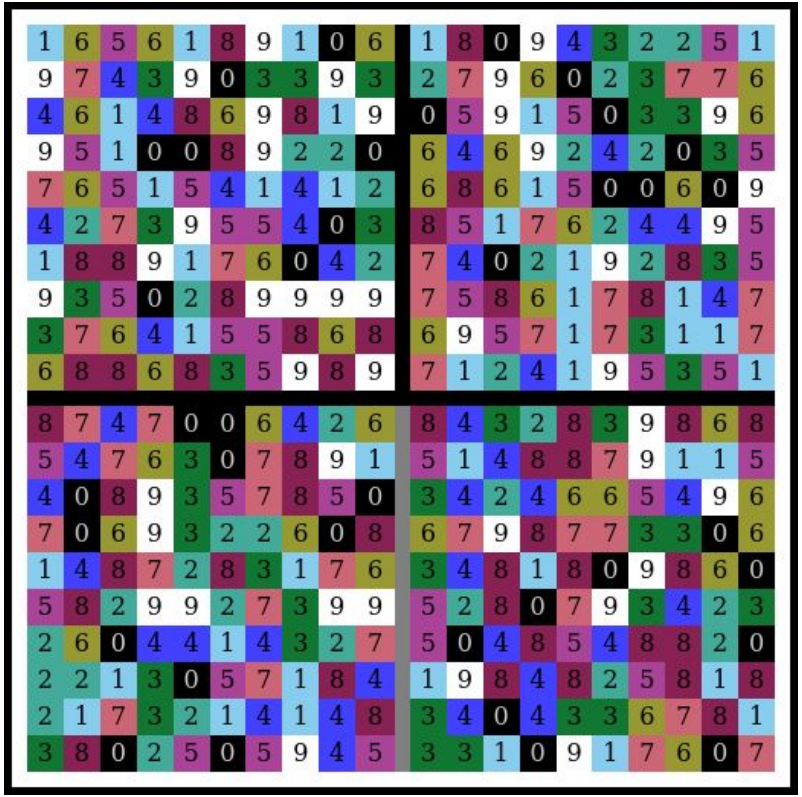
This can be extended to more than just two variables.

Groups of variables can be checked as well.

An outcome does not need to be a single value, we can define a probability of a set of cells taking on specific values.

This is more useful, but generally needs more data.

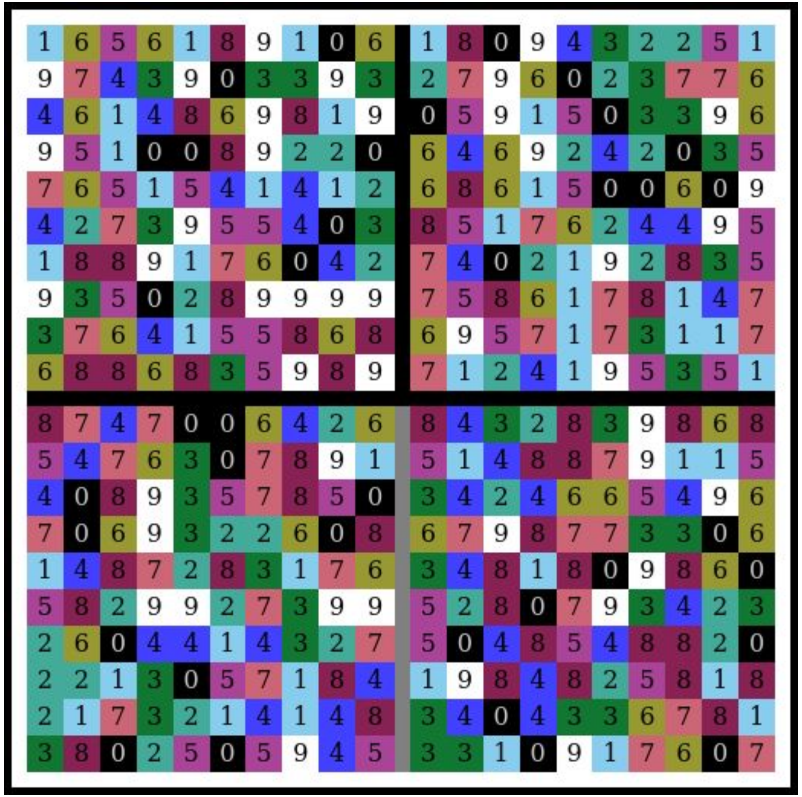
Information Theory



When dealing with a problem that looks like that 👈 it is common to call a mask a "kernel" instead.

The kernel checks a cell's neighbors to see if their values influence its value (in addition to that cell's value).

Information Theory

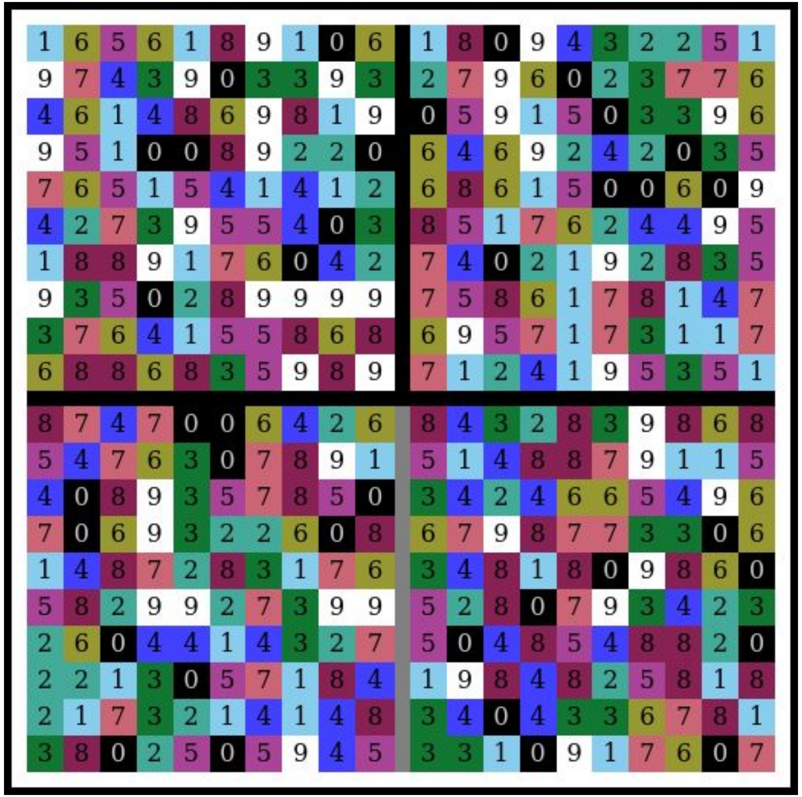


S_1	S_2	S_3
S_4	S_5	S_6
S_7	S_8	S_9

$S_5 = f\ (S_1, S_2, S_3, S_4, S_5, S_6, S_7, S_8, S_9)$

We can also change the shape of the neighborhood of S_5, and its radius

Information Theory



This is not the way. This is a way.

Isomorphisms

If an abstraction is isomorphic to a previously solved problem, a general solution already exists. Apply it!

Power of Abstraction

If you need to develop tools yourself, you at least have an idealized abstraction

Power of Abstraction

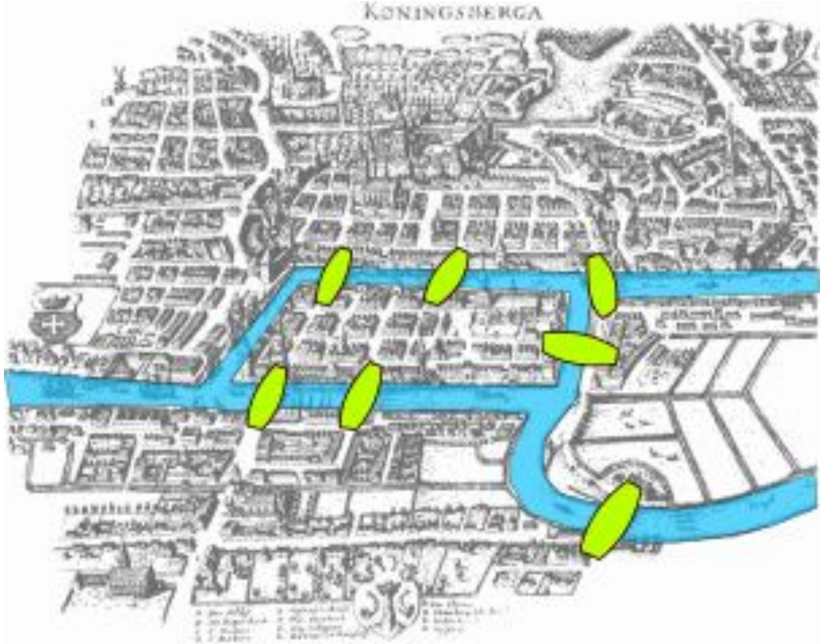


Image from Wikipedia: Seven Bridges of Königsberg

Power of Abstraction

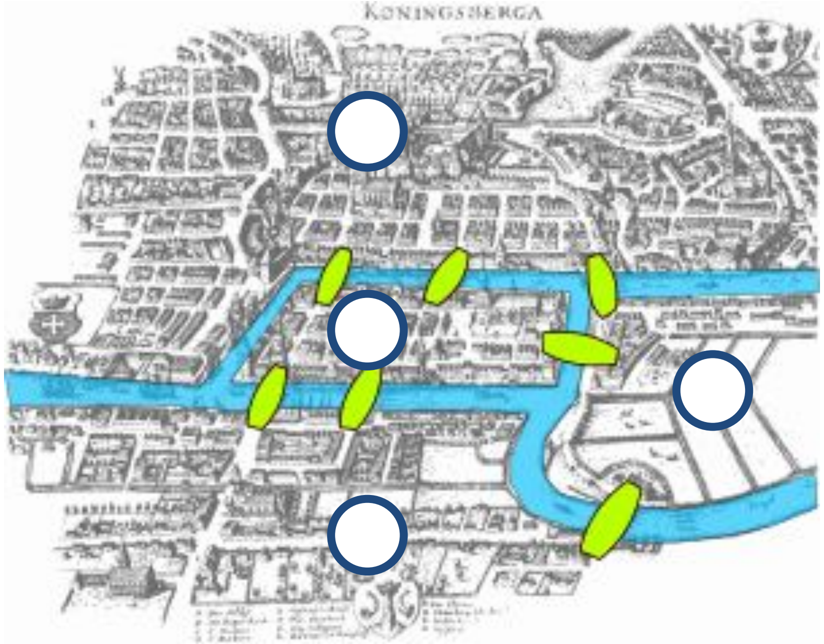
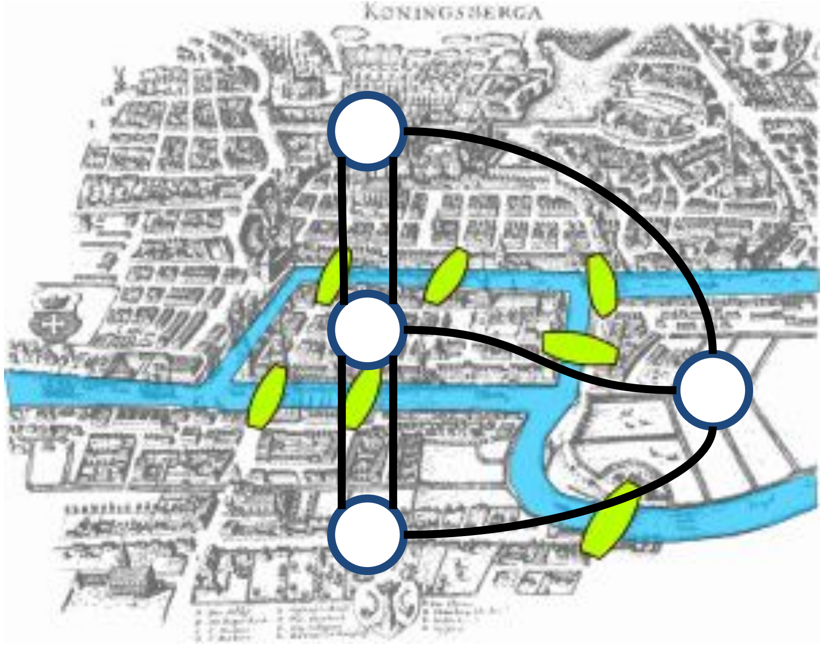


Image adapted from Wikipedia:
Seven Bridges of Königsberg

Power of Abstraction



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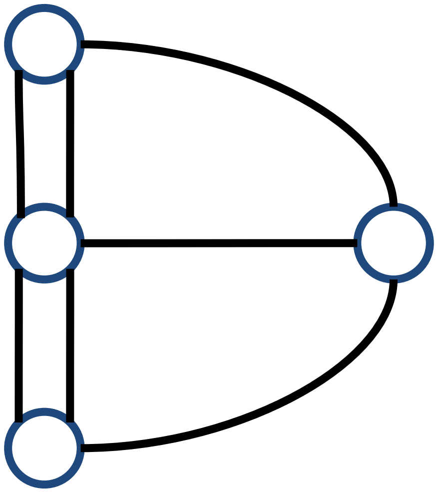
Power of Abstraction



Reconstructability Analysis

More of a class of methodological tools in GSPS

Find a relationship between the overall system and its subsystems

Reconstructability Analysis

There is an *identification* problem, and a *reconstruction* problem

Identification starts with a generative structure system

Reconstruction starts with a generative system

Reconstructability Analysis

We are either identifying the subsystems that make up the whole, or reconstructing the whole based on given subsystems

Reconstructability Analysis

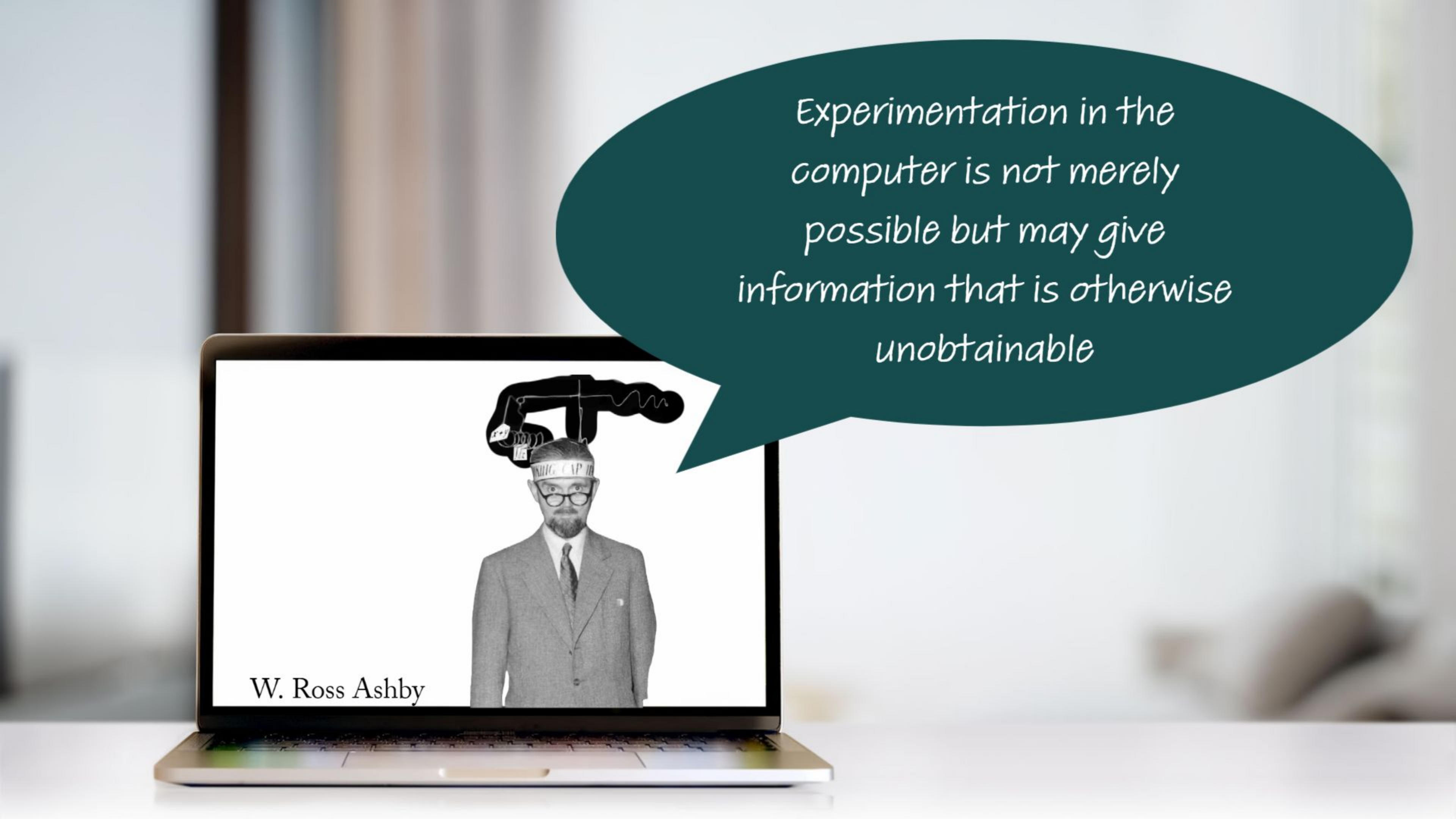
"Reconstructability analysis is just one example of an important methodological area which would have no practical significance without the aid of sophisticated computer technology. Such examples are not rare in systems problem solving; on the contrary, they are rather typical."

-Klir in *Architecture of Systems Problem Solving*

Reconstructability Analysis

One example of RA that heavily relies on computer tools is a model distance.

Run a simulation, then compute "how far away" the simulation is from the real system.


Experimentation in the computer is not merely possible but may give information that is otherwise unobtainable
W. Ross Ashby

GSPS Concerns

Interpreted to General

Need to have enough domain specific knowledge to know what features are important

Interpreted to General

What if variables are not sufficient?

Missing key information about the model

Interpreted to General

Too many variables?

Expensive computation

Some methods will simply not work with certain data

General to Interpreted

Need to know about the tools you are using to interpret the solution in the context of your system

What is the interpretation of a shortest path in your network? Is 3.12 bits of entropy large or small for your problem?

Other Considerations

Your model *must* make sense

You can define a network on anything, but certain metrics are only coherent in certain contexts

Other Considerations

We also have different properties of systems:

Stochastic vs Deterministic

Memory

Organized vs Disorganized

Open vs Closed

…and so on. What properties does your system have?

Other Considerations

Two functions might *look* the same, but the mechanisms are completely different.

This is different from an isomorphism

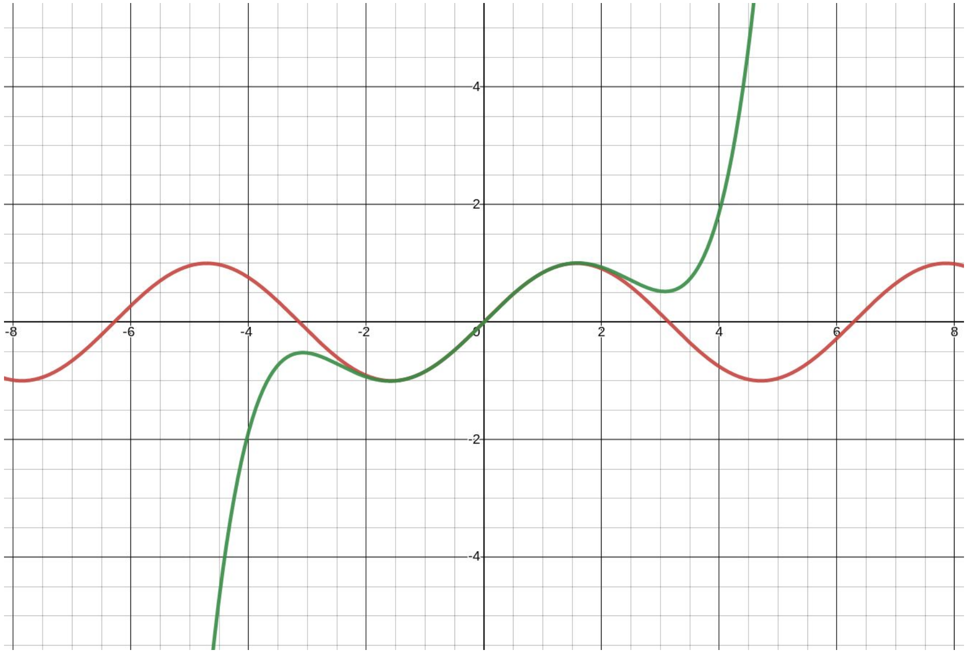
Other Considerations

Why might this occur?

1) Lack of data

(short observation time)

2) Bad validation



All models are wrong, but some are useful.

-George Box

Connection to Machine Learning

Building a Model

Machine learning is a way to use data to "learn" a task: classification, regression, generation, etc

We can use methods such as linear models, decision trees, symbolic regression, artificial neural networks (ANNs), and more

Selecting a Model

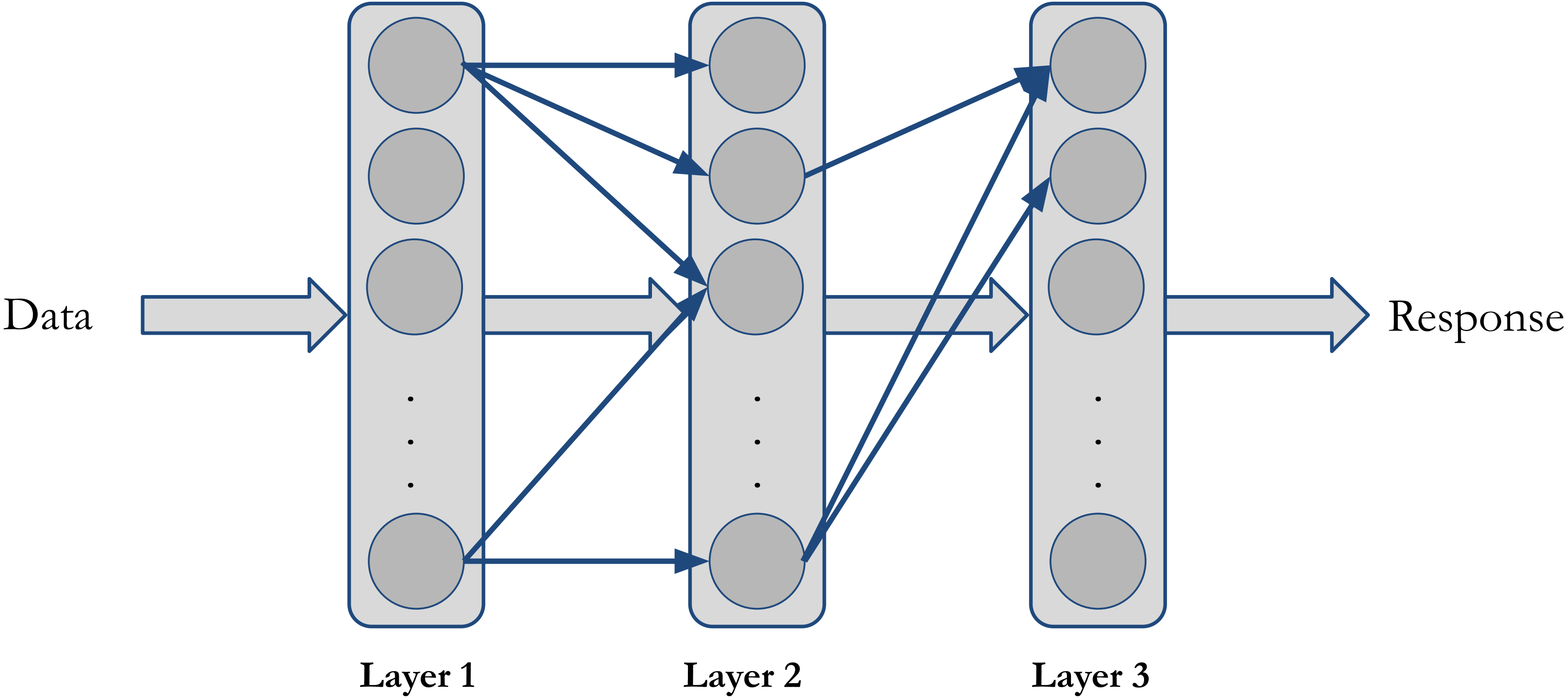
Each model is different

Regressions/linear models require data transformations and an intelligent way to select a specific equation form

Decision trees, ANNs, and symbolic regression are data hungry and require some hyperparameter tuning

ANNs also require selecting an architecture

ANN Overview



Mask Analysis

Just like with mutual information, we can use ML methods to deduce relationships between our variables

Thinking back to the kernel example of:

$S_5 = f\ (S_1, S_2, S_3, S_4, S_5, S_6, S_7, S_8, S_9)$, we can learn a function f

Or learn a function based on other inputs. Can we get a good fit with the data we collected?

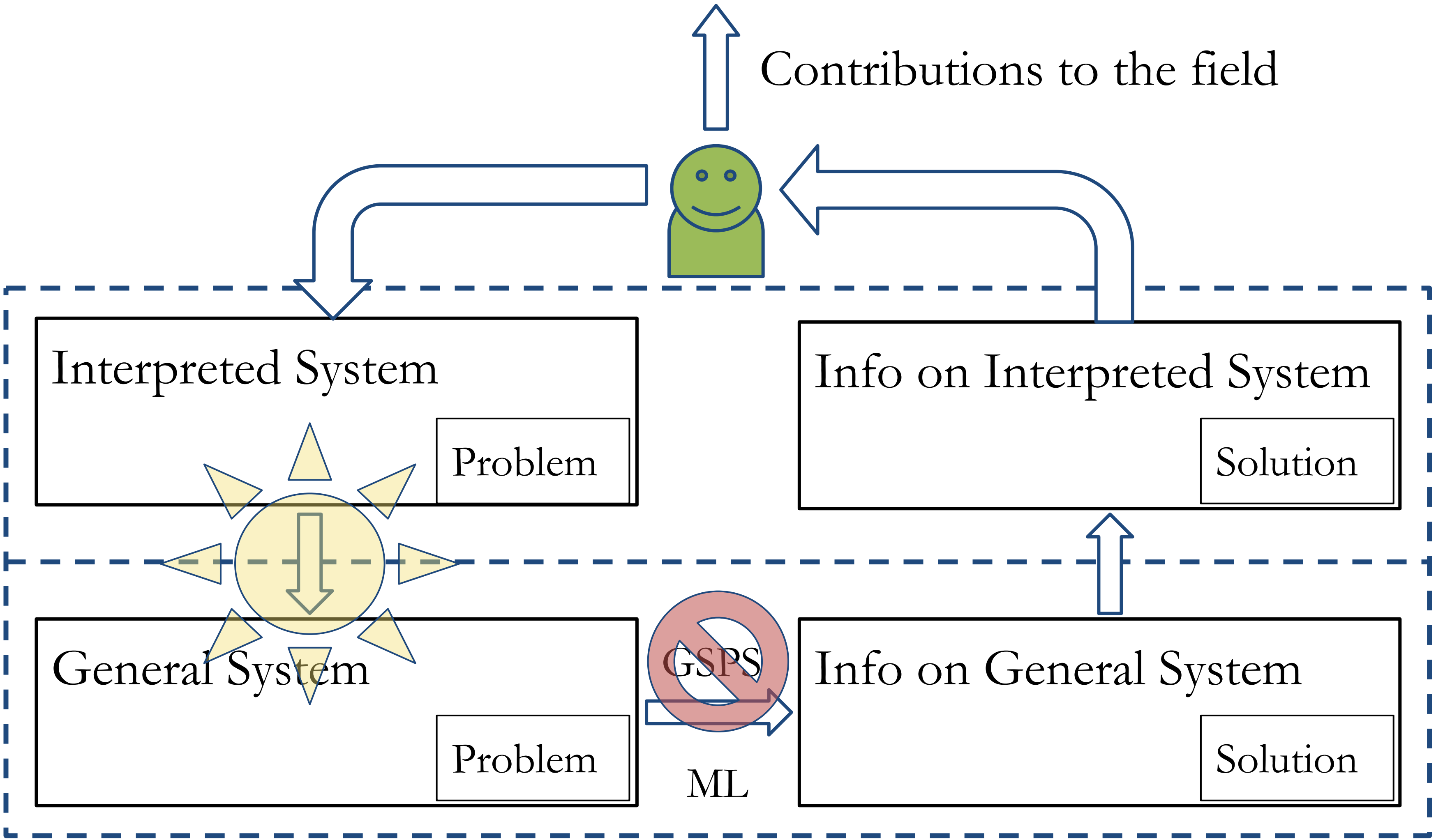
Mask Analysis

Be aware of other issues:

We can *overtrain* models where it fits training data extremely well, but underperforms on testing data

Need to perform other analyses to figure out which variables were important to the function *f*

This can take a long time, especially if performing an exhaustive search

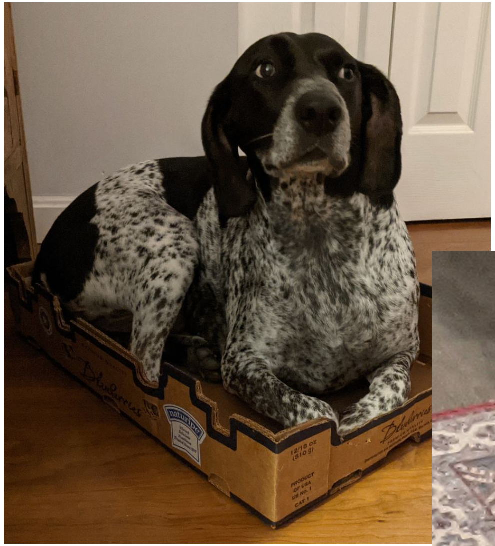

Contributions to the field
Interpreted System
Problem
Info on Interpreted System
Solution
General System
Problem
GSPS
ML
Info on General System
Solution

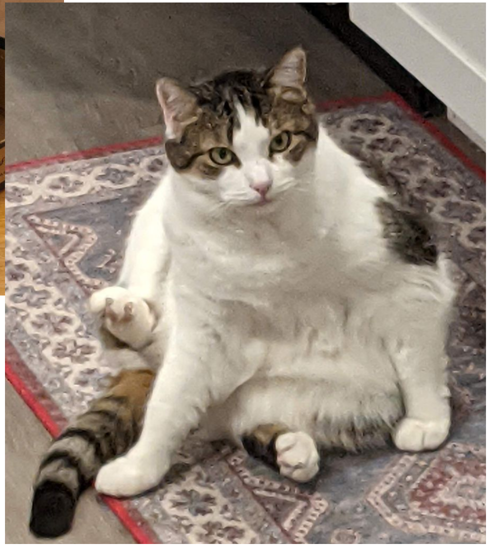
What Data is Available?

A lot of data is available from websites (Kaggle, etc), published papers, and elsewhere.

Or run experiments, collect observations, scrape data to get your own

Data Representation





Each image is a matrix of pixels that are easy for us to understand

We can instead represent images as a matrix of pixel ID and their RGB values

Pixel	R	G	B
1	50	100	20
2	55	120	18
…	…	…	…

Data Representation

"Monte Cristo remembered that on that very spot, on the same rock, he had been violently dragged by the guards, who forced him to ascend the slope at the points of their bayonets."

Excerpt from *The Count of Monte Cristo* by Alexandre Dumas

Text is unstructured data

We can pull features such as *n*-grams and count occurrences

Each row in a matrix is a document (piece of text) and each column counts the number of these features

Document	"that"	"on"	"Monte"	"Monte Cristo"	…
CoMC	2	2	1	1	…
…	…	…	…	…	…

Data Representation

Respondent	Q1	Q2	Q3	…
Respondent 1	yes	1	a	…
Respondent 2	yes	2	b	…
Respondent 3	no	2	c	…
Respondent 4	no	2	d	…
…	…			…

We might already have a matrix in the event of survey responses

Data Representation

See the theme?

We can abstract data into a matrix representation by pulling meaningful features from the data we want to learn from


ML
Methods
Matrix
Representations
of Data
Image adapted from @cottonbro

A Metaproblem

A problem: we might have another black box

Some methods are easy to interpret: by looking at coefficients in a regression equation, we can see how much of an effect each variable has on the response.

A Metaproblem

A problem: we might have another black box

In an ANN, it is difficult to interpret what edge weights mean in context

However, there is a field of explainable AI (XAI) working on these kind of problems


GARBAGE IN,
GARBAGE
OUT

Summary

This can also be seen as a general way to perform scientific modeling/research

Think critically about your problem and the methods you want to use!

Sources

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- Torres, Leo, Ann S. Blevins, Danielle Bassett, and Tina Eliassi-Rad. [2021] "The Why, How, and When of Representations for Complex Systems." *SIAM Review* **63**(3): 435–85.

Science is a continuous living process...Science differs from mere records in much the same way as a teacher differs from a library

– G Spencer Brown

Questions?

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