Building Economic Models of Human-Computer Interaction Part III

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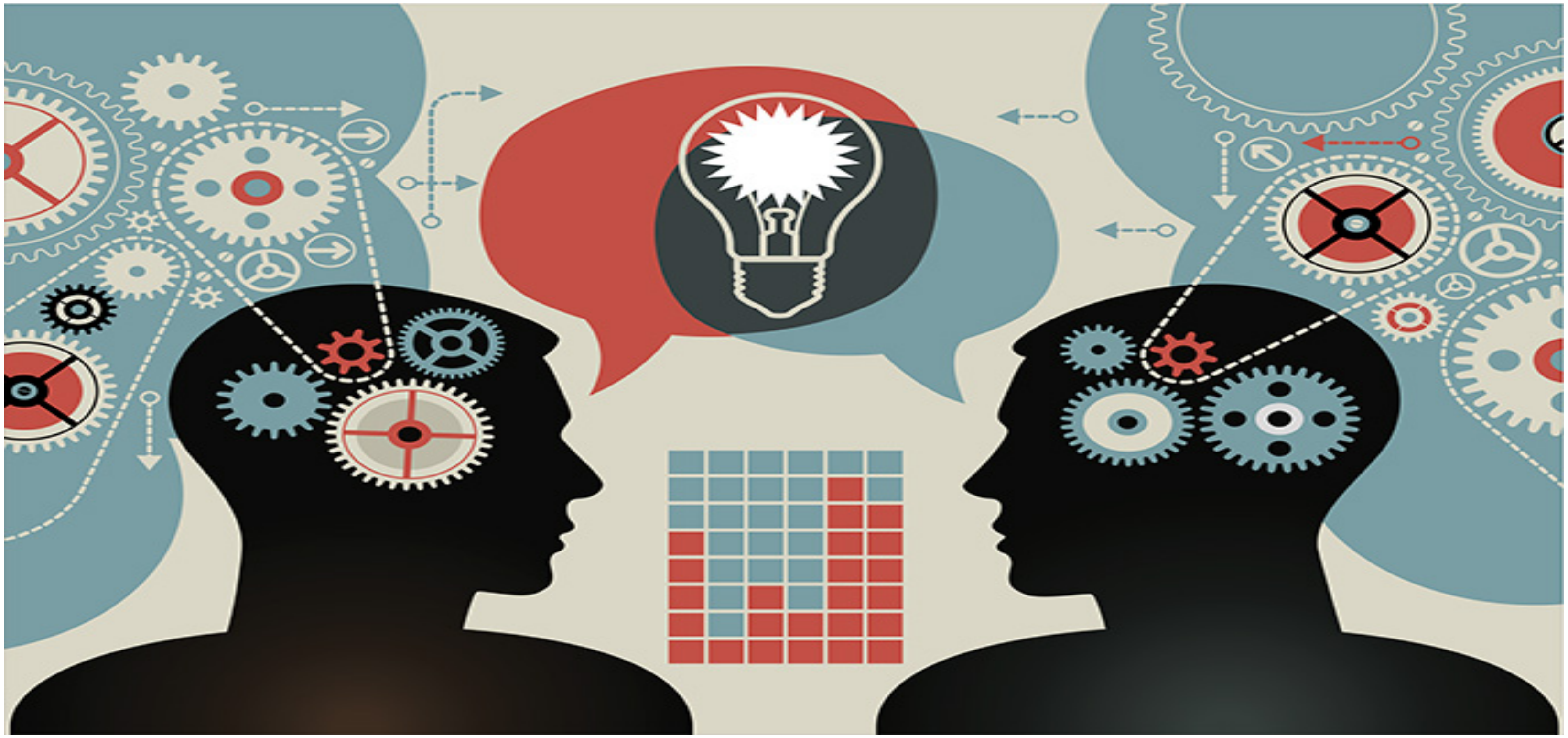


SENSE MAKING & COST STRUCTURES

Sensemaking & Cost Structures

- **Sensemaking** is the **process** of:
  – searching for information,
  – encoding that information within a representation
  – to answer task specific questions.
- **Representations**
  – Provide a way to consume the information
  – Some are more efficient than others.
  – It is assumed that representations are chosen/changed to reduce the cost of information processing to the user

Russell et al (1993)

Costs & Interactions in Sense making

- Performing an **information rich task** requires internal **cognitive resources** and **external resources** (storage and computation)
- To carry out a **task** requires a series of **operations**
  - Each **operation** requires particular **resources** (**costs**) and provide a certain **benefit** (**utility**)
- These factors and the trade-off between methods for sensemaking affect the choices made by the user.

Russell et al (1993)

Learning and Sensemaking

- **Sensemaking** and the **retrieval** of **information** form a key part of the **learning process**
- The way a person represents the information affects how they
  - **understand**, **store**, **access** and **use** that **information**
  - for particular tasks or activities.
- It is assumed that people **revise** their **representations** to:
  - **reduce** the **time/cost** of performing overall tasks
  - **improve** the **cost** versus **quality trade-off**

Russell et al (1993)

Learning and Sensemaking

- The **speed** at which a **person** can **learn** something depends up the representations they can find/create and access/update.
- The **speed** at which they can
  - **accomplish** a **task depends** on
  - how **efficiently** they can **use** the **information/knowledge** that they have and
  - how well they have encoded it.

Russell et al (1993)

Learning and Sensemaking

- How do we compare different systems designed for sense making?

- New technologies may change the effectiveness and/or the efficiency of the overall process.

Russell et al (1993)

Optimization

- **Cost** is defined as the cost of sensemaking plus the cost of the task
- **Gain** is defined as the increase of the quantity of work performed, or quality attained by using a particular method
- Optimization rule **maximise** the **expected gain** to **cost ratio**

Russell et al (1993)

Types of Tasks

- **One-off tasks**: sensemaker chooses method to maximize the expected gain given a fixed cost or fixed time limit

- **Recurring Tasks**: sensemaker attempts to maximize their long-term rate of gain over many task cycles.

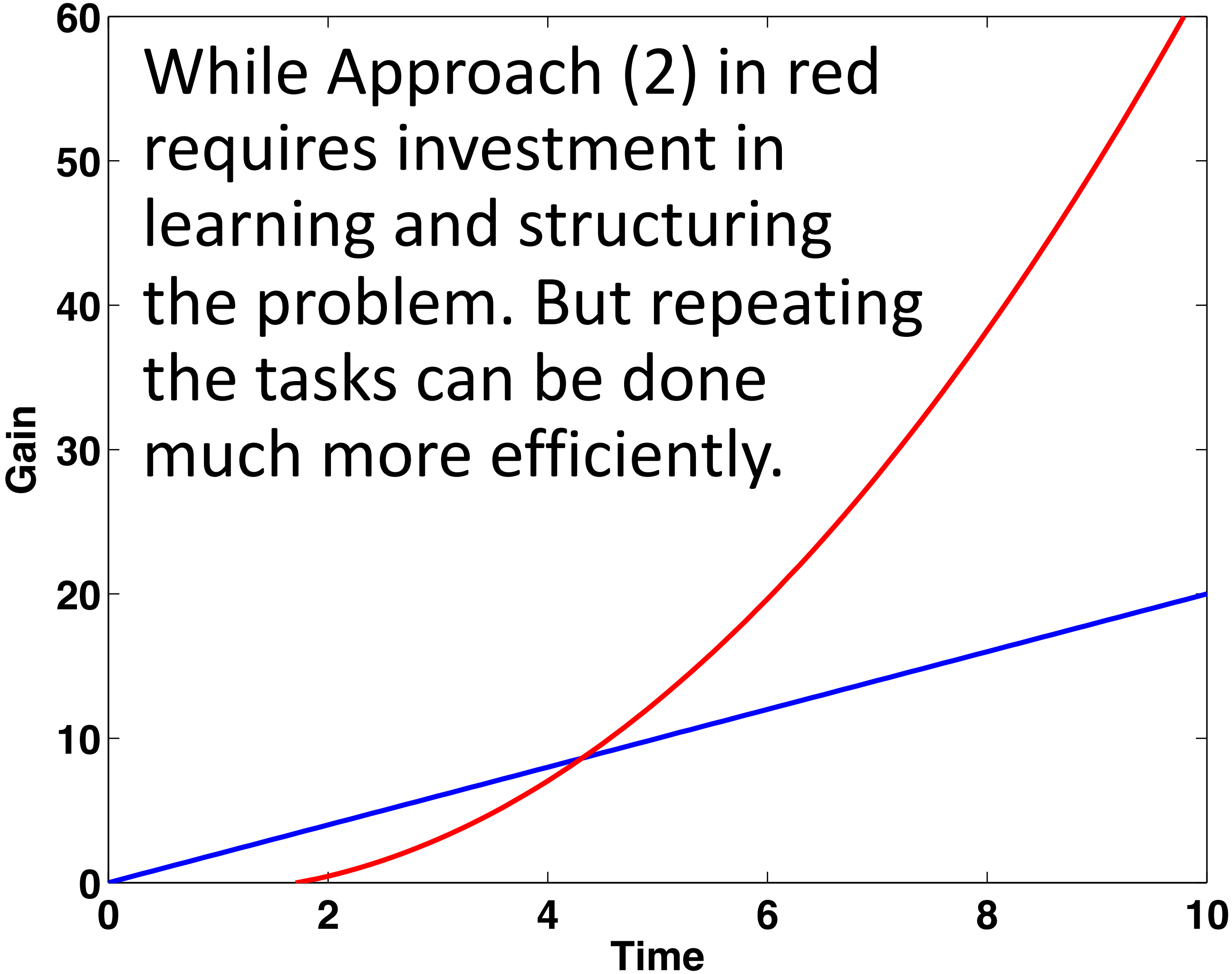
Russell et al (1993)

Example: To script or not to script?

- Imagine that you want to run a batch style experiment where you need to create a parameter file specifying the collection, retrieval model, the model parameter b, etc.
- **Approach 1:** manually create the file and run the retrieval app.
  - Repeat for as many different variations as needed.
- **Approach 2:** write a script to generate these parameter files, etc.
  - Need to learn how to script, search for code snippets, make sense of the experiment space, etc.

Russell et al (1993)

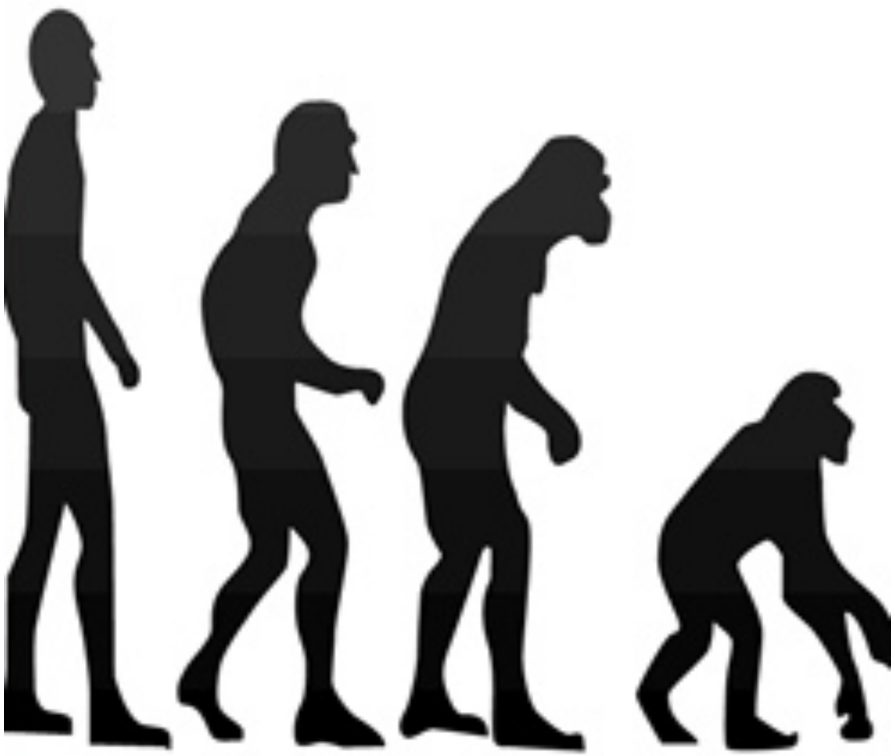
Insights from Sensemaking

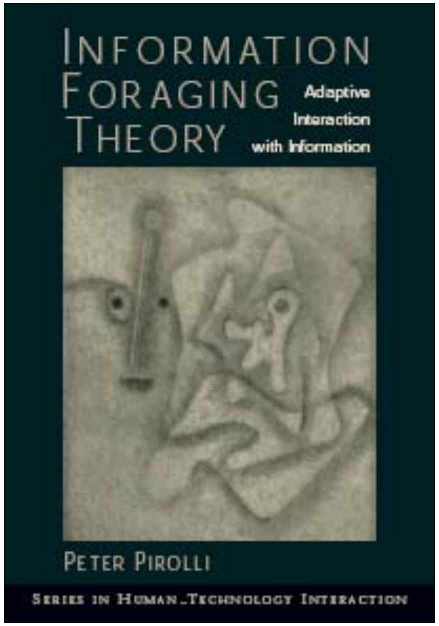


While Approach (2) in red requires investment in learning and structuring the problem. But repeating the tasks can be done much more efficiently.

Approach (1) in blue means that the task takes a linear amount of time to complete. The work performed is proportional to the time.

Russell et al (1993)





INFORMATION FORAGING THEORY

Optimal Foraging Theory

- **Foraging theory** aims **to understand** the **rules** that **shape** the foraging **behavior** of animals.
  – A key assumption is that animal aim to **maximize** the **energy gain per unit of time**, as this resource is likely to increase their chances of survival and reproduction.

For a good overview of OFT see Sinervo (2006)

- Foraging Theory has been proposed by a number of researchers including:
  – Resnikoff (1989), Russell et al (1993), Sandstrom (1994), Pirolli & Card (1999), Sandstrom (1999)

Currency

$$\text{Profitability of prey} = \frac{\text{Energy per prey item} - \text{Cost to acquire prey}}{\text{Time taken to acquire prey}}$$

Where,

$$\text{Time taken to acquire prey} = \text{Search time} + \text{Handling Time}$$

Key Constraints

- **Temporal Constraints**
  - The time it takes to find and process food.
- **Energy Constraints**
  - The metabolic cost of each foraging activity per unit of time.
- **Cognitive Constraints**
  - The amount that can be remembered and learnt about the environment.
- **Processing Constraints**
  - The size of prey that can be processed.

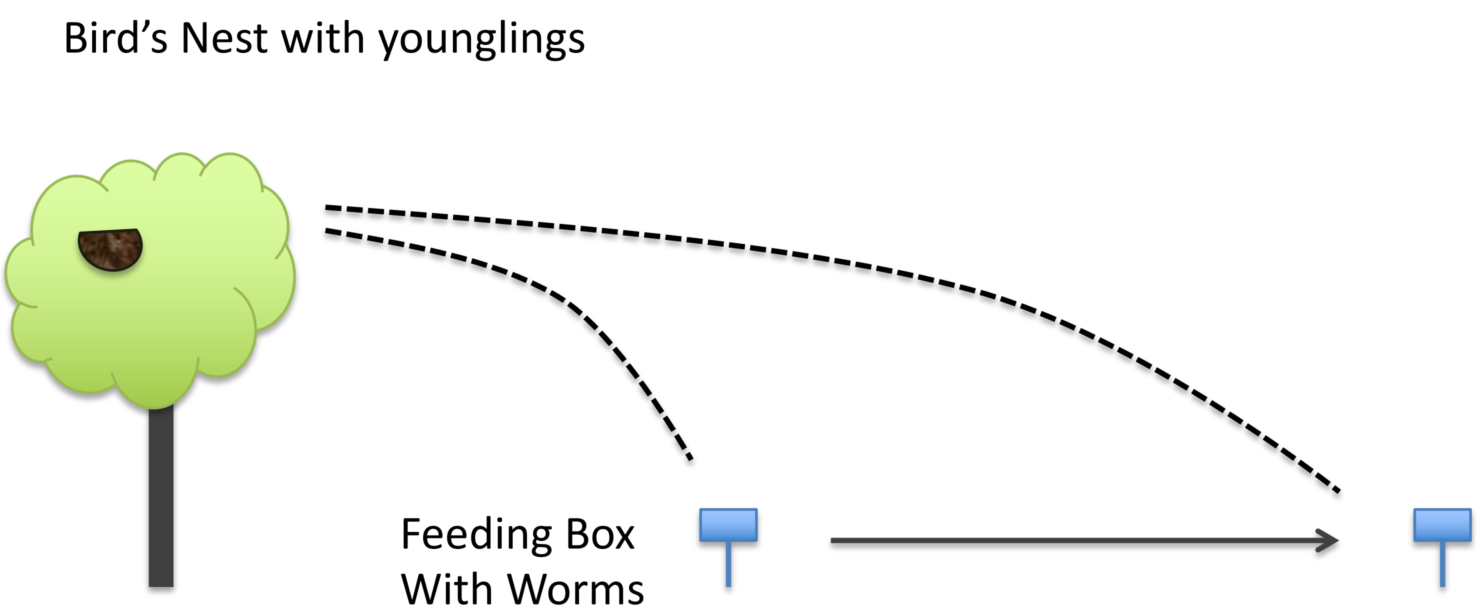
Example

Example

A mother bird needs to forage food for her chicks.

She will stay longer in patches that are further away, and collect more worms before returning.

Each additional worm gets hard to catch!



Information Scent Model

- Describe how foragers follow information cues to find patches with relevant information.
  - If there is a strong scent foragers are able to more directly to a patch, otherwise moves are more random.
- Aims to explain how people identify the value of information based on cues.

Chi et al (2000)

Chi et al(2001)

Information Diet Model

- Describes how foragers decide which information to use/consume
  - What information sources should be used, or consumes?

- If a **forager** is too **generalized**, then they will **waste** too much **time** on **handling** unprofitable information
- If a **forager** is too **specialized**, then they may **waste** too much **time** **searching** for profitable information

Information Patch Model

- Describe how foragers move between and within information patches.
  - When information is distributed in a number of patches the forager needs to decide which patch to go to, and how long to stay in a patch
- Predicts the amount of time a forager would/should spend within a patch
  - Assumes that the forager will go the patch that they expect to yield the highest profitability, first then next.

Information Foraging Theory

- **People** will **modify** their **strategies** or interface, in order to **maximize** their **rate** of gaining **valuable information**.

- **People** will **learn** over time through their interactions with the environment.

Resnikoff (1989)

Russell et al (1993)

Pirolli & Card (1999)

Information Foraging Theory

- There is an expectation that **information systems** will **evolve** so as to **maximize** the **gain** of **valuable information per unit cost**.

- **Evaluation:** One strategy or interface is superior to another if it yields more valuable information per unit cost.

Russell et al (1993)

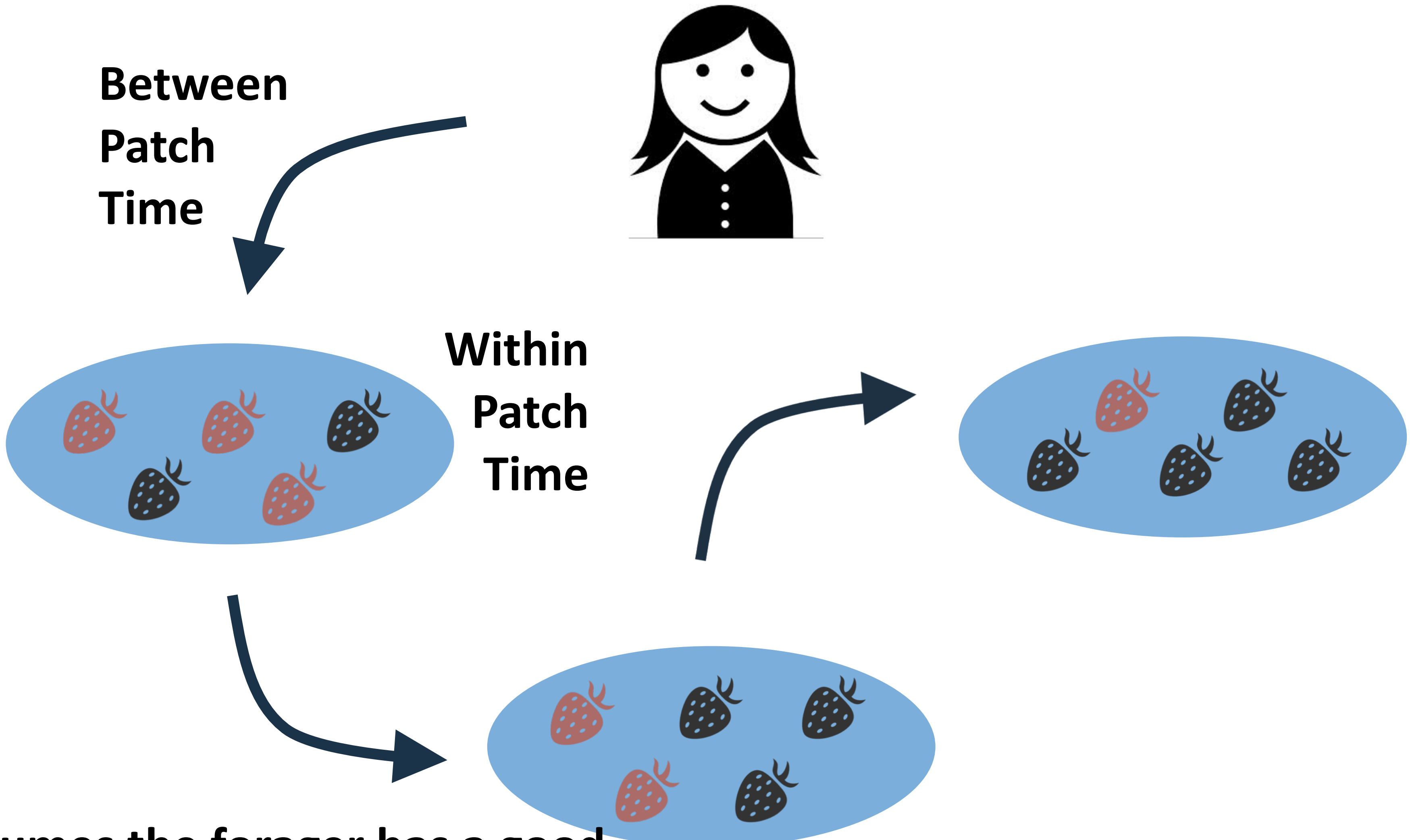
Resnikoff (1989)

Pirolli & Card (1999)

EXAMPLE

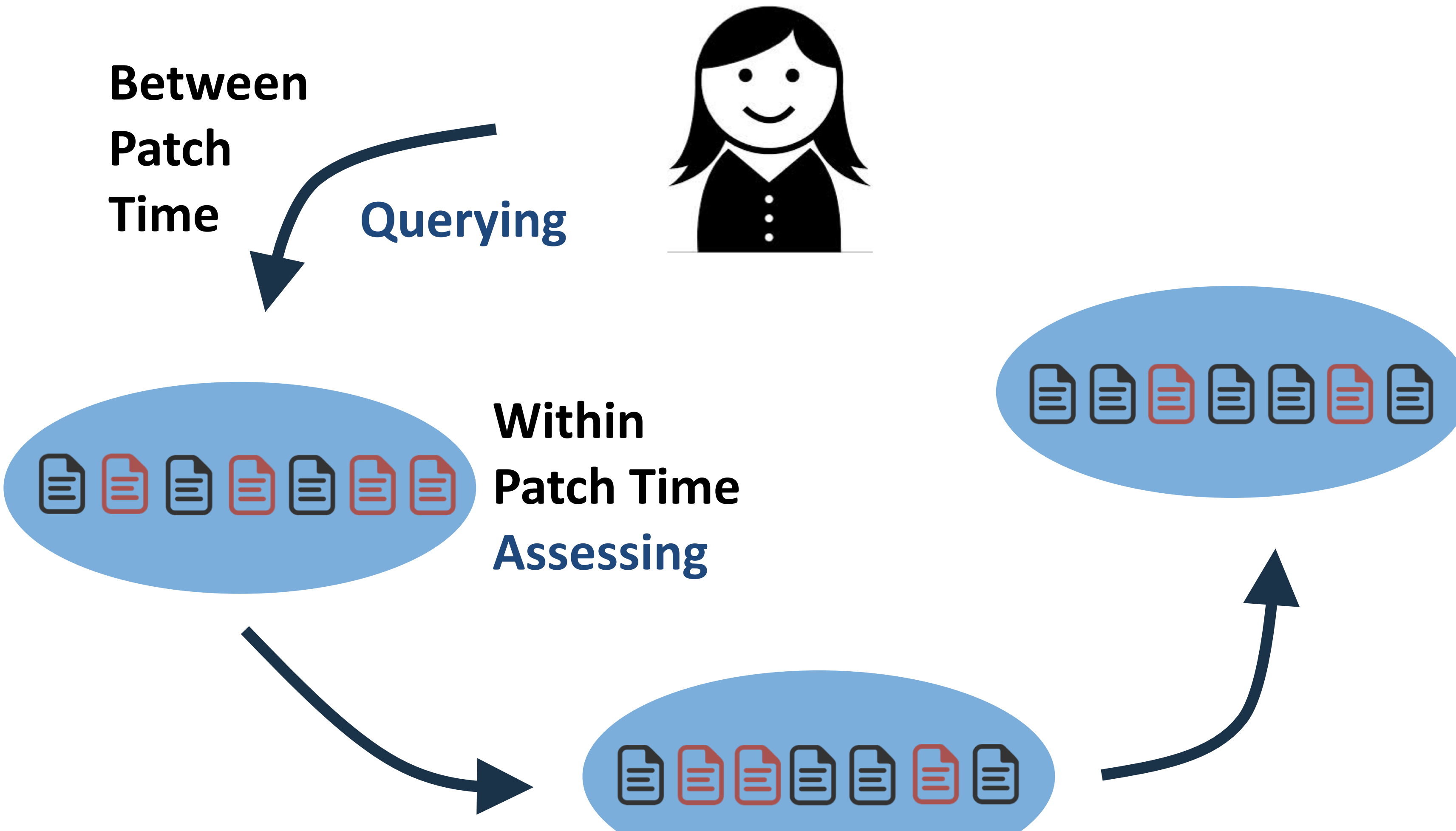
Berry Picking

Bates' Berry Picking Models



Assumes the forager has a good estimate of the distribution of berries.

Applied to Search

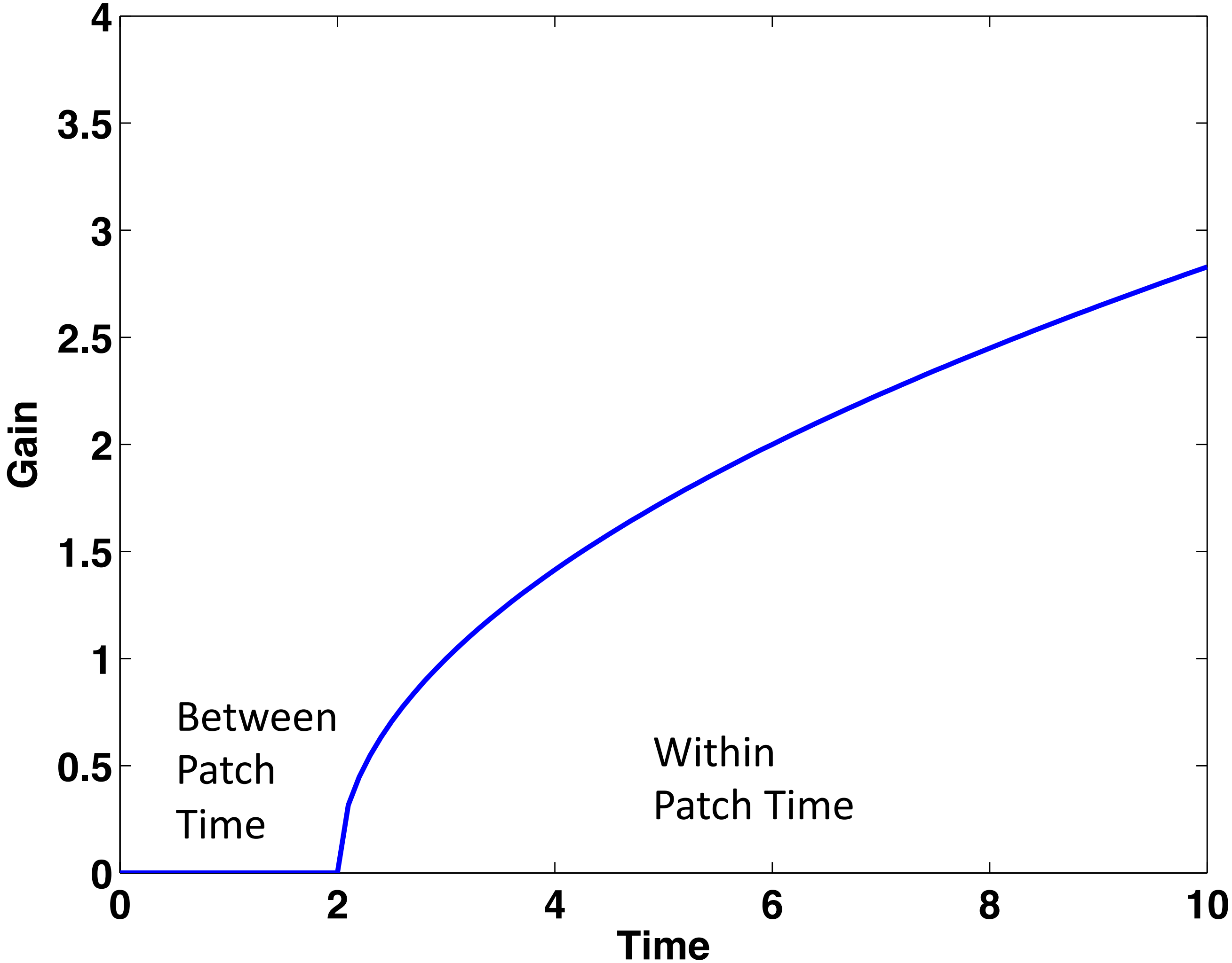


Assumes the user has a good estimate of the distribution of relevant documents.

Patch Example: Web Search

- User submits a query to a search engine
  - Between patches
- User examines the list of results
  - Within patch
- Costs
  - Entering/Formulating Queries
  - Scanning the snippets
  - Interacting with the SERPs
  - Examining links
- Given a gain function and fixed amount of time, how long should a forager stay in each patch?

Patch Example

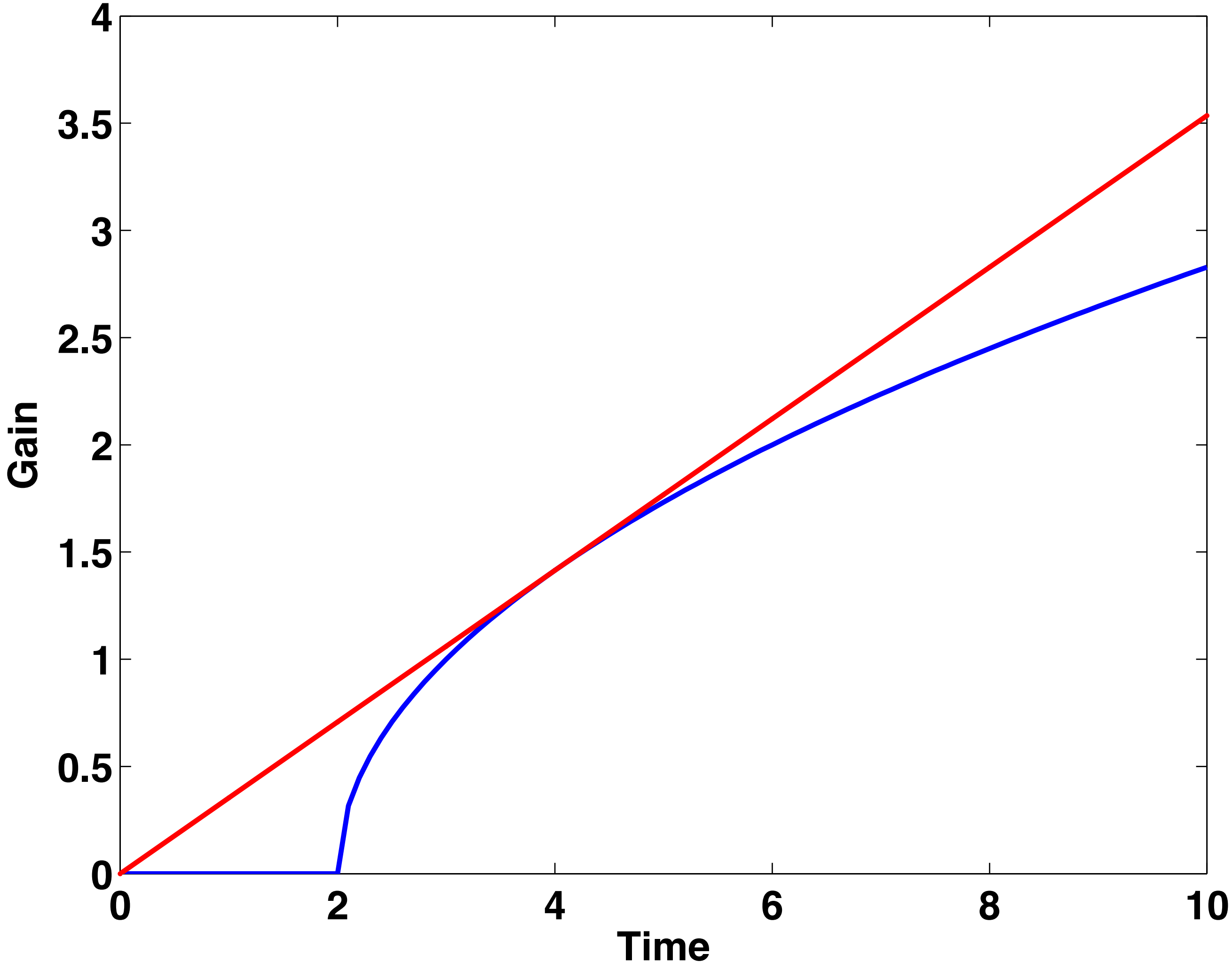


As a forager spends more time in the patch they receive more gain.

The rate of gain will tend to zero as the patch becomes exhausted.

i.e. they will experience diminishing returns.

Patch Example

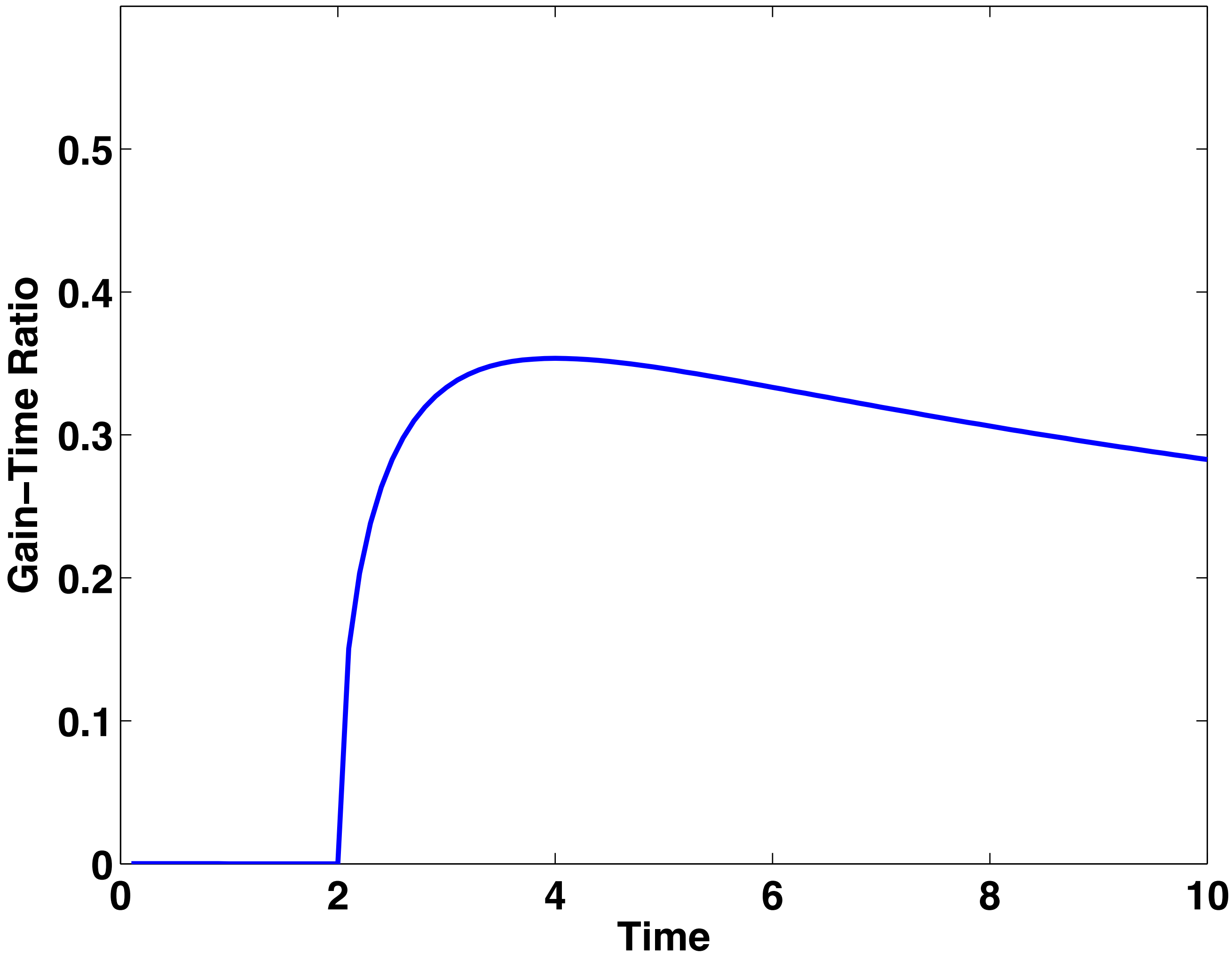


To work out when gain/time is maximised, we need to draw a line from the origin to the tangent of the gain curve (the derivative).

The gain-time ratio is maximized at 4. So once the user has spent 2 minutes in the patch, then it is time to leave.

This assumes that each patch follows a similar distribution.

Ratio of Gain/Time over Time



Over time the ratio of Gain-Time increases to a maximum at 4, and then decreases.

i.e. stopping at any other point would not be rational.

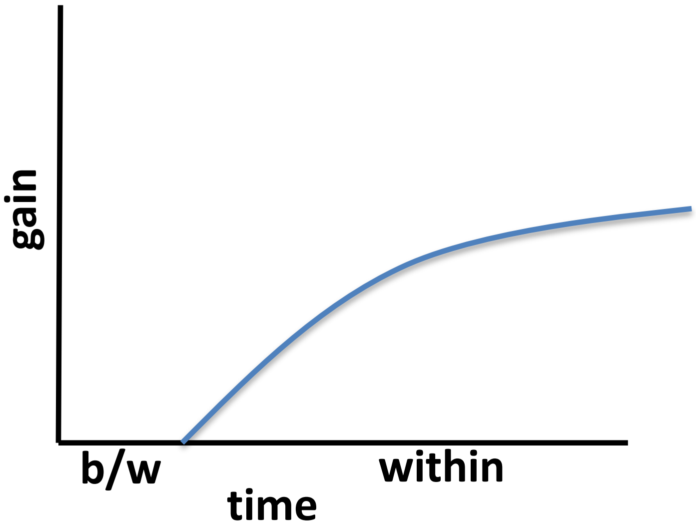
The Patch Model Exercises

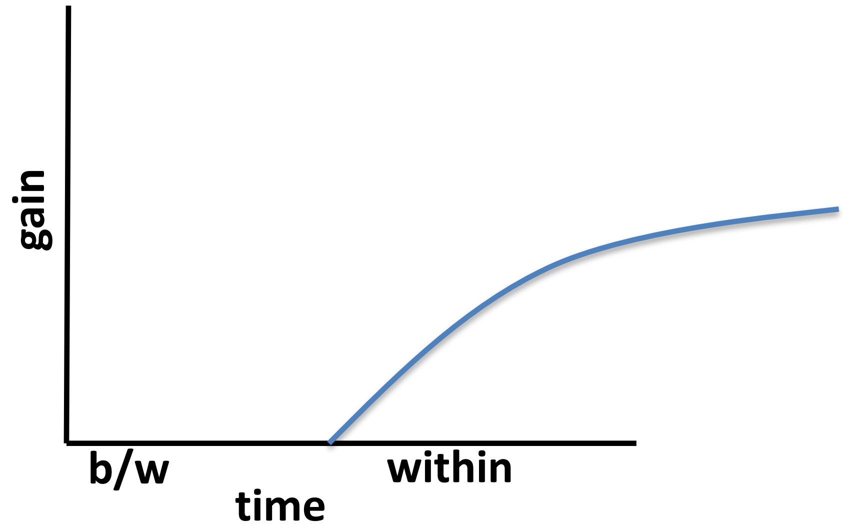
How will the user change their behavior:

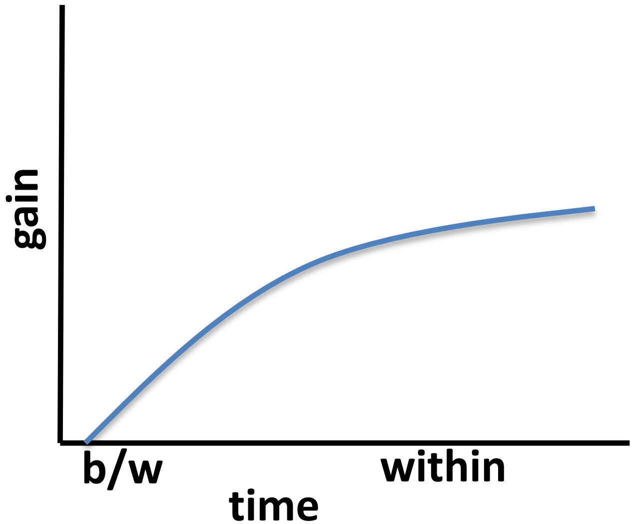
- When the time to get between patches:
  - Increases?
  - Decreases?
- When the gain function:
  - Yields more early on?
  - Yields a constant amount, until a certain point
  - Yields a random amount?

Different Between Patch Times

Using the patch model, predict where the user will stop on each of these patches?

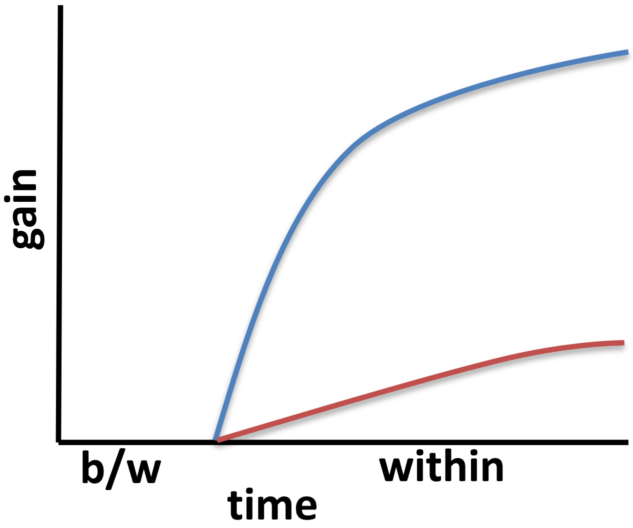


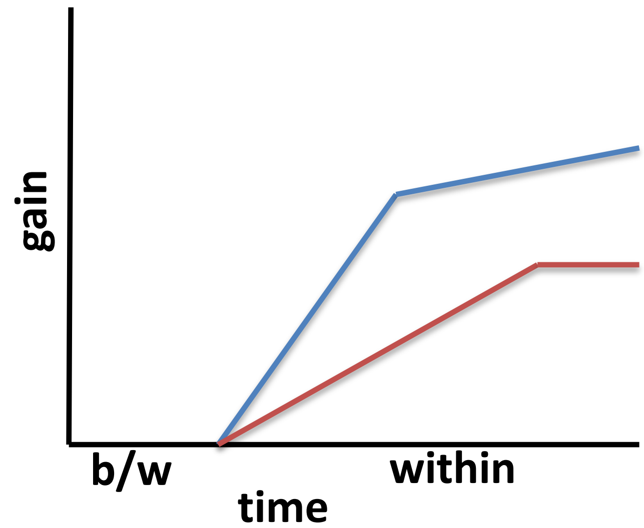


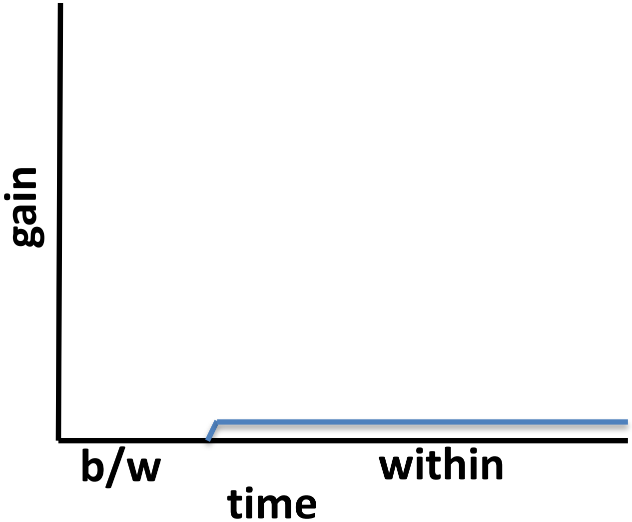


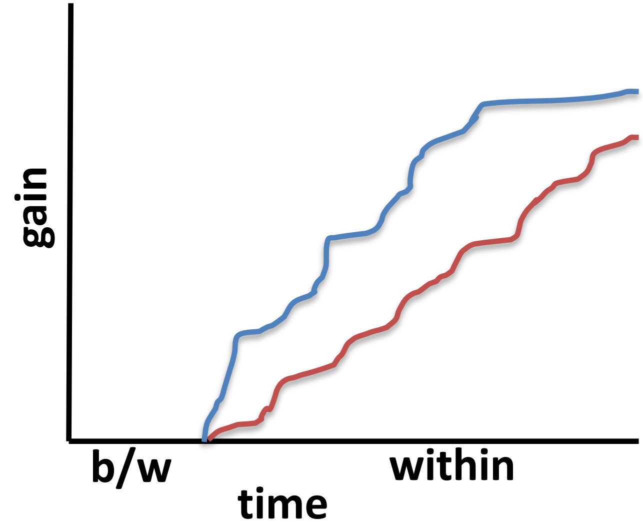
Different Gain Curves

Using the patch model, predict where the user will stop on each of these patches?









CHARNOV'S
MAXIMAL MARGINAL THEOREM

Patch Distribution

- In the previous examples, we have **assumed** that **all the patches** are distributed in a **similar** fashion.
- However, as forager move from patch to patch they are likely to experience **different yields**.
- In which case, simply maximizing the rate of gain in each patch results in a local optima.

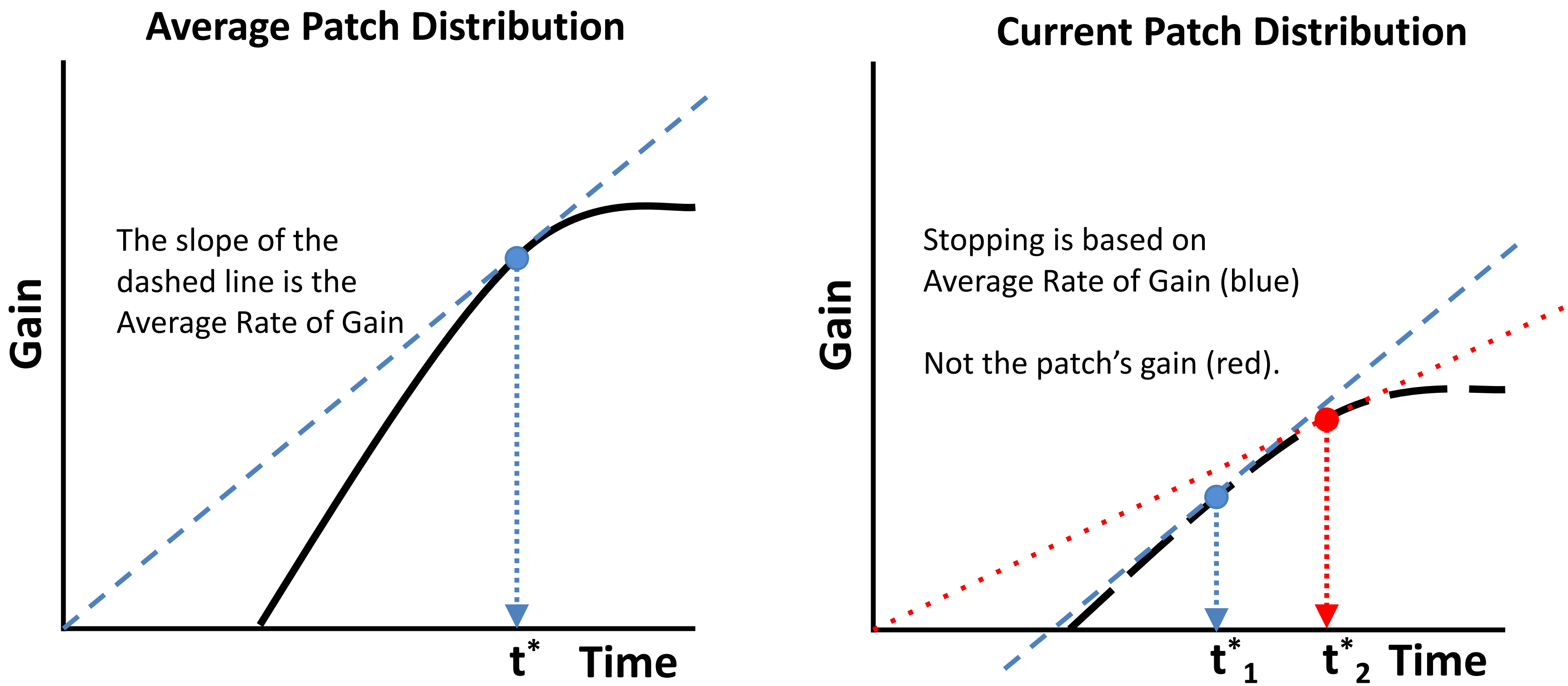
Charnov’s Marginal Value Theorem

- The theorem was developed to deal with the analysis of time allocation for patch that yield diminishing returns.

- The theorem predicts that a **forager** should **remain** in a patch so long as the **slope** of the **gain function** is **greater** than the **average rate** of **gain** in the **environment**.

Charnov (1976)

Applying Charnov's Theorem



1. Compute the average rate of gain.
2. In the current patch,
if the rate of gain is higher than average continue, else stop.

Issues

- Can a forager really work out the rate of gain?
- Can they develop an intuition for the average rate?
- In foraging theory, other explanations have been offered, i.e. simple stopping rules, which approximate the theory, e.g.:
  - stop after ***n*** seconds.
  - stop if no prey have been found in ***n*** seconds

Insights from IFT's Patch Model

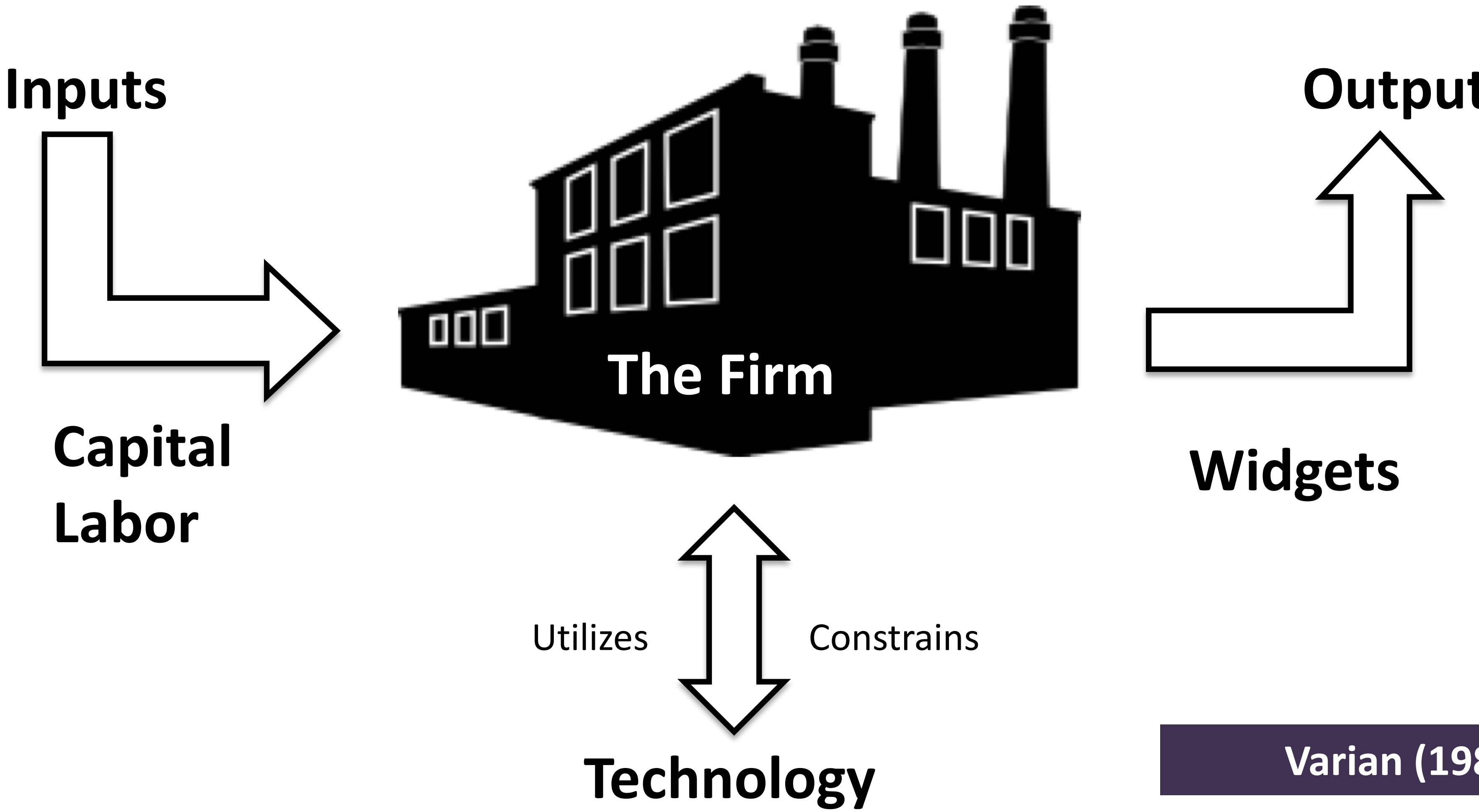
- If the **between-patch time increases**,
  - Foragers will spend more time within the patch.
- If the **average gain** in a **patch increases**,
  - Foragers will spend less time within patches
- If the **average gain** in the **patch** is **constant**
  - Foragers will stay in the patch, until they have ran out of time, reached their saturation point, or exhausted the patch.

PRODUCTION THEORY

An economic model of production

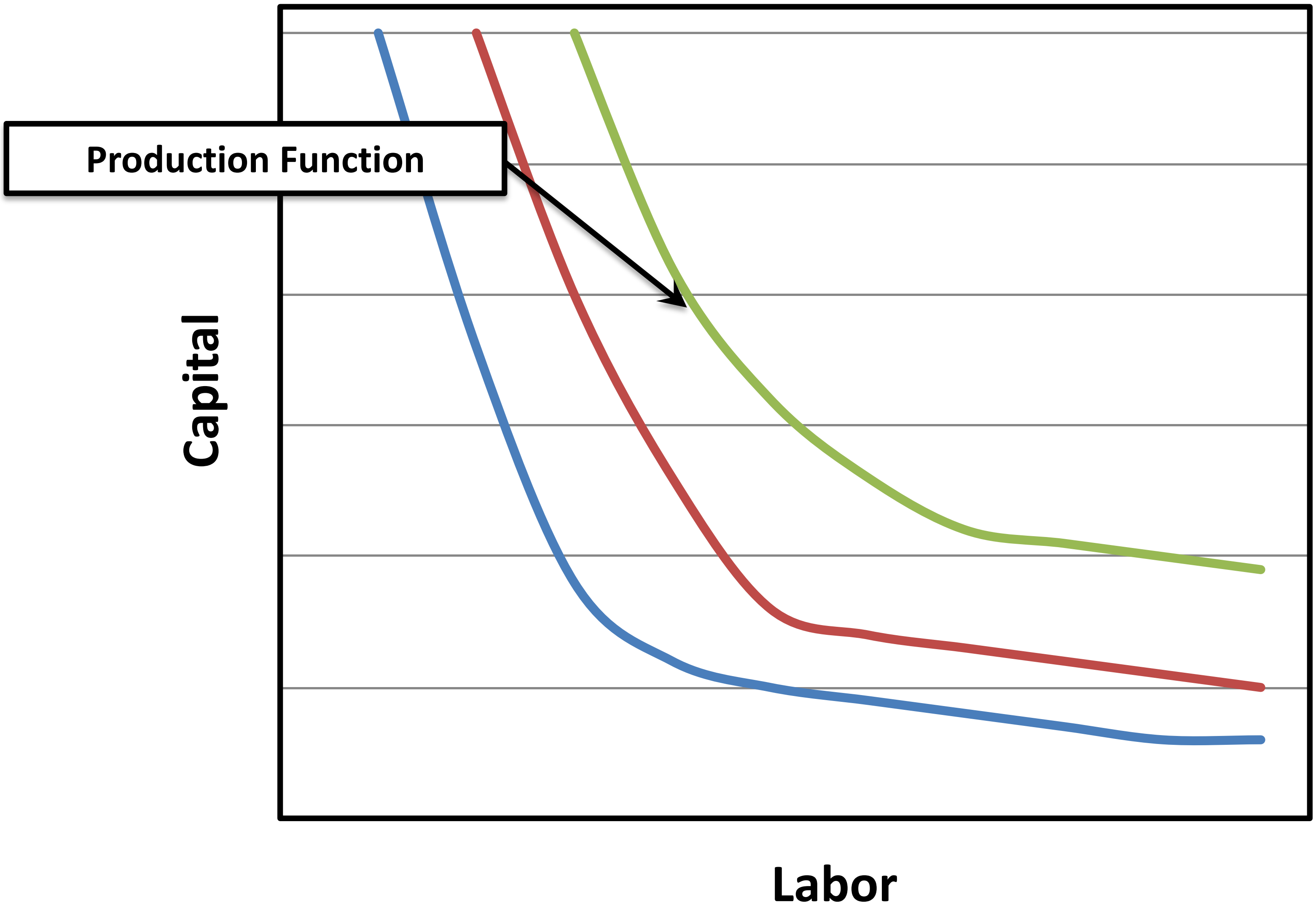
Production Theory

a.k.a. Theory of Firms

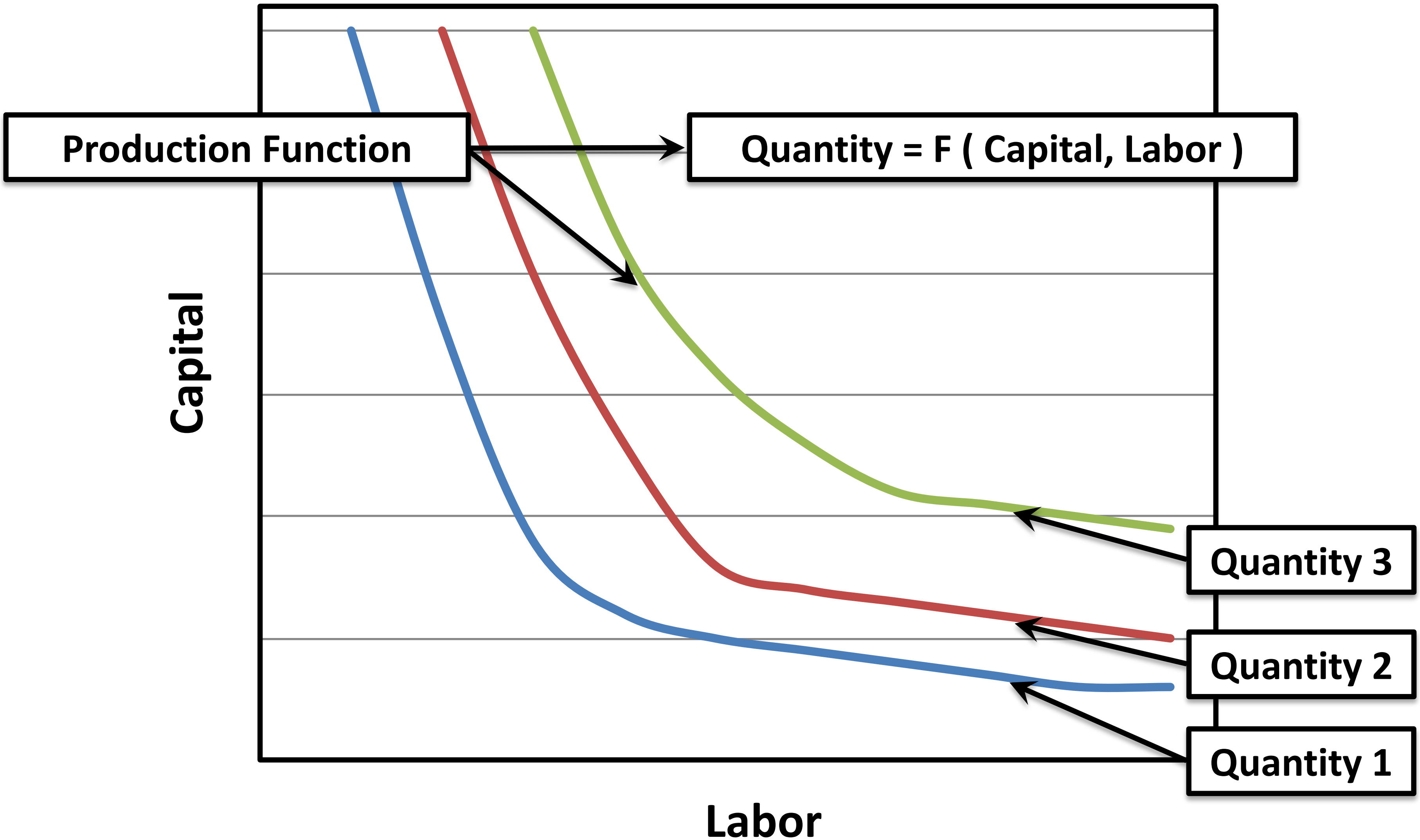


Varian (1987)

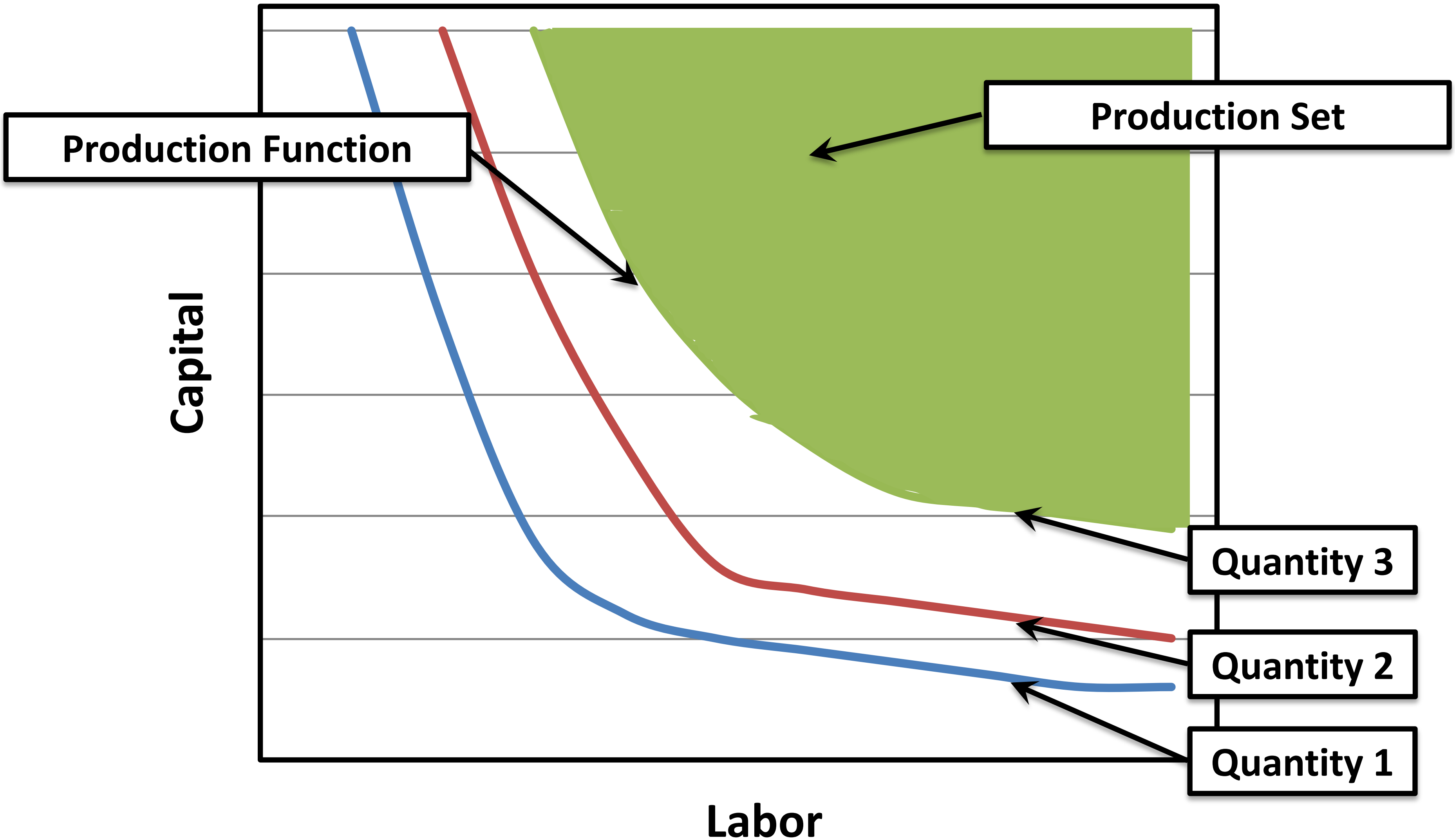
Production Functions



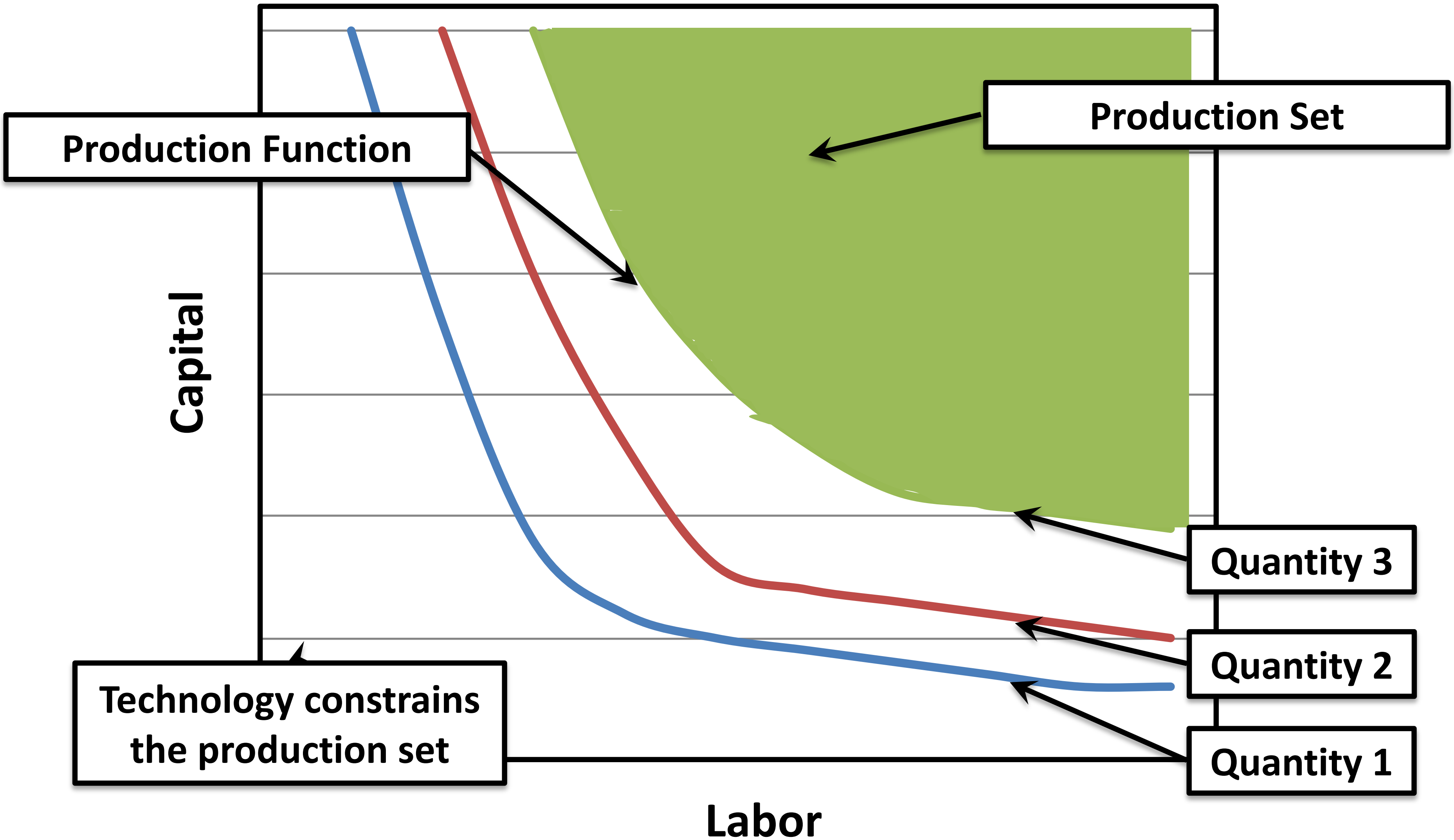
Production Functions



Production Functions



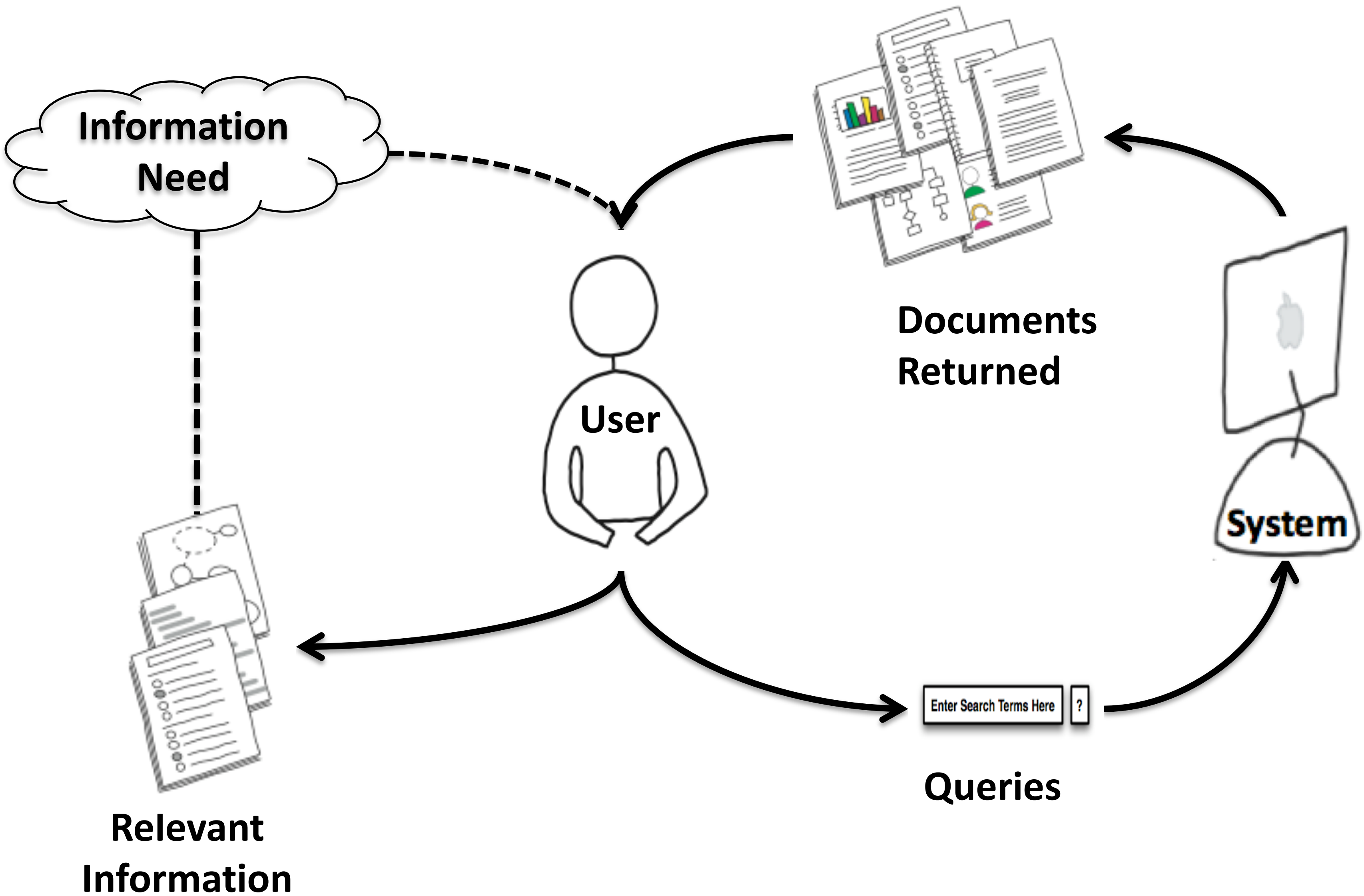
Production Functions



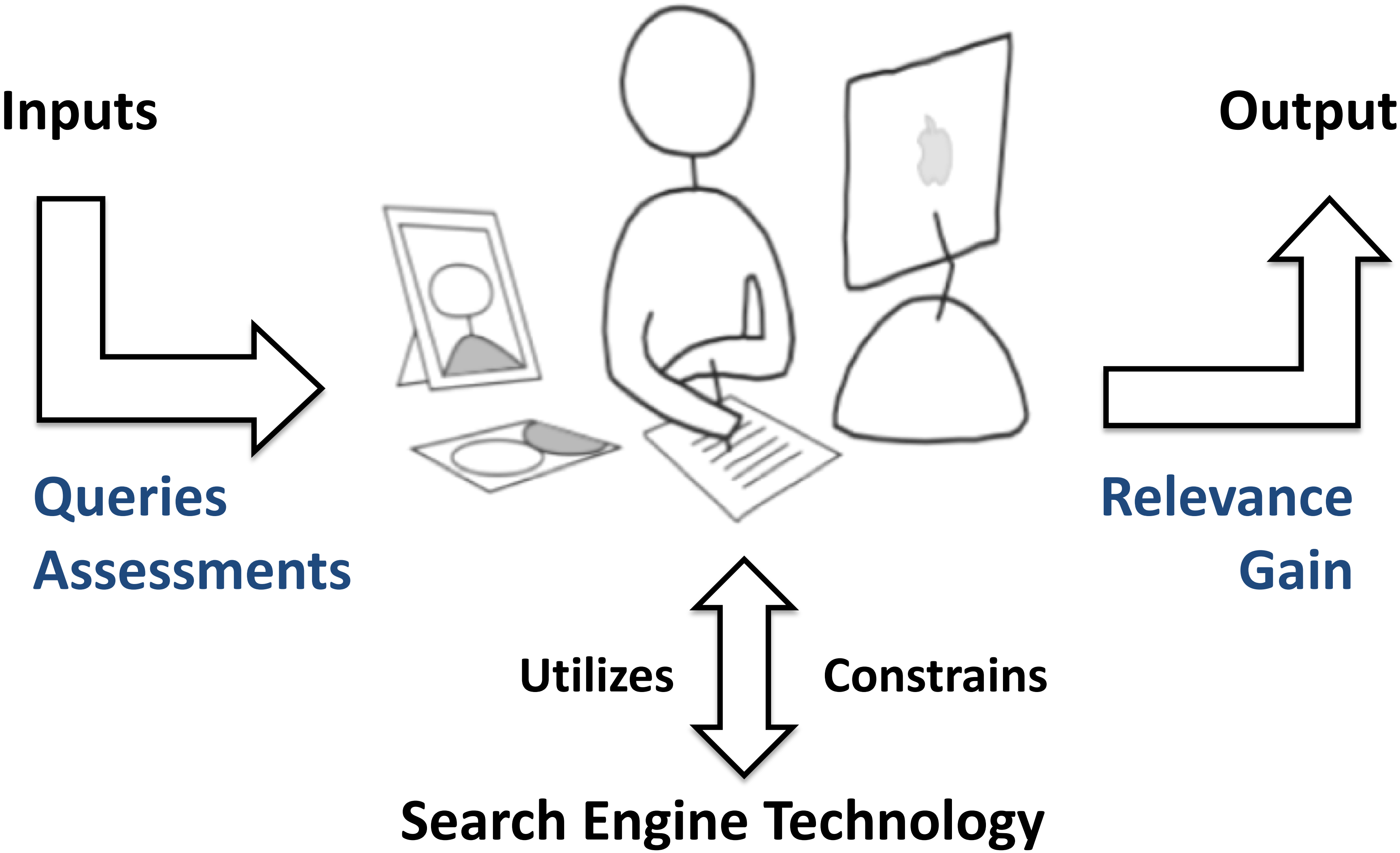
Applying Production Theory to Interactive and Iterative Search

Interactive and Iterative Search

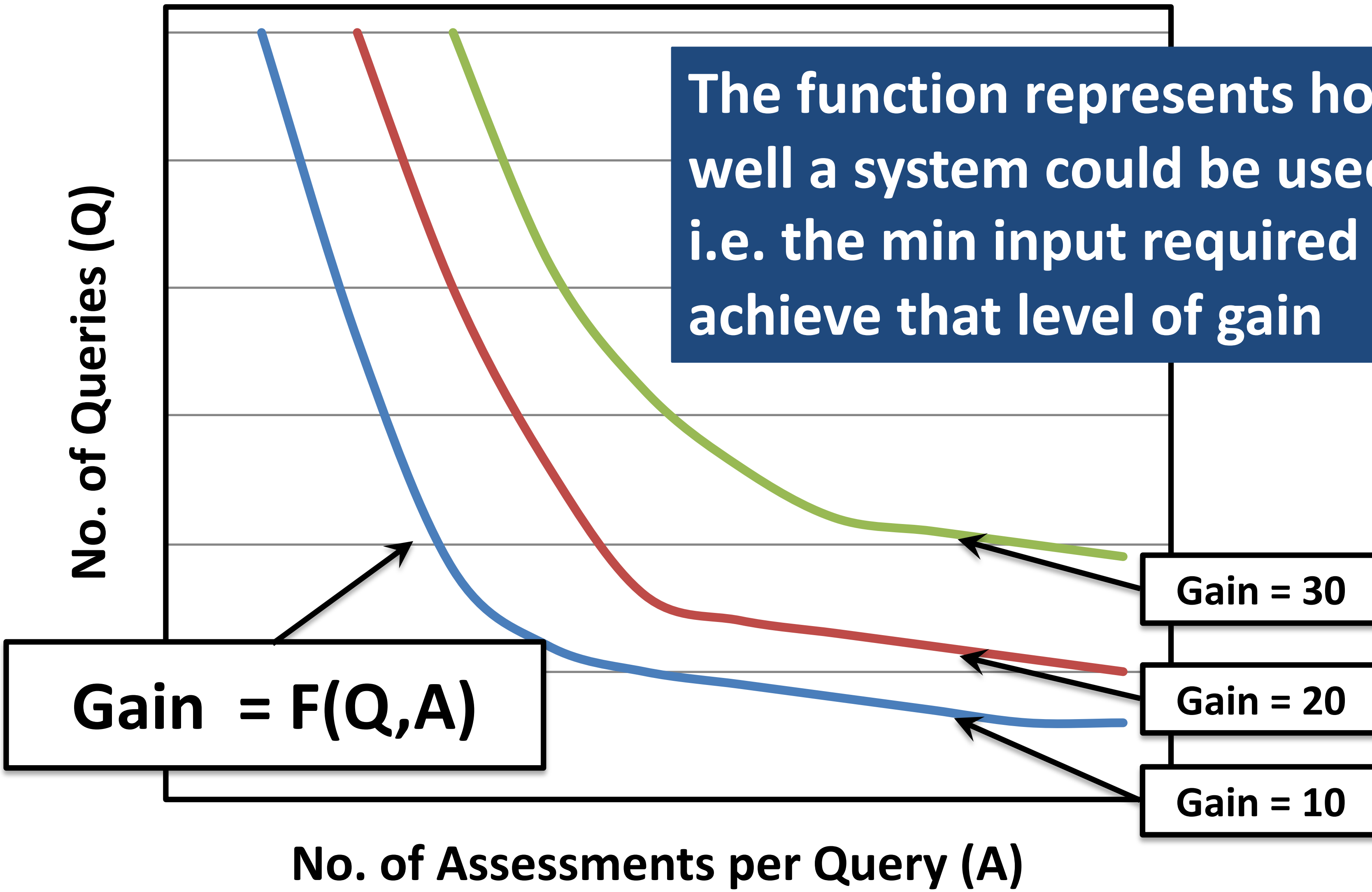
A simplified, abstracted, representation



Search as Production



Search Production Function



The function represents how well a system could be used. i.e. the min input required to achieve that level of gain

Gain Function for the Search Process

Let the gain the user receives through their interaction be:

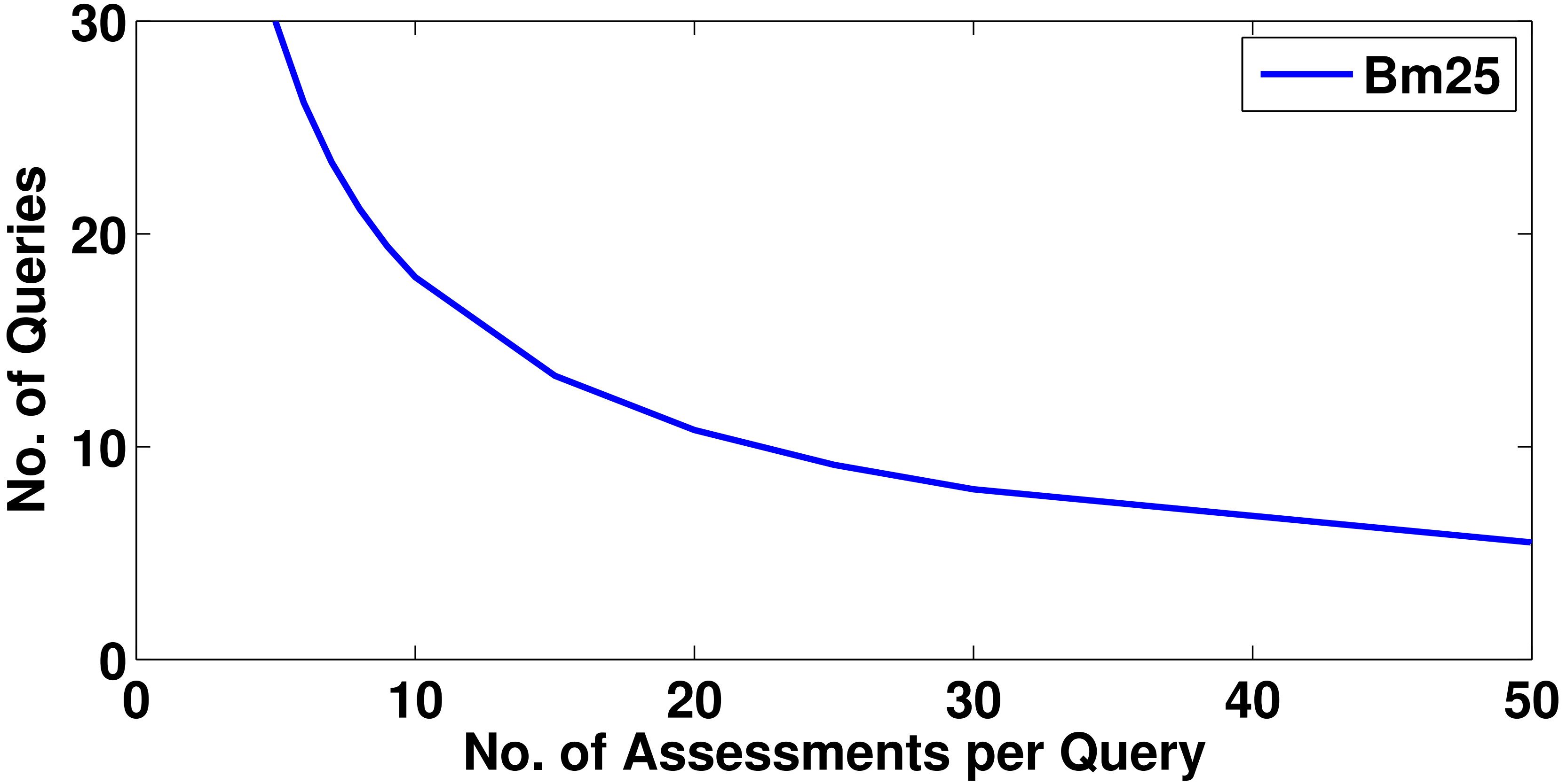
$$g(Q, A) = k.Q^{\alpha}.A^{(1-\alpha)}$$

Where:

Q is the number of queries, and
A is the number of documents examined per query.
α is the relative efficiency of querying to assessing
k is the efficiency of the technology/user to extract/ identify relevant information returned

Azzopardi (2011)

Gain Curve



Each point on the curve represents a combination of interactions that will yield the same gain.

Cost Function for the Search Process

The total cost can be calculated by:

$$c(Q, A) = c_q.Q + c_a.A.Q$$

Where:

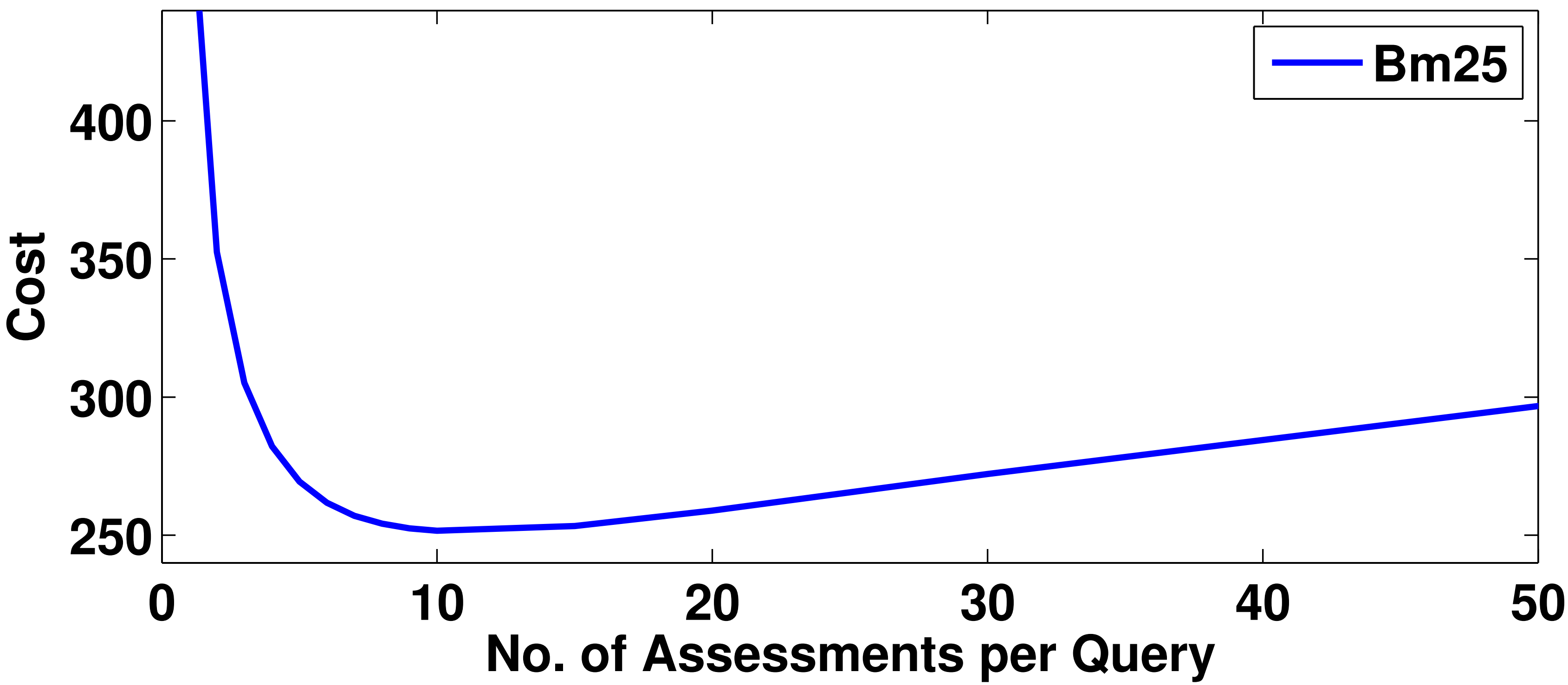
– $\boldsymbol{c_q}$ is the cost of a query

– $\boldsymbol{c_a}$ is the cost of a assessing a document

– ***A.Q*** is the total number of documents assessed

Azzopardi (2011)

Cost Curve



The total cost is minimized when **A = 10**, which corresponds to **Q = 18**. Any other combination will result in a higher total cost.

Using the Cobbs-Douglas Search Function

We can differentiate the function to find the rates of change of the input variables

Marginal Product of Querying

$$\frac{\partial f(Q,A)}{\partial Q}$$

- the change in gain over the change in querying
- i.e. how much more gain do we get if we pose extra queries

Marginal Product of Assessing

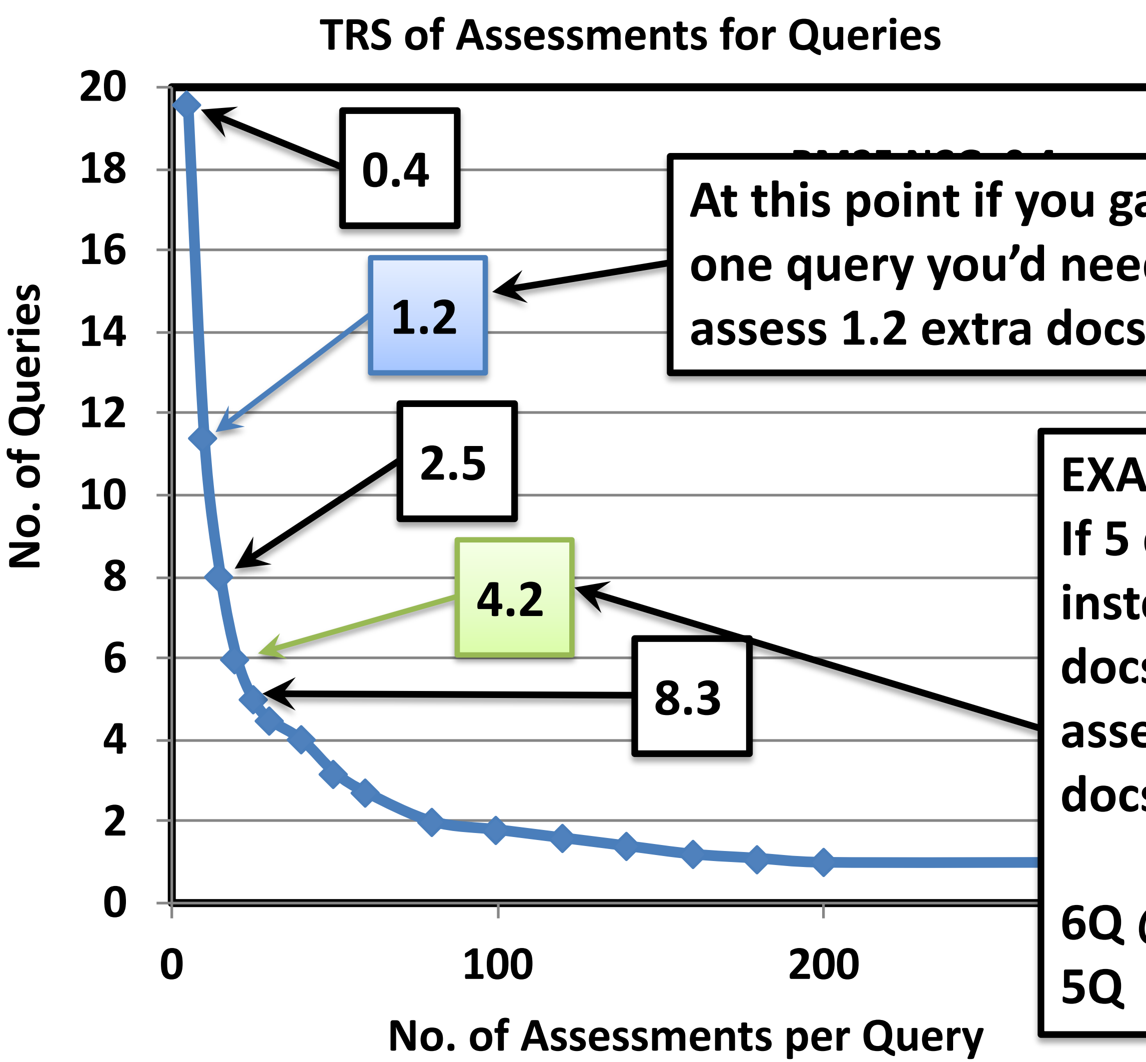
$$\frac{\partial f(Q,A)}{\partial A}$$

- the change in gain over the change in assessing
- i.e. how much more gain do we get if we assess extra documents

Technical Rate of Substitution

How many more assessments per query are needed, if one less query was posed?

$$TRS(A,Q) = \frac{\partial A}{\partial Q}$$



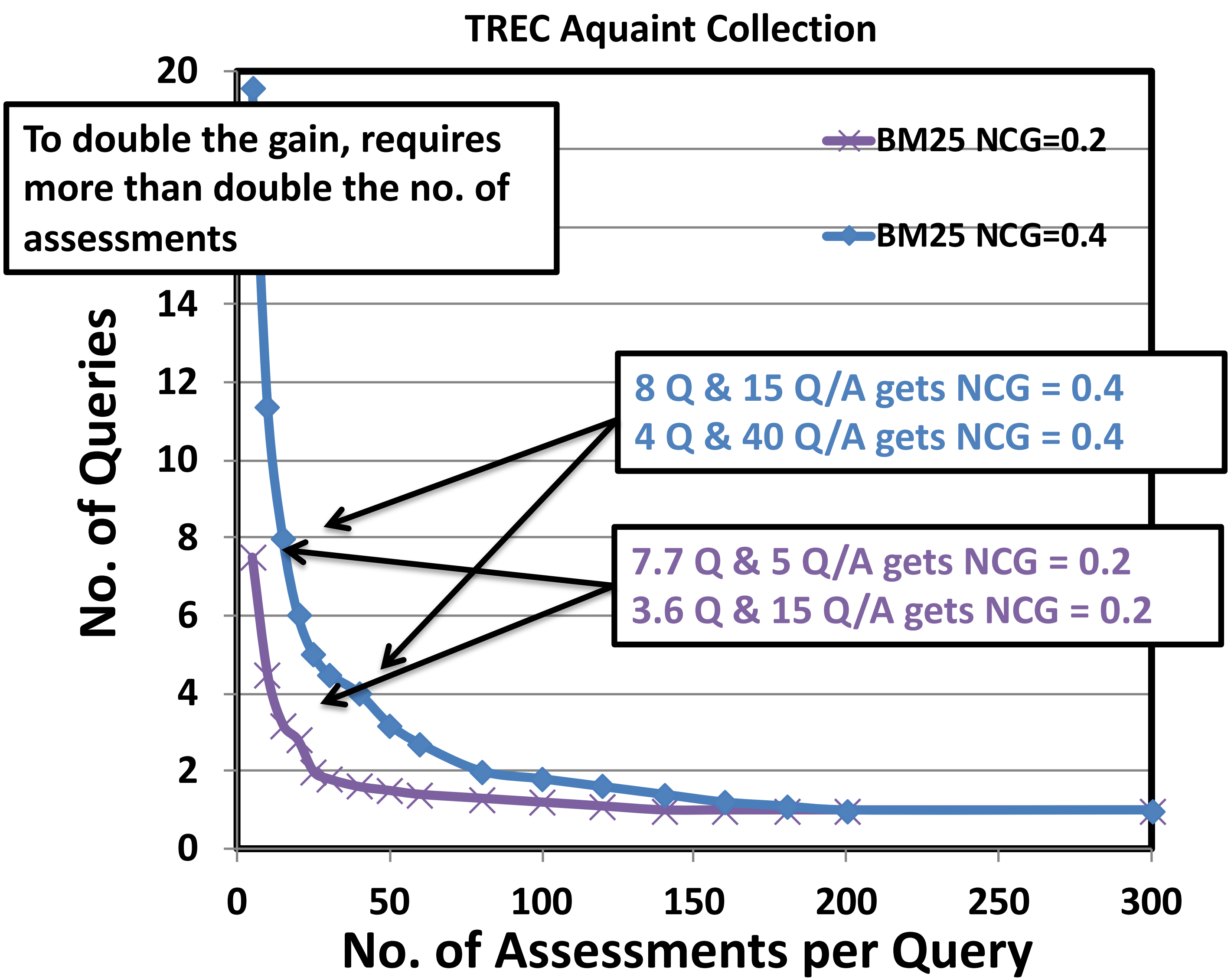
At this point if you gave up one query you'd need to assess 1.2 extra docs/query

EXAMPLE:
If 5 queries are submitted, instead of 6, then 24.2 docs/query need to be assessed, instead of 20 docs/query

6Q @ 20A / Q = 120 A
5Q @ 24.2 / Q = 121 A

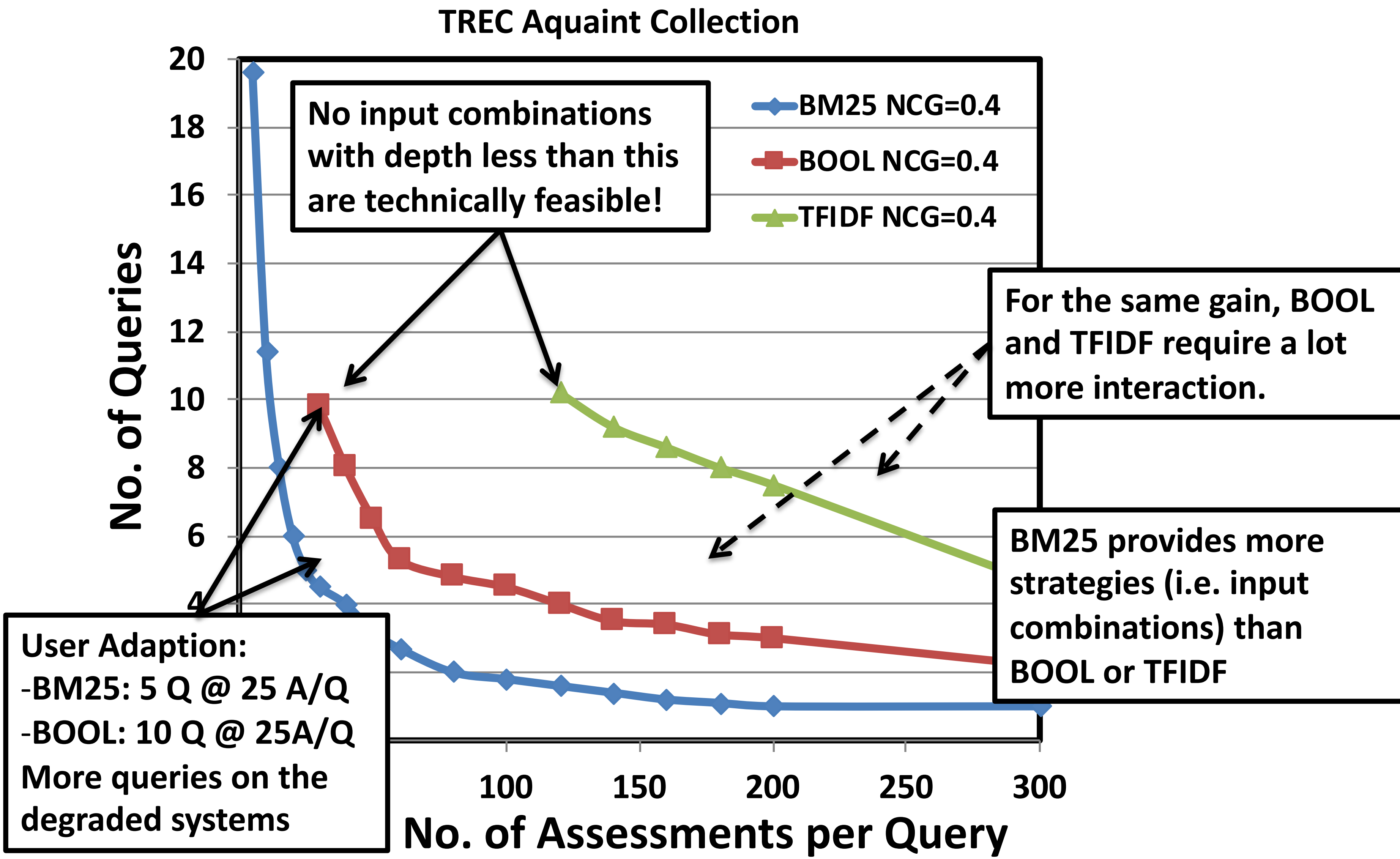
Search Production Curves

Same Retrieval Model, Different Gain



Search Production Curves

Different Retrieval Models, Same Gain



What strategies can the user employ

when interacting with the search system to achieve their end goal

What is the most cost-efficient way for a user to interact with an IR system?

All models are wrong

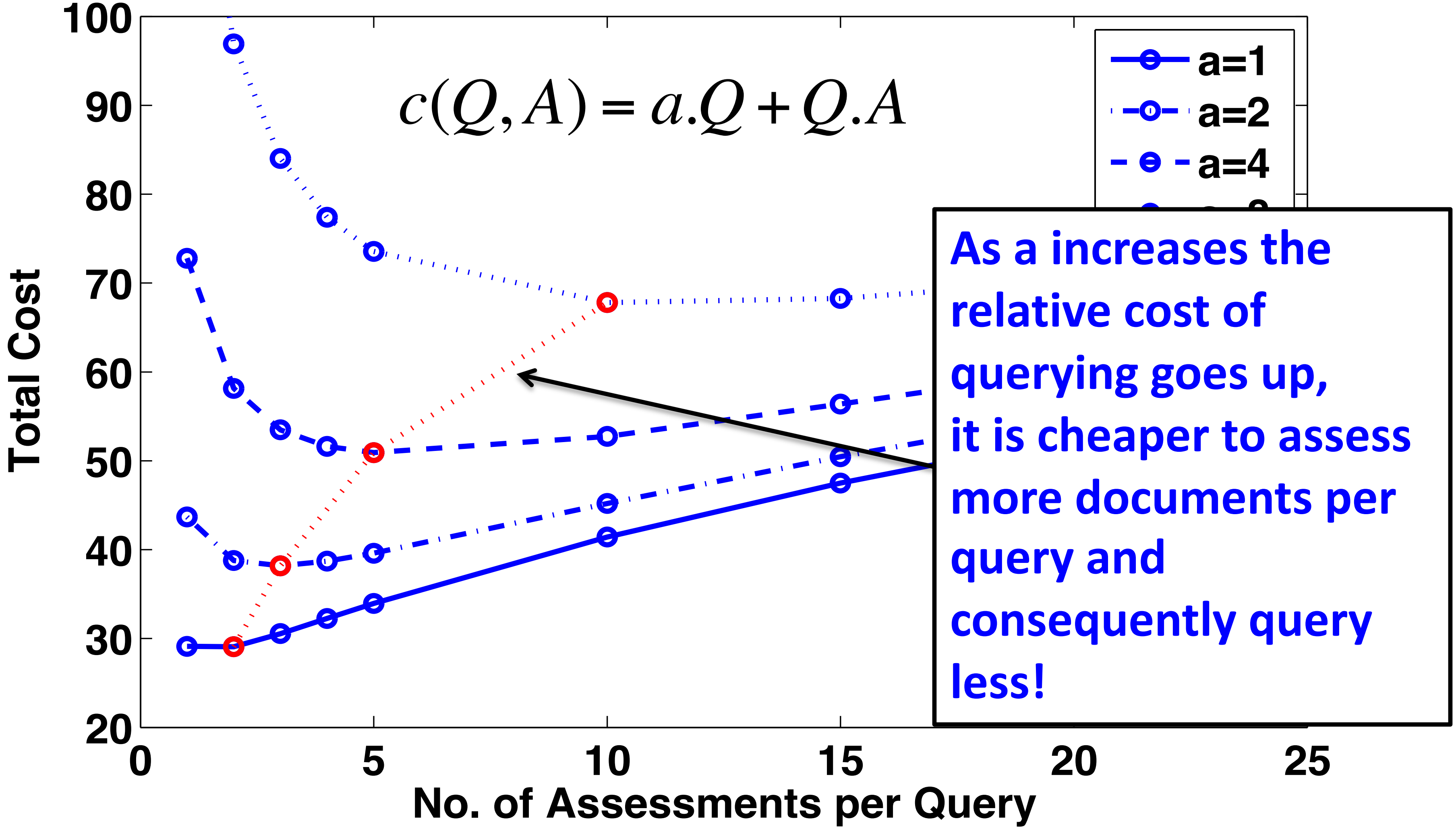
but some are useful

George E.P. Box

What does the model tell us about search & interaction?

Changing the Relative Query Cost

- On BM25:



A Hypothetical Experiment

What happens if

Querying costs go down?

$$$$

Querying costs go up?

More queries issued

Decrease in queries issued

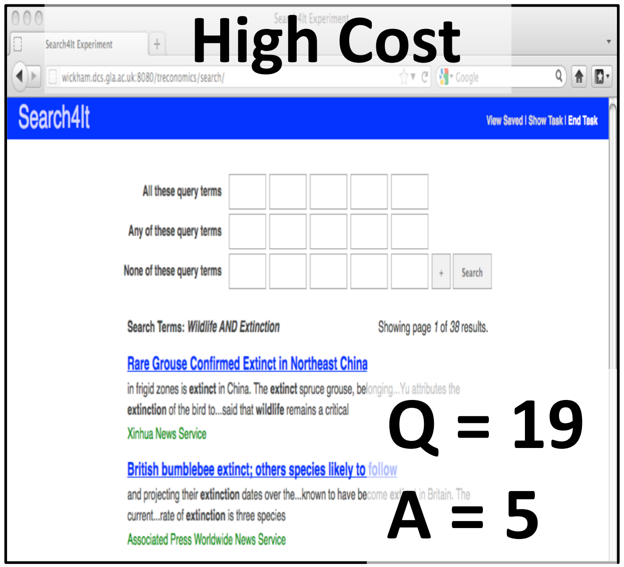
Decrease in assessments per query

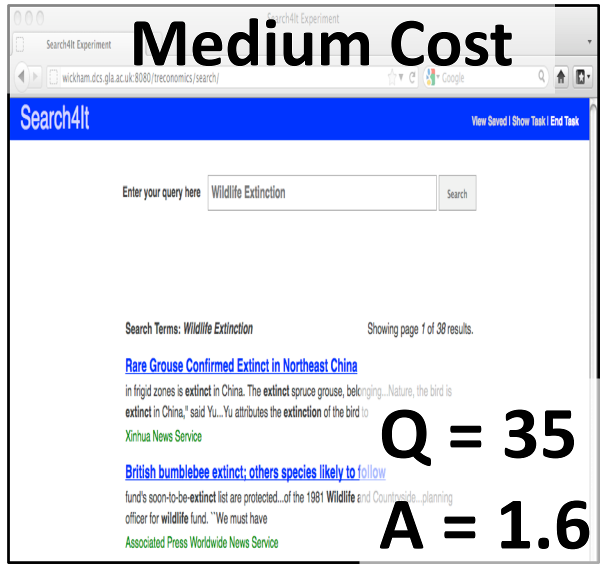
Increase in assessments per query

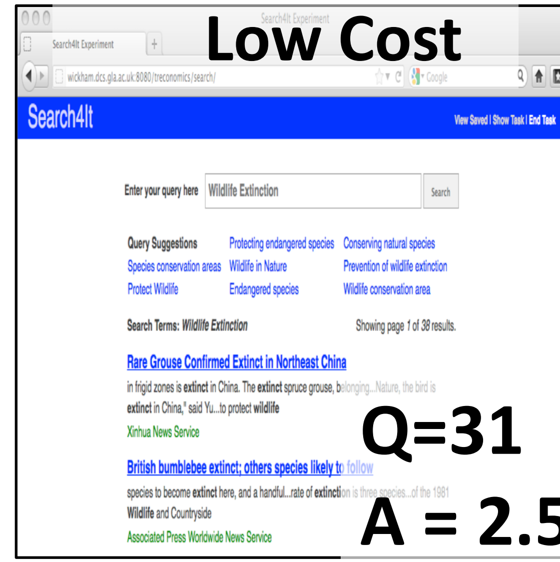
But, what do user’s actually do?

Testing the Query Cost Hypothesis

Structured | **Standard** | **Suggestion**







Structured vs Standard and Suggestion : **YES**

Standard vs Suggestion: **NO**

Model does not account for the **time spent on the search result page** nor **the interaction with snippets**.

Azzopardi, Kelly & Brennan (2013)

Is the model useful?

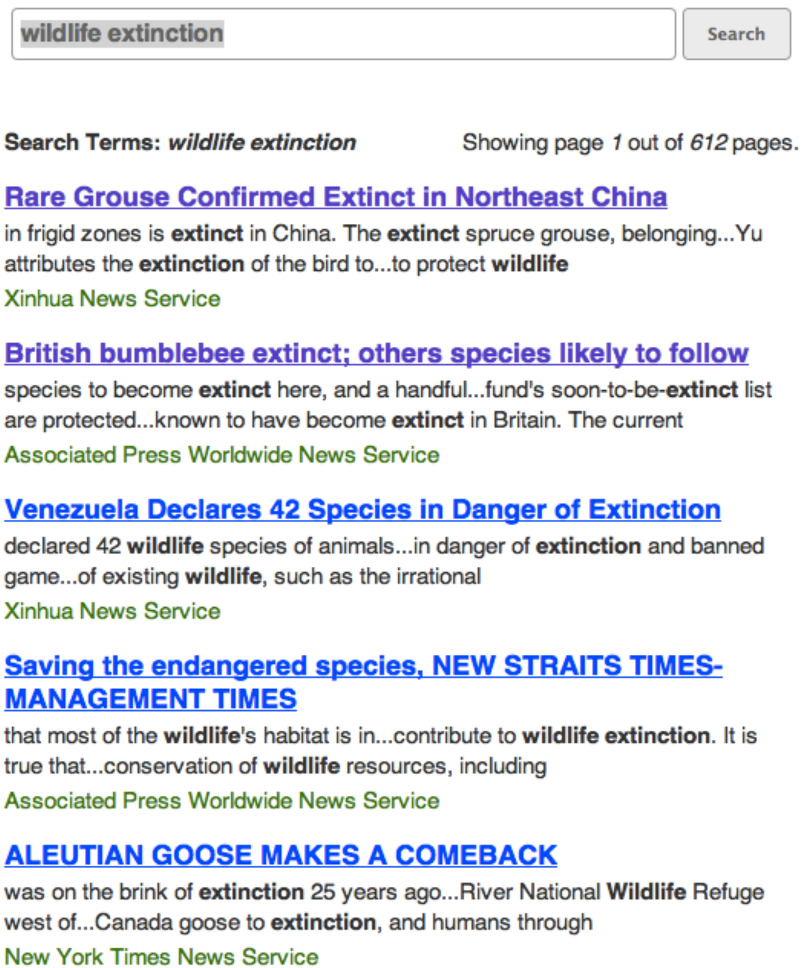
Limitations

- Assumes **users** are **rational**
- Assume **interaction** is **fixed**
- **Model of interface too simplified**, the search process is more than just querying and assessing
  - There are lots of **other costs** involved when searching
  - There are lots of **other interactions** that can be performed too

REFINING THE MODEL

Adding detail to build a more useful (but more complex) model

Modeling Other Costs



Cost to enter a query (c_q)

Cost to load search page per query

Cost to examine each snippet

Cost to view a document

Cost of return back to search page

Cost to assess the document (c_a)

Cost to view next page

Modeling Other Costs

- Let's also include the:
  - cost of viewing pages ($\mathbf{c_v}$) and
  - cost of examining snippets ($\mathbf{c_s}$)

  in the cost model, such that:

$$c(\mathbf{Q}, \mathbf{V}, \mathbf{S}, \mathbf{A}) = \mathbf{c_q}.\mathbf{Q} + \mathbf{c_v}.\mathbf{V}.\mathbf{Q} + \mathbf{c_s}.\mathbf{S}.\mathbf{Q} + \mathbf{c_a}.\mathbf{A}.\mathbf{Q}$$

Assumptions

- Let's assume that the number of page views is equal to some constant **v**
  - Typically this would be **v=1**
  - But could be the average number of pages examined i.e. **v=1.1**
- Let's further assume that $\boldsymbol{A = S.p_a}$
  - Where $\mathbf{p_a}$ is the probability of assessing a document given a snippet.

Reducing the Cost Function

- Given these assumptions, the cost function can be simplified down to the following:

$$\mathbf{c}(\mathbf{Q},\mathbf{A}) = (\mathbf{c_q} + \mathbf{c_v}.\mathbf{v}).\mathbf{Q} + \left(\frac{c_s}{p_a} + c_a\right).A.Q$$

New Gain Function

- Previously, **Q** and **A** were linked via **α** and **1-α**,
- Here we decouple this relationships
  - – which enables us to estimate the parameters
  - – and so becomes more intuitive

$$\mathbf{g}(\mathbf{Q}, \mathbf{A}) = \mathbf{k}.\mathbf{Q}^{\alpha}.\mathbf{A}^{\beta}$$

Optimization Problem

- Given our model, we wish to minimize the cost **c(Q,A)**, subject to the constraint that **g(Q,A) = g**
- To do this we used a Lagrangian multiplier

$$\Delta = (\mathbf{c_q} + \mathbf{c_v}.\mathbf{v}).\mathbf{Q} + \left(\frac{\mathbf{c_s}}{\mathbf{p_a}} + \mathbf{c_a}\right).\mathbf{A}.\mathbf{Q}$$
$$-\lambda\left(k.Q^{\alpha}.A^{\beta} - g\right)$$

Optimal Interaction

The optimal number of assessments per query:

$$\mathbf{A}^{\star} = \frac{\beta.(\mathbf{c_q} + \mathbf{c_v}.\mathbf{v})}{(\alpha - \beta).\left(\frac{\mathbf{c_s}}{\mathbf{p_a}} + \mathbf{c_a}\right)}$$

The optimal number of queries:

$$\mathbf{Q}^{\star} = \sqrt[\alpha]{\frac{\mathbf{g}}{\mathbf{k}.\mathbf{A}^{\beta}}}$$

How does querying behavior change?

$$\mathbf{Q}^{\star} = \sqrt[\alpha]{\frac{\mathbf{g}}{\mathbf{k}.\mathbf{A}^{\beta}}}$$

- So we can say more precisely that:
  - If **g** increases then ***Q*** will go up
  - If ***k*** increases then ***Q*** will go down
  - If **β** increases, then ***Q*** will go down
  - If **α** increases, then **Q** will go up

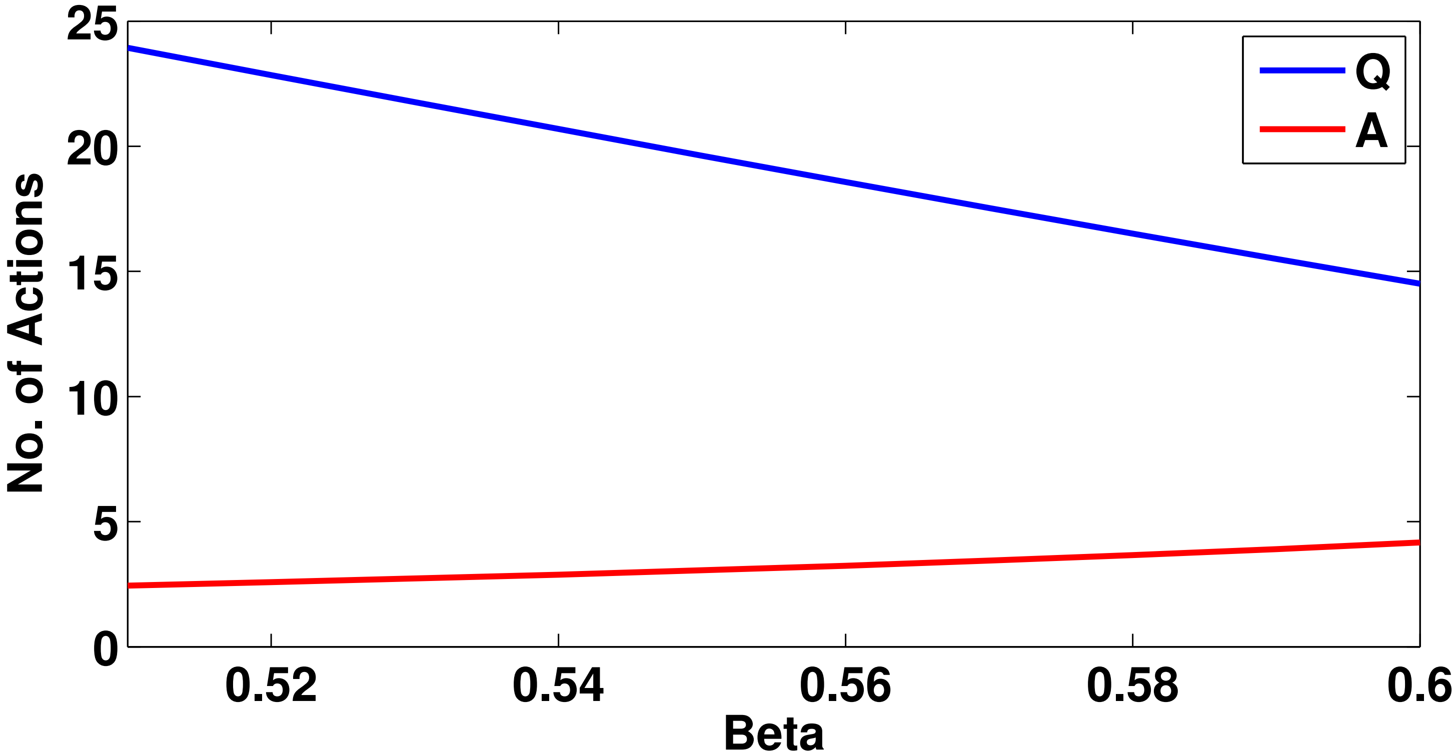
Some Cost Hypotheses

$$\mathbf{A}^\star = \frac{\beta.(\mathbf{c_q} + \mathbf{c_v}.\mathbf{V})}{(\alpha - \beta).\left(\frac{\mathbf{c_s}}{\mathbf{p_a}} + \mathbf{c_a}\right)}$$

- **Document Cost Hypothesis:** as the cost of document increases, **Q** increase, **A** decreases.
- **Snippet Cost Hypothesis**: as the cost of examining snippets increases, **A** decreases, while **Q** increases.

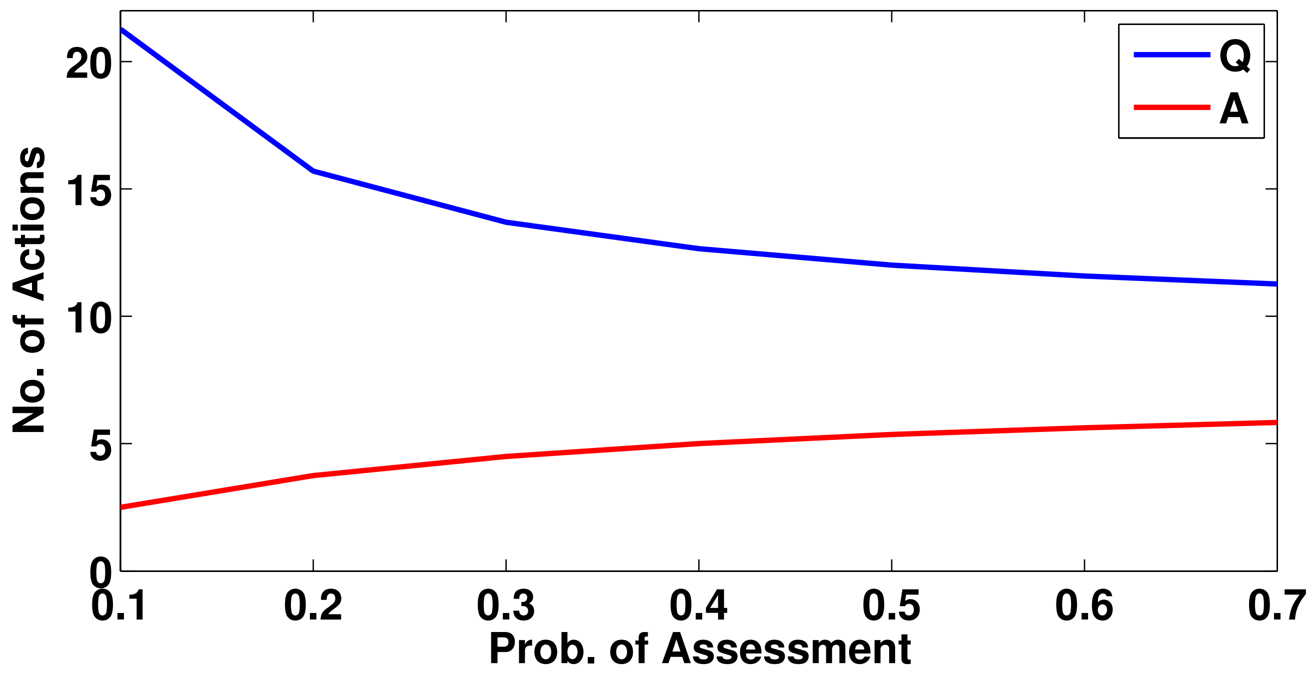
Performance Hypotheses

- **Beta-Performance Hypothesis:**
  as **β** increases, **A** will increase,
  while **Q** will decrease.



Assessment Probability Hypothesis

- **Assessment Probability Hypothesis:**
  as the probability of assessment increases, **A** increases, while **Q** decreases.

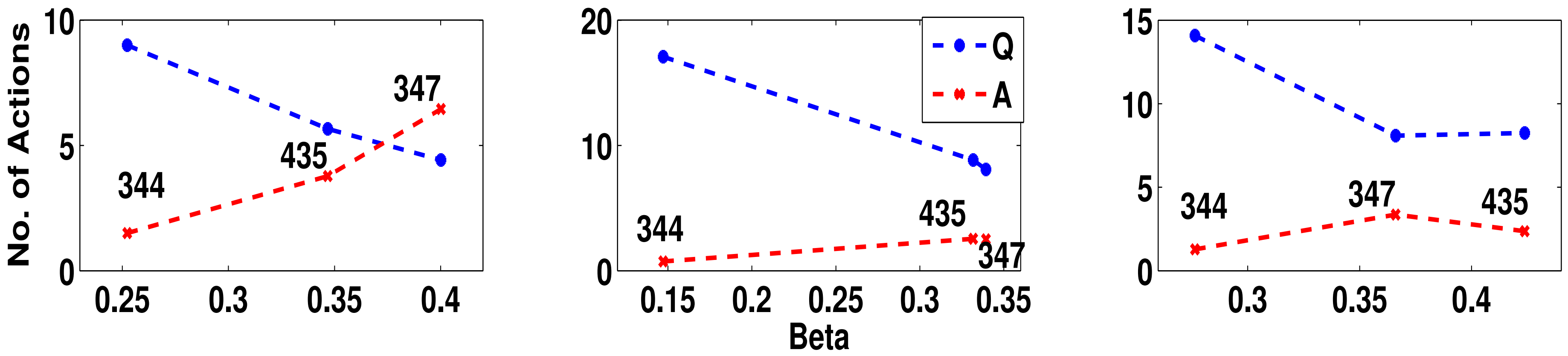


ACTUAL VERSUS OBSERVED

Analysis of Empirical Data

- Re-examined the experimental data from Azzopardi, Kelly & Brennan (2013).
- Where we considered the different interactions over topics for each condition
- And tested seven of the hypotheses that we generated

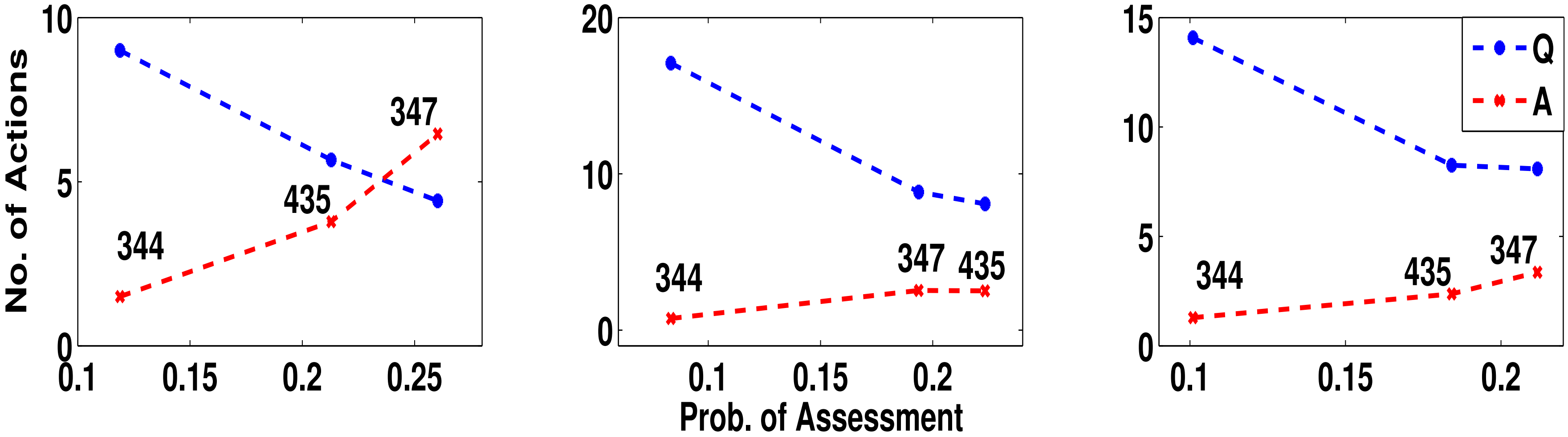
Beta Interaction Hypothesis



- Hypothesis states as **β** increases,

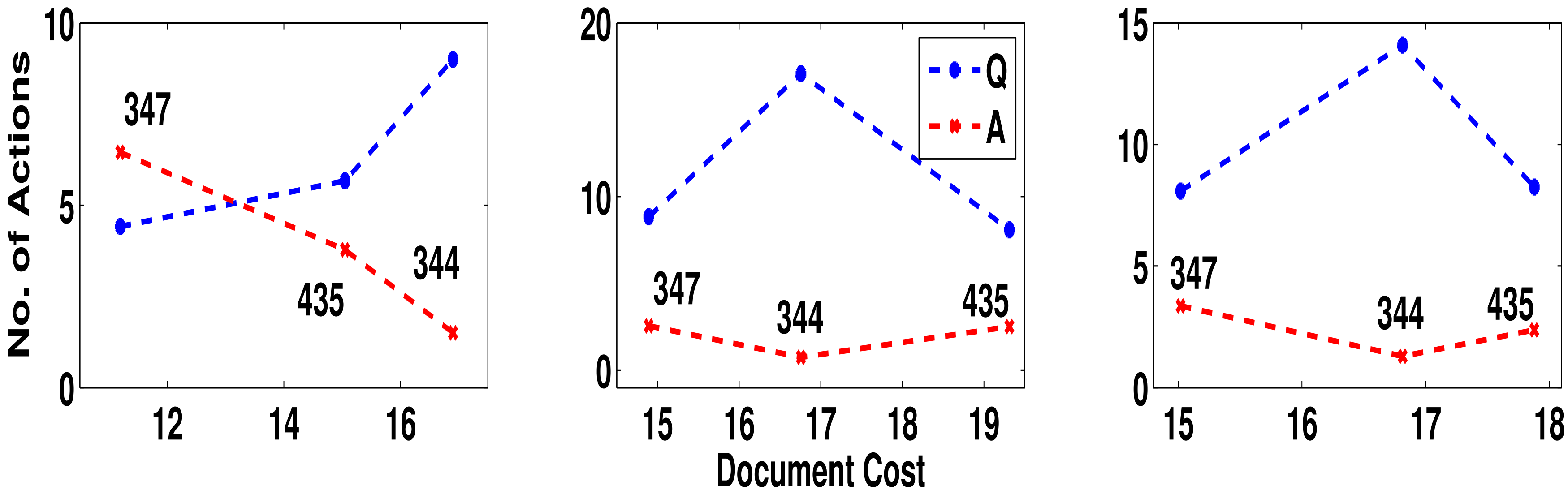
  Q will decrease and **A** will increase.
- Observations tend to match theory

Assessment Probability Hypothesis



- Hypothesis states that as $\mathbf{p_a}$ increases, **Q** decreases, **A** increases
- Observations match theory
- Similar finding for snippet cost hypothesis

Document Cost Hypothesis



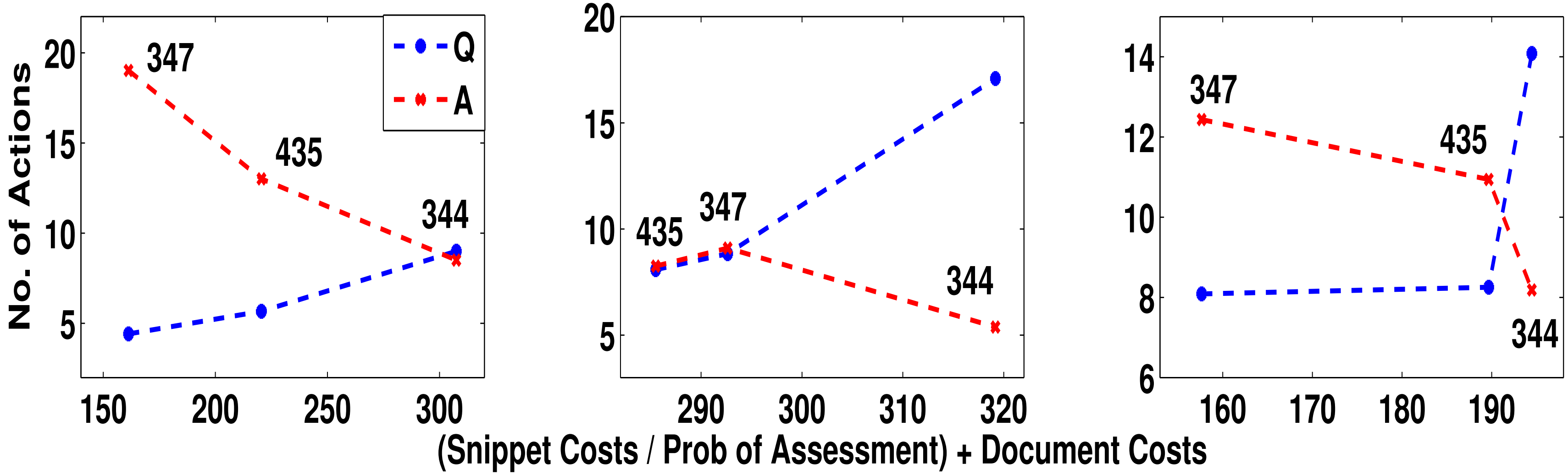
- Hypothesis suggests that as $\mathbf{C_d}$ increases, **Q** should increase, while **A** should decrease
- But clearly this is not the case.

An explanation

$$\mathbf{A}^\star = \frac{\beta.(\mathbf{c_q} + \mathbf{c_v}.\mathbf{V})}{(\alpha - \beta).\left(\frac{\mathbf{c_s}}{\mathbf{p_a}} + \mathbf{c_a}\right)}$$

- $\mathbf{C_s / p_a}$ dominates $\mathbf{C_a}$, so when considered together, the result matched our expectation
- i.e. $\mathbf{C_s / p_a}$ is bigger than $\mathbf{C_a}$, and thus has a greater influence on the results.

An explanation



- As $\left(\frac{\mathbf{c_s}}{\mathbf{p_a}} + \mathbf{c_a}\right)$ increases, then **Q** should increase, while **A** should decrease.
- Considering all three variables we see that this tends holds in practice.

Summary of Empirical Findings

- **The new model generally fits the empirical data**
  - When there were deviations, we could explain these through other variables having a greater influence on the interaction
- **β tends to dominate interaction**
  - i.e. Low **β**, leads to fewer documents being assessed per query
  - $\mathbf{c_s}$ and $\mathbf{p_a}$ also play a major role in shaping interaction

Summary

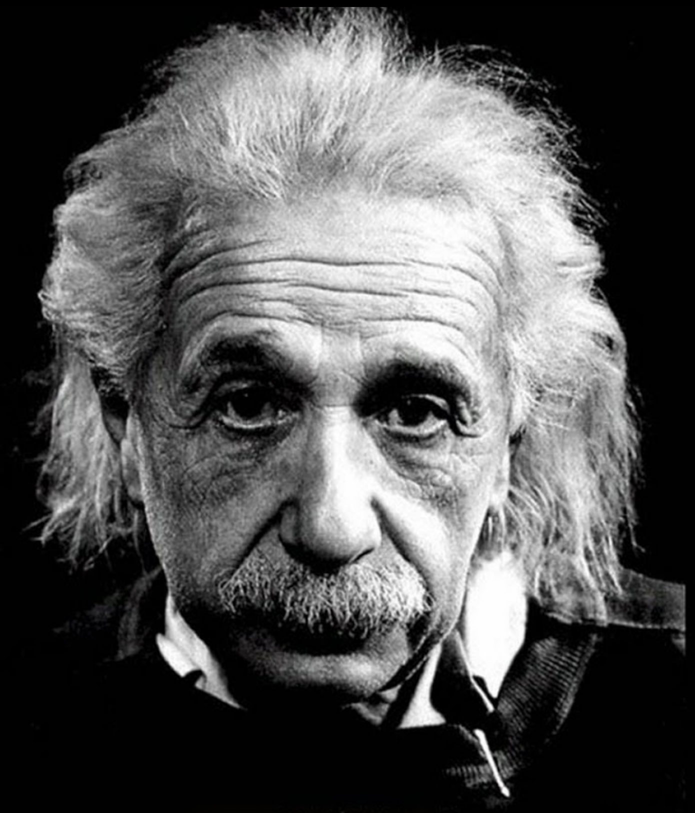
- This new models provides a better description of the search process
- By framing tasks as **economic optimization problems** we can derive **testable hypotheses**!
- These models provide the functional relationships between **interaction**, **performance**, and **cost and how it affects information behaviors**.

Other Scenarios beyond Search

- How much paying vs. playing in pokemon/clash of clans/etc.?
- How much farming vs. fighting in MOBAs?
- How much input when collaborating between players, agents, etc.?
- How many ads vs. content in Spotify, YouTube, PodCasts, etc.?

In theory, theory and practice are the same. In practice, they are not.

Albert Einstein



Is Spotify too good to pay for?

END OF SESSION THREE