# Quantifying Nescience: A Decision Aid for Practicing Managers

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# Abstract

Aristotle's dictum *scio nescio* (I know that I don't know) may serve as a source of enhanced performance for organizations. Awareness of nescience sets the direction for further inquiry, as managers tend to move in the direction that they believe will reduce nescience most. However, nescience is difficult to quantify, so, to date, managers have primarily relied on intuition. Observing business analytics practices in three industries—semiconductor manufacturing, medical diagnostics and social media analytics—suggests that nescience can be measured using metrics from information theory. In semiconductor manufacturing, strategies for problem solving can be explained in terms of Shannon's entropy formula, which indicates the most effective pathway for reducing nescience and identifying the practice with the highest benefit/cost ratio. In medical diagnostics, variants of this formula can be used to reduce nescience to improve the quality of diagnosis. Social media analytics firms reduce nescience to identify loci of influence in online social networks. Nescience is measured by centrality and centralization metrics from information theory. In the aggregate, these observations suggest that metrics for nescience that are based on information theory may serve as a decision aid for practicing managers.

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# Outline

- Introduction
- Background
- *Case 1:* Finding Faults in Semiconductor Manufacturing
- *Case 2:* Braincon Technologies: Predictive Diagnosis in Osteoarthritis
- *Case 3:* Locating Influencers in Online Social Networks
- Conclusions and Discussion

# Introduction

"Scio, Nescio."

(I know that I don't know.)

Aristotle

# What is Nescience?

*(Garcia-Leiva [40])*

- "… a lack of knowledge or awareness."
- Nescience ≠ Ignorance
  - *Ignorance:* Implies choice; knowledge is there.
  - *Nescience:* Knowledge is not there.

# *Known Unknown* vs. *Unknown Unknown*

*(Garcia-Leiva [40])*

- ***Unknown Unknown:***
  - "… the collection of unknown problems, that is, all those problems that have not been found yet, …" *([40] p. 23)*.
  - Example: AIDS in the 1960s
    - Complex of phenomena associated with AIDS
    - had not yet been observed by the medical establishment.
- ***Known Unknown:***
  - "all those already known problems for which we do not know their solutions …" *([40] p. 23)*.
  - Example: AIDS today
    - No cure for the syndrome yet,
    - but studied regularly.
    - Research directions are generally set by knowledge about what we don't know.

# Nescience in Management

*(Hasenauer [46])*

- May serve as a source of enhanced performance for organizations.
- Sets the direction for further inquiry
  - Managers tend to move in the direction that they believe will reduce nescience most.
- Difficult to quantify
  - Managers still primarily rely on intuition.

# Nescience and Problem Solving

- Solving well-structured problems

  *(Pople [79], Ch. 5, Reitman [82], Simon [95])*
  - relies heavily on iterative trial-and-error processes

    *(Baron [15], pp. 43-47),*
  - especially if the problems to be solved are of a technical nature.

    *(Allen [6], Marples [63])*
- Problem solver partitions ‘solution space’
  - —the domain in which the problem’s solution is known to lie—
  - until the problem is solved *(von Hippel [108])*.
- Essentially,
  - the problem solver reduces nescience
  - until nescience is no more.

# *Nescience:* State of the Art

- Lots of theory
- Little empirical work
- Theories have not been put into practice.
- ***Key Issue:***
  - Nescience needs to be quantified,
  - for theory to become useful.

# Further research is needed!

- *Quantitative* analysis of how nescience in its various forms affects organizational performance
- *Qualitative* analysis of the processes through which nescience is reduced.
- Even simple documentation
  - of how nescience is applied in industry
  - would help advance the cause of further study
  - or further application of the approaches discussed above.

# Purpose of Paper

To provide simple theory that quantifies nescience using concepts from information theory.

***Information entropy*** acts as a proxy for nescience.

Validate theory with three cases from industry.

# Information

"A source of information reveals an amount of information $I(X_i)$ whenever the source is in state $X_i$." *(Beckmann [16])*

$I(X_i)$ is known as the ***self-information*** . It is given by

$$I(X_i) = -\log_{10} P(X_i) \text{ hartleys} \qquad (1),$$

where $P(X_i)$ is the probability of occurrence of state $X_i$.

The base of $\log P(X_i)$ determines the units of information. The binary $\log_2 P(X_i)$ is given in "bits"; the decimal $\log_{10} P(X_i)$ is given in "hartleys"; and the natural $\log_e P(X_i)$ is expressed in "nats". *[16]*

# Information Entropy

- ***Information entropy*** is defined as the expectation of $I(X_i)$, or the average amount of self-information per state.
  *(Shannon & Weaver [93])*

- It is given by the random variable

$$H(X_i) = \langle I(X_i) \rangle = \sum_{i=1}^{m} P(X_i)\, I(X_i)$$

$$= - \sum_{i=1}^{m} P(X_i) \log_{10} P(X_i) \text{ hartleys/state.} \qquad (2)$$

# Methodology

- Primarily Action Research *[29] [81]*
  - One of the authors was involved in each case.
- Secondary Sources
  - Articles from the academic literature,
  - Presentations at practitioners' conferences
  - Over 100 semi-structured interviews
    - with technologists, technology managers and entrepreneurs.

# Three Cases

1. Finding Faults in Semiconductor Manufacturing
2. Braincon Technologies: Predictive Diagnosis in Osteoarthritis
3. Locating Influencers in Online Social Networks

# *Case 1:* Finding Faults in Semiconductor Manufacturing

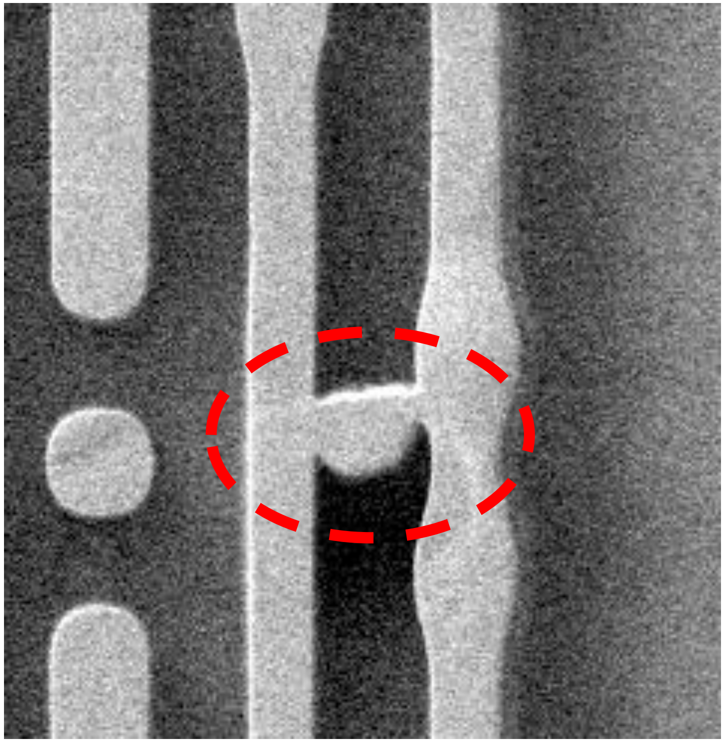


Fig. 1. A physical defect in an integrated circuit interconnect layer that is likely to cause an electrical fault (Courtesy: Applied Materials Corporation).

# *Characteristics of* Semiconductor Manufacturing

- Urgent environment

  *(Gersick [41] [42], Terwiesch & Bohn [104])*
  - Unit price of the IC’s to be sold erodes over time.

    *(Leachman & Ding [52], Weber [111] [113])*
  - A yield problem can easily cost $20,000 per minute

    *(Weber [110])*
- Success depends upon rapid and early learning.

  *(Leachman & Ding [52], Weber [111] [113])*
- Problems need to be solved as rapidly and early as possible.
- Rapid problem localization is critical.
  - Process step that generates faults must be identified ASAP.

# Problem Localization

- Can be accelerated in one of two ways:
  - 1) Extract more information per experimentation cycle
    - Design experiments that look at the complete process .
      *(Sankaran, et al. [86])*
  - 2) shortening the experimentation cycle.
    - Design short-cycle experiments.
      *(e.g., Weber [109], Wein [126])*.
- *Key Question:* How do we reduce nescience the most rapidly:
  - By designing a more comprehensive experiment that runs on a longer cycle,
  - or by performing a sequence of head-to-tail experiments with shorter cycles that reveal less information in the aggregate?

# Managing Experimentation: *Stylized Example*

- Start with baseline of maximum nescience: equiprobability among steps X101-X110.
- Performing E2 reduces entropy (nescience) more than performing E1 does.
- Thus, model recommends performing E2.

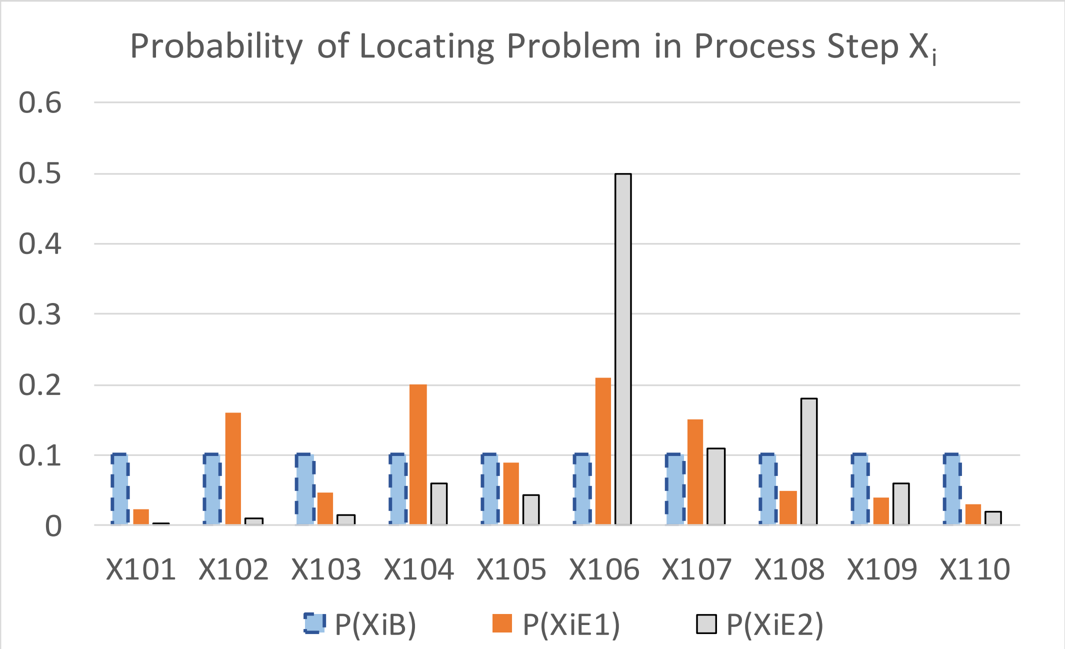



Fig. 2. Probability distributions of a fault occurring in process steps $X_{101}$ - $X_{110}$.

| $H(X_{iB})$ | $H(X_{iE1})$ | $H(X_{iE2})$ | $H(X_{iE1})-H(X_{iB})$ | $H(X_{iE2})-H(X_{iB})$ |
|---|---|---|---|---|
| 1.000 | 0.893 | 0.681 | -0.107 | -0.319 |

Table 1. Comparing information entropies (in hartleys per process step) to localize electrical faults in integrated circuits.

# Limitations of Approach

- Cost of ownership matters.

  *(e.g., Chao, Dance & DiFloria [27], Dance & Jimenez [31], Leckie [53], Martinez et al. [64], Secrest & Burggraaf [90])*

  - Cost of experiments traded off against value
  - Urgency determines value.
  - Mathematical models developed and validated in IC manufacturing

    *(Leachman & Ding [52]; Terwiesch & Bohn [104]; Weber et al. [110]-[113])*

- Problem structure
  - Ill-structured problems

    *(Pople [79], Ch. 5, Reitman [82], Simon [95], von Hippel [108])*

  - Contain ambiguity and uncertainty.

    *(Schrader, Riggs & Smith [89])*

  - Solution space cannot really be defined.
  - Trial-and-error procedures cannot really be implemented successfully.

# *Case-2:*
# Predictive Diagnosis of Osteoarthritis

- Osteoarthritis (OA)
  - Most common form of arthritis
  - Major cause of disability

    *(Bijlsma, Berenbaum & Lafeber [18])*
  - Especially in the knee joint

    *(Pereira, et al. [77])*
- Diagnosis
  - Historically, done by fractal analysis of X-ray images.
  - The assessment of bone surface roughness of the trabecular bone structure seems to be a strong indicator of potential early signs of disease presence and progression

    *(e.g., Benhamou, et al. [17], Pothaud, et al. [80], Rocha, et al. [83])*

# Assessment of Knee-OA

- Based on visual examination
- And subjective grading by physicians

  KL-score *(Kellgren & Lawrence [48])*
- Limiting factor when assessing OA

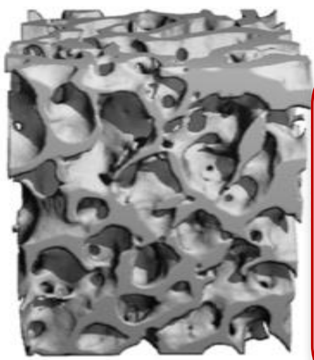
  *(Ljuhar, et al., [58])*
- Limited capabilities when investigating the *early onset* of OA.

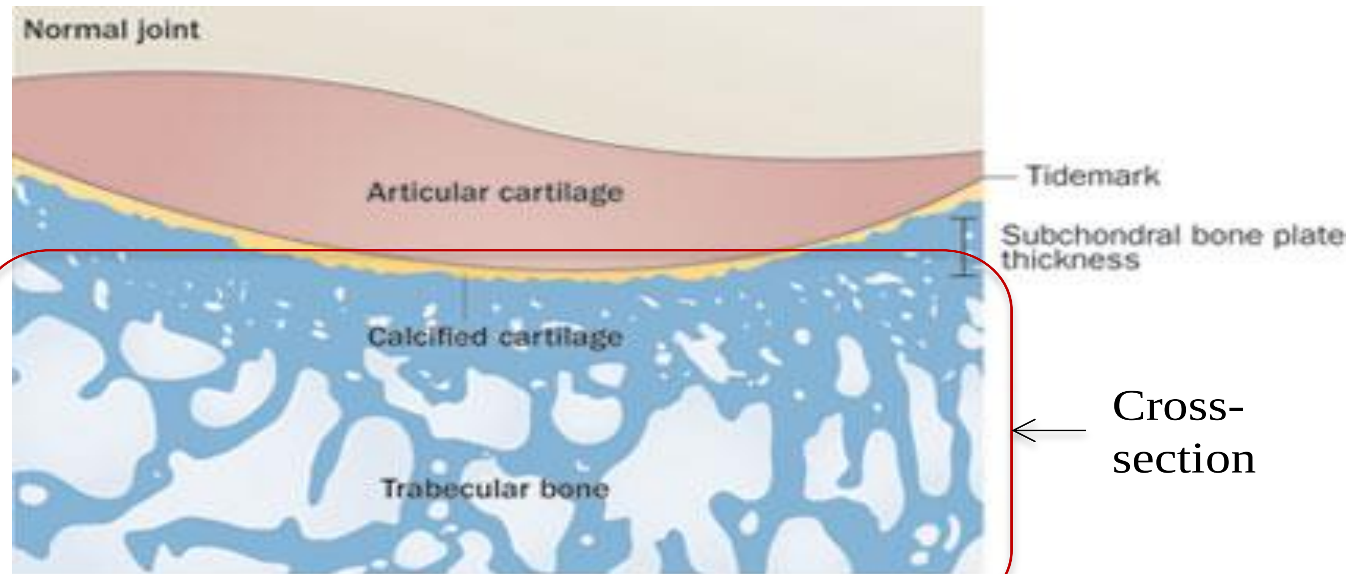
# Cross Section of Normal Knee Joint

*(Ljuhar [56])*

a) Normal joint

3D image
of bone





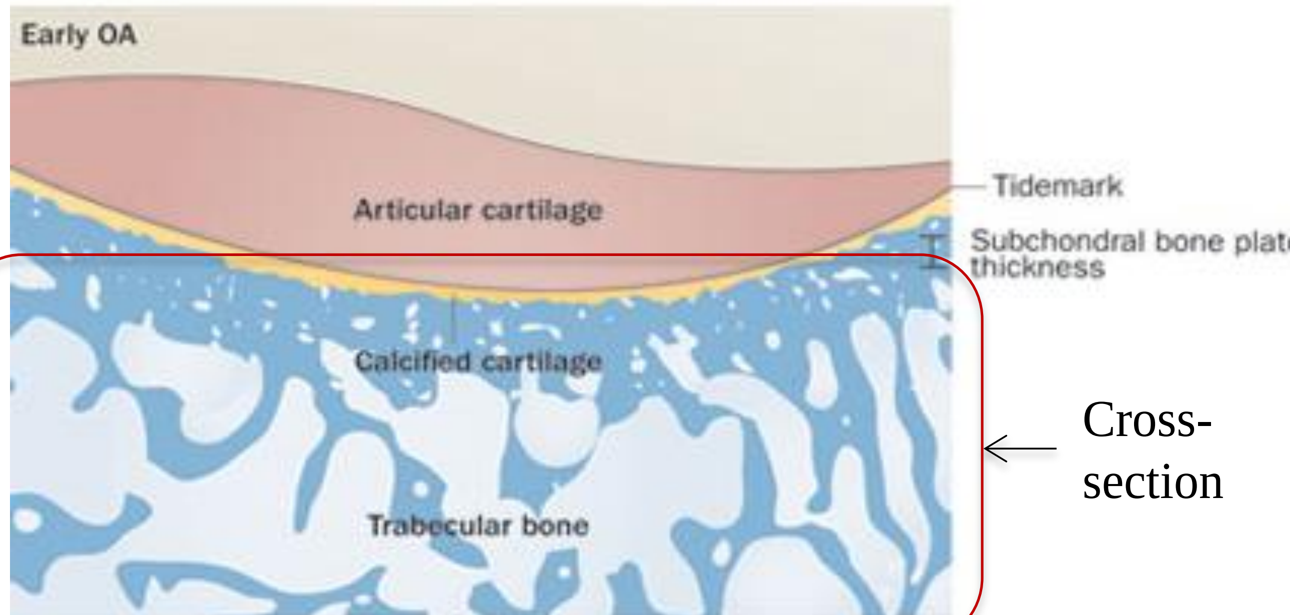

Cross-
section

- Dense bone structure; thick layer of cartilage.

# Early Osteoarthritis

*(Ljuhar [56])*

b) Early OA




Cross-section

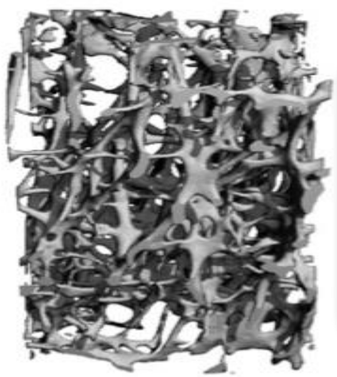
- Subchondral bone plate thickness decreases.

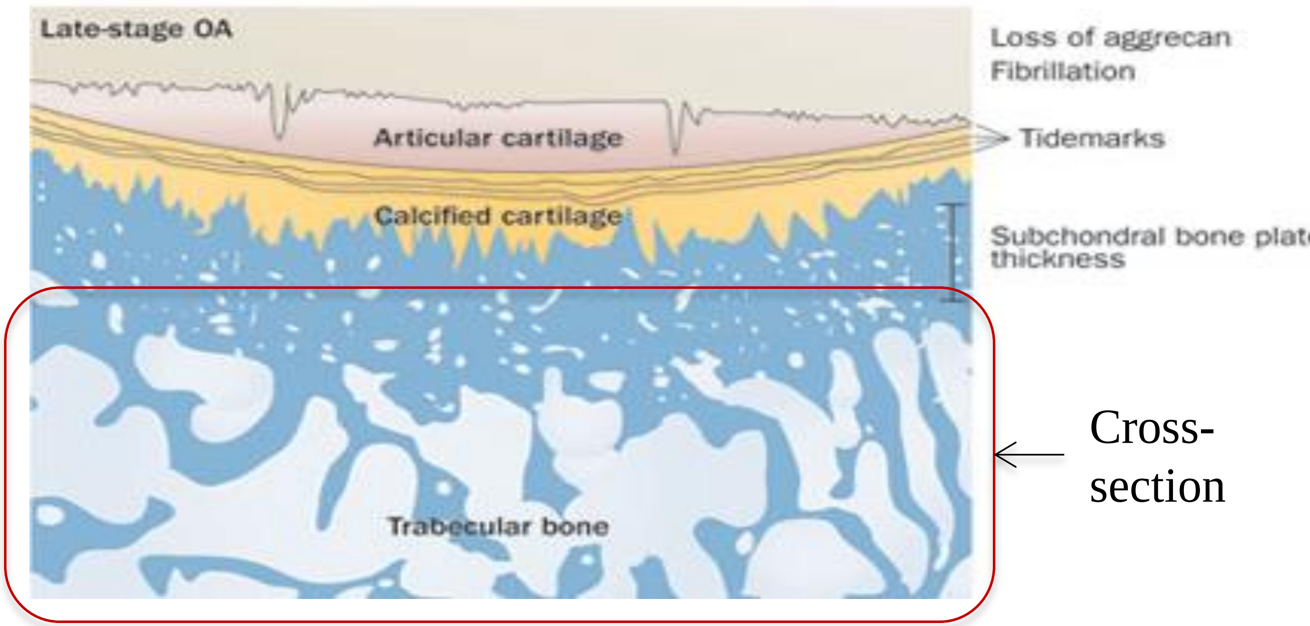
# Advanced Osteoarthritis

*(Ljuhar [56])*

c) Advanced OA

3D image
of bone






Cross-
section

- Cartilage deteriorates.
- Bone structure become brittle.

# Diagnosis of Osteoarthritis

*(e.g., Benhamou, et al. [17], Pothaud, et al. [80], Rocha, et al. [83])*

- Historically done by fractal analysis of X-ray images.
- Surface roughness of bone structure
  - Apparently a strong indicator of potential early signs of disease presence and progression
  - To date, no adequate standard to detect change in bone surface roughness

# Braincon Technologies *(Ljuhar [56])*

- Consortium of technology firms
- Active in industries related to health care.
- Founded in 1992.
- Located in Vienna, Austria
- Wholesaler, developer and solutions provider
- In radiology, medical imaging and medical hygiene.
- Developed the i3A to diagnose OA

# The i3A *(Ljuhar and colleagues [56]-[59])*

- Hardware and software solution for predictive diagnosis of osteoarthritis
- To date, primarily applied to knee.
- Can identify arthritis in its early stages
- by looking at the surface roughness
- of bone structure surrounding the knee joint.
- Helps doctors decide whether patient needs surgery, pharmaceutical treatment or no treatment at all.
- The goal is to minimize risk of fracture.

# How the i3A Works

- The i3A algorithm
  - investigates self-similarity of the grey values in an X-ray
  - by calculating the Bone Structure Value (BSV),
  - a normalized entropy value that has a range from 0 to 1.
- A higher BSV
  - is the result of a high grade of self-similarity,
  - which can be linked to a stable bone micro-architecture.
    - (For formulae of BSV and its relationship to entropy *[93]*, please see *[56]-[59] [83]*.)

# Reduction of Nescience

- Analogous to problem solving in semiconductor industry
  - In both cases, nescience is reduced automatically,
  - i.e. faults are localized by sophisticated diagnostic imaging tools *[86] [120]*.
- Start with assuming  equiprobability, i.e. a BSV of 1.
- Compare gray scale value of each pixel to the gray scale values of all adjacent pixels.
- High differentials in gray scale translate into a concentration of probability, or a low BSV.
- Location becomes increasingly ‘suspicious’.

# *Problem Solving:* i3A vs. IC Manufacturing

## *i3A*

- Operates in two physical dimensions
- Scans the *surface* of the bone

## *IC Manufacturing*

- Operates in one virtual dimension
- Takes place on a virtual *number line*
  - the sequence of steps in the manufacturing process.

# Impact of i3A

- improves quality of diagnosis,
  - which allows it to act as a decision aid.
- Before i3A
  - bones diagnosed as healthy or unhealthy
  - depending on the measurement of bone mineral density.
- i3A provides three options:
  - no arthritis, early-stage arthritis , and late-stage arthritis.
- Each of these stages warrants different treatment.
  - no treatment; pharmaceutical approach; mandatory surgery.

# Impact of i3A (Continued)

- Instrument of predictive maintenance.
- Enabling widespread deployment of pharmaceutical approaches.
- Physician
  - prescribes less invasive pharmaceutical approach,
  - preventing more intrusive surgery at a later date.
- Reduces the frequency of calamitous false negatives.
- An incorrect diagnosis of ‘healthy’ on a brittle bone is becoming increasingly rare.

# *Case-3:* Identifying Influencers Online

- Xilinx
  - Silicon-Valley-based semiconductor firm
  - Primarily produces floating point gate arrays (FPGAs).
- In 2011, Xilinx's management
  - realized that there was a lot about their markets that they did not know,
  - especially when it came to social media.
- Hired a social media analytics firm (codenamed SMAF)
  - to analyze the Twitter conversations
  - about its products, services and technologies.
- Xilinx hoped that SMAF's analysis
  - would provide feedback
  - on how it Xilinx is doing its existing markets
  - and perhaps identify some new market opportunities.

# SMAF

- Identified key influencers
  - by deploying a multi-step process
  - that reduced nescience.
- Recorded all traffic pertaining to Xilinx's Twitter account, @xilinx,
  - for a period of two months
  - from 01/12/2012 to 03/12/2012.
- Bi-directional analysis
  - Differentiated between consumption and propagation of information
- Ranked nodes by propagation potential
  - Information theory provides measures of influence.
- Generated visual formalisms for network
- Conducted semantic analysis of network

# Entropy Centrality

*(e.g., Mayande & Weber [67], Nikolaev, et al. [73], Tutzauer [107])*

- Identifies key influencers in network
- Entropy-based centrality for information flow for all shortest paths (geodesics) between a node $v_i$ and all other nodes in the network $v_j$ is given by

$$H_i = \sum_{j=1}^{n-1} P_{i,j} \log P_{i,j} \, , \qquad (3)$$

- where $i \neq j$,
- where $n$ denotes the total number of nodes in the network,
- and where $P_{i,j}$ represents the probability that information flows between $v_i$ and $v_j$ .

# Entropy Centralization

*(e.g., Mayande & Weber [67], Nikolaev, et al. [73], Tutzauer [107])*

- Quantifies concentration of information within the whole network
- Identifies key regions of influence within a network

The total entropy centrality for geodesic serial flow, or entropy centralization for the whole network, is given by

$$H_T = \sum_{i=1}^{n} H_i \quad . \qquad (4)$$

# Community Identification

- Identified community of 571 accounts (nodes),
- Moderately active community
  - communicated a total of 1176 times
  - 453 @mentions and 723 retweets
- Served as the solution space
  - of any subsequent analysis
  - because any node that was neither directly nor indirectly connected to @xilinx
  - could not exert influence on that node.

# Propagation Potential

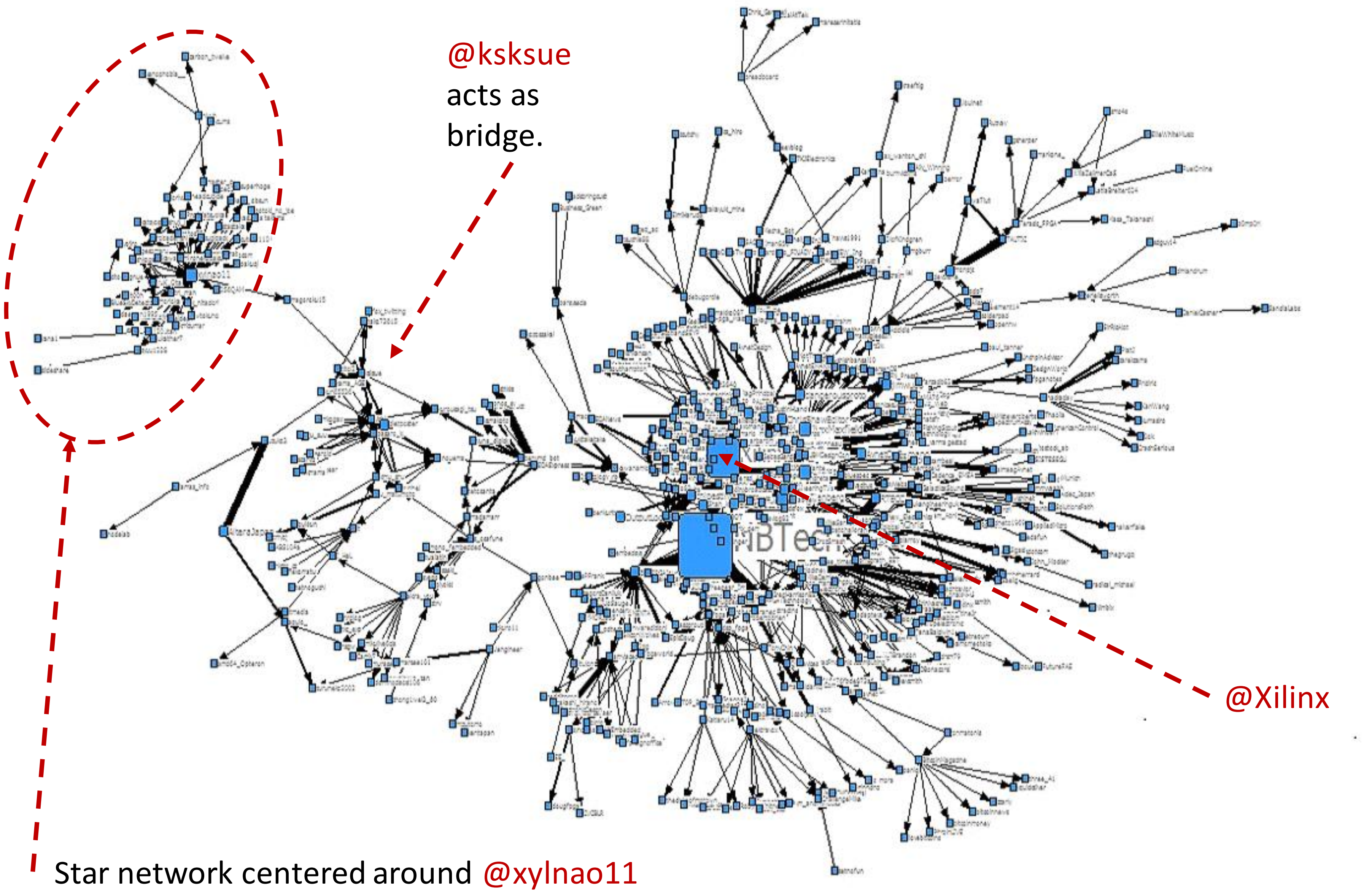
## *(Normalized Entropy Centrality)*

| *Rank* | *Screename* | *Normalized Propagation Potential* |
|---|---|---|
| 1 | ***xylnao11*** | 1.000 |
| 2 | alteracorp | 0.723 |
| 3 | AvnetOnDemand | 0.685 |
| 4 | dietposter | 0.369 |
| 5 | FPGATechnology | 0.240 |
| 6 | basaro_k | 0.174 |
| 7 | ***ksksue*** | 0.122 |
| 8 | ee_times | 0.110 |
| 9 | yishii | 0.088 |
| 10 | s_osafune | 0.077 |

- Who are these people?
- Why is their propagation potential for your message so high?

Table 2. Top 10 screen names by propagation potential

# Community Visualization



# Further Analysis by SMAF

- Xilinx can get to star network via *@ksksue*.
  - Link to star network would collapse without him/her.
- Semantic analysis of star network
  - reduces nescience even more.
  - Revealed that community
  - was a group of automotive engineers in Japan,
  - who were talking about using FPGAs
  - to detect pedestrians through vision sensors.
- Conversations were definitely of interest to Xilinx,
  - a leading maker of FPGAs,
  - as they comprised a potential market opportunity.

# Conclusions

- Paper described three cases of how managing nescience facilitated problem solving in high technology settings.
- In all three cases, variants of Shannon's original entropy formula *[93]* acted as a proxy measure for nescience.
- Reduction of nescience is tantamount to reducing entropy
  - by localizing a problem
  - or by shrinking its solution space.
- Nescience-based approaches act as decision aid for managers, if nescience can be measured in terms of entropy.
- Managers can pursue the approach that is projected to reduce entropy the most.
- Degree to which reduction of nescience determines problem-solving strategies in practice depends upon context.
- *Contribution to theory:* Paper showed that nescience can be quantified using metrics from information theory.

# Additional Lessons Learned

- Motivations for reducing nescience are highly context specific.
  - *IC Manuf.:* Urgency → Problem–solving speed
  - *Braincon:* Quality of diagnosis → Quality of Life
  - *Xilinx:* Discovery leads to opportunity.
- Reduction of nescience is valued higher in the Braincon and Xilinx cases

# Observation

- Practitioners do not use ‘nescience’ in day-to-day conversations.
  - Many may not know what ‘nescience’ means.
  - ***Semiconductor*** engineers talk about ‘localizing the problem’.
  - Solution providers in ***Braincon*** case use ‘entropy’ quite openly.
  - Their customers, the physicians, do not.
  - Neither group openly discusses nescience.
  - Centrality metrics are at the center of many discussions in ***social network analysis***.
  - However, the term nescience is not.

# Explanation

- Problem-solving practitioners
  - focused on resolving their particular problems
  - instead of developing generic approaches to problem solving
    - (Baron *[15]*, Marples *[63]*, Pople *[79]*, Reitman *[82]*, von Hippel *[108]*).
  - Contributions to a more general theory of problem solving are likely to come from more academic study.

# Limitations of Research

- Nescience implies absence of knowledge
  - rather than absence of information,
  - and entropy is a measure of information rather than knowledge.
  - "… knowledge is more than information. It is information that is sufficiently certain *[93]* and sufficiently contextualized to enable human action *[101]*." (Weber & Mayande *[117]*, p. TBD)
- Findings are based on action research
  - rather than a broadly based quantitative study.
  - They may thus not be generalizable.
- Attempts to build a more general theory of nescience (e.g., Garcia-Leiva *[40]* and Klein *[50]*)
  - could make significant contributions to understanding nescience.
  - These endeavors will hopefully stimulate further empirical studies through which evolving theories of nescience can be validated.

Thank you for your attention!

# QUESTIONS AND ANSWERS

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