

MASSIVIZING COMPUTER SYSTEMS

= MAKING COMPUTER SYSTEMS SCALABLE, RELIABLE, PERFORMANT,
ETC., YET ABLE TO FORM AN EFFICIENT ECOSYSTEM

THE SCIENCE OF DISTRIBUTED ECOSYSTEMS

@Large Research
Massivizing Computer Systems



<http://atlarge.science>

Co-sponsored by:



WHO AM I?

PROF. DR. IR. ALEXANDRU IOSUP

- Education:
 - > Systems Architecture (BSc)
 - > Distributed Systems (MSc)
- Research:
 - > Massivizing Computer Systems

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- Education:
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- Research:
 - > Massivizing Computer Systems
- About me:
 - > Worked in 7 countries, NL since 2004
 - > I like to help... I train people in need
 - > VU University Research Chair
 - > NL ICT Researcher of the Year
 - > NL Higher-Education Teacher of the Year
 - > NL KNAW Royal Young Academy



NOI RADACINI .nl — 22,000 ROMANIANS IN NL 60% WORKING, 30% STUDENTS (SOME AT VU)



BY CLAUDIA MARCU AND ALEXANDRU IOSUP + MANY VOLUNTEERS



Mihai Netea

<http://bit.ly/NR-Mihai>



Ana Maria Oprescu

<http://bit.ly/NR-AnaMaria>



Teodor Cătănicu

<http://bit.ly/NR-Teodor>

<http://noiradacini.nl>

WHO AM I? PROF. DR. IR. ALEXANDRU IOSUP

- Early vision, age 14, in 1994:
 - > Computers for everyone
 - > Education for everyone
 - > The Netherlands

Van Basten.

părinți. **Jubesc calculatorul** și am câștigat acest concurs tocmai propunând celor mari ca din miliard să cumpere 1.000 de calculatoare pentru a se realiza **în școli o rețea națională**, spune Alexandru.

INȚĂȚĂMÂNT

ADEVĂRUL

"România trebuie să devină o putere"

- consideră un câștigător (ne)obișnuit -

Alexandru Iosup are 14 ani (născut în 12 iunie 1980) și este elev al Școlii nr. 19 din București. Mic la stat, dar mare la sfat, Alexandru este unul din cei patru câștigători ai concursului. „Ce să faci cu un miliard” inițiat de MTS. Cei 50 de mil de lei primiți ca premiu al revistei „Modelism” i-a cheltuit cu „cap”, luându-și o minge de fotbal **adeverată** pentru că este **microbist convins** și are ca idoli pe Maradona și **Van Basten**. În privința banilor, copilul are o nedumerire: „Am primit exact 42 de mil lei. De ce s-o fi impozitând și premiul, nu înțeleg”. Nici noi nu pricepem, dar asta e. Oricum, din ce i-a rămas, își va luat ceva pentru calculatorul pe care de curând (după premiere) l-a primit ca dar de la părinți. **Jubesc calculatorul** și am câștigat acest concurs tocmai propunând celor mari ca din miliard să cumpere 1.000 de calculatoare pentru a se realiza **în școli o rețea națională**, spune Alexandru.



vine de la faptul că s-ar simți sărac.

VISION:
WHAT DOES OUR SOCIETY NEED?

prosperous society

blooming economy

inventive academia

wise governance

VISION: WHAT DOES OUR SOCIETY NEED?

ISN'T THIS ALREADY HAPPENING?

“A world where **individuals** and **human-centered organizations** are **augmented by an automated, sustainable layer of technology**. At the core of this technology is ICT, and at the core of ICT are **computer ecosystems**, interoperating and performing as utilities and services, under human guidance and control.”

- People, good orgs = ICT clients:
 - > Fundamental right to ICT
 - > Understanding
- ICT professionals:
 - > Experiment and create
 - > Operate
- ICT = ecosystems:
 - > Utilities and services
 - > Automated
 - > Efficient
 - > Controlled
 - > Ecosystems
 - > Human-guided

THIS IS THE GOLDEN AGE OF DISTRIBUTED ECOSYSTEMS



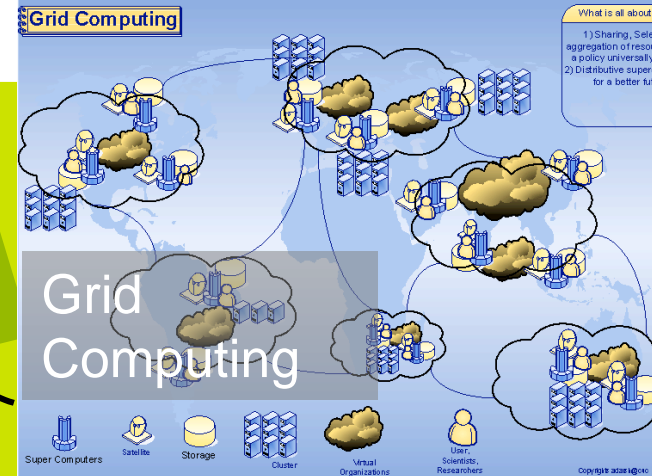
Education for Everyone (Online)



Business Services



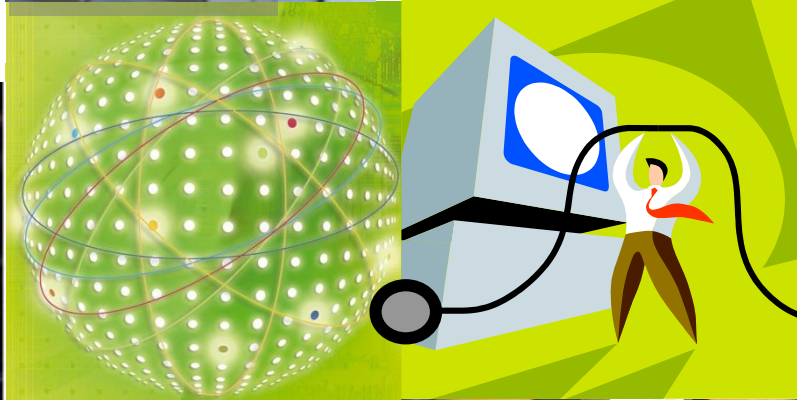
Cloud Computing



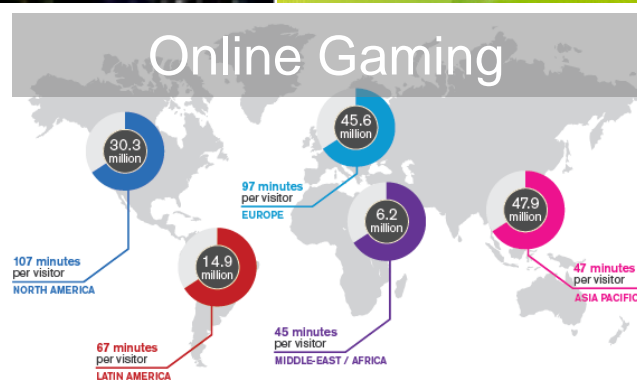
Grid Computing



Big Science



Online Gaming



AVERAGE DAILY ONLINE GAMERS WORLDWIDE

Source: comScore MMX, Worldwide, April 2013, Age 15+



Datacenters



Daily Life



BIG DATA

THIS IS THE GOLDEN AGE OF DISTRIBUTED COMPUTER SYSTEMS



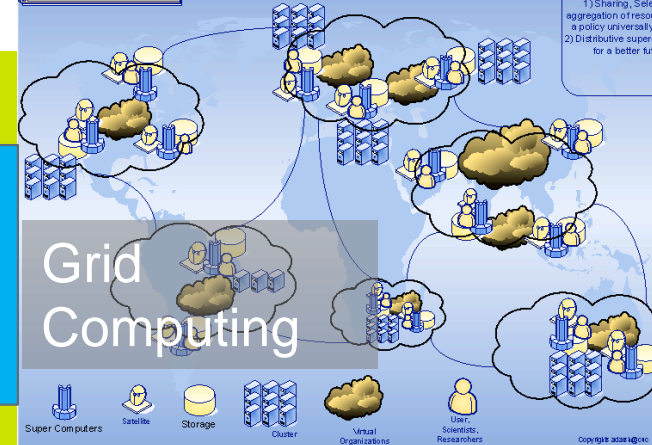
Education for Everyone (Online)



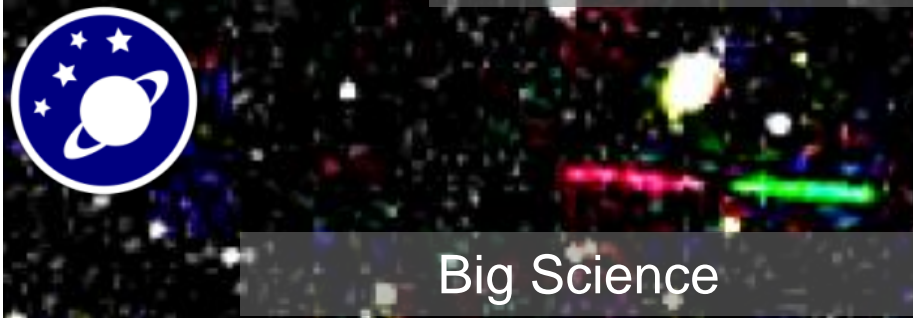
Business Services



Grid Computing



Grid Computing

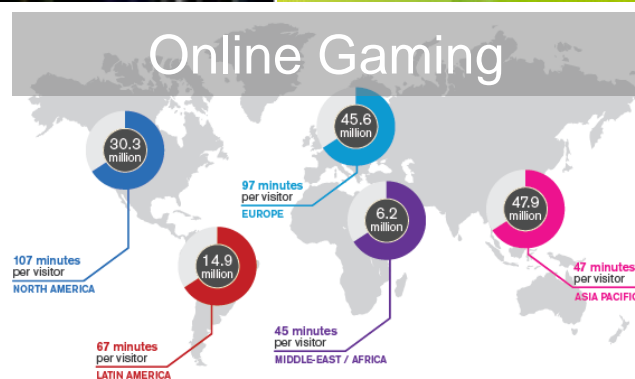


Big Science

Here is how this works...



Daily Life



AVERAGE DAILY ONLINE GAMERS WORLDWIDE

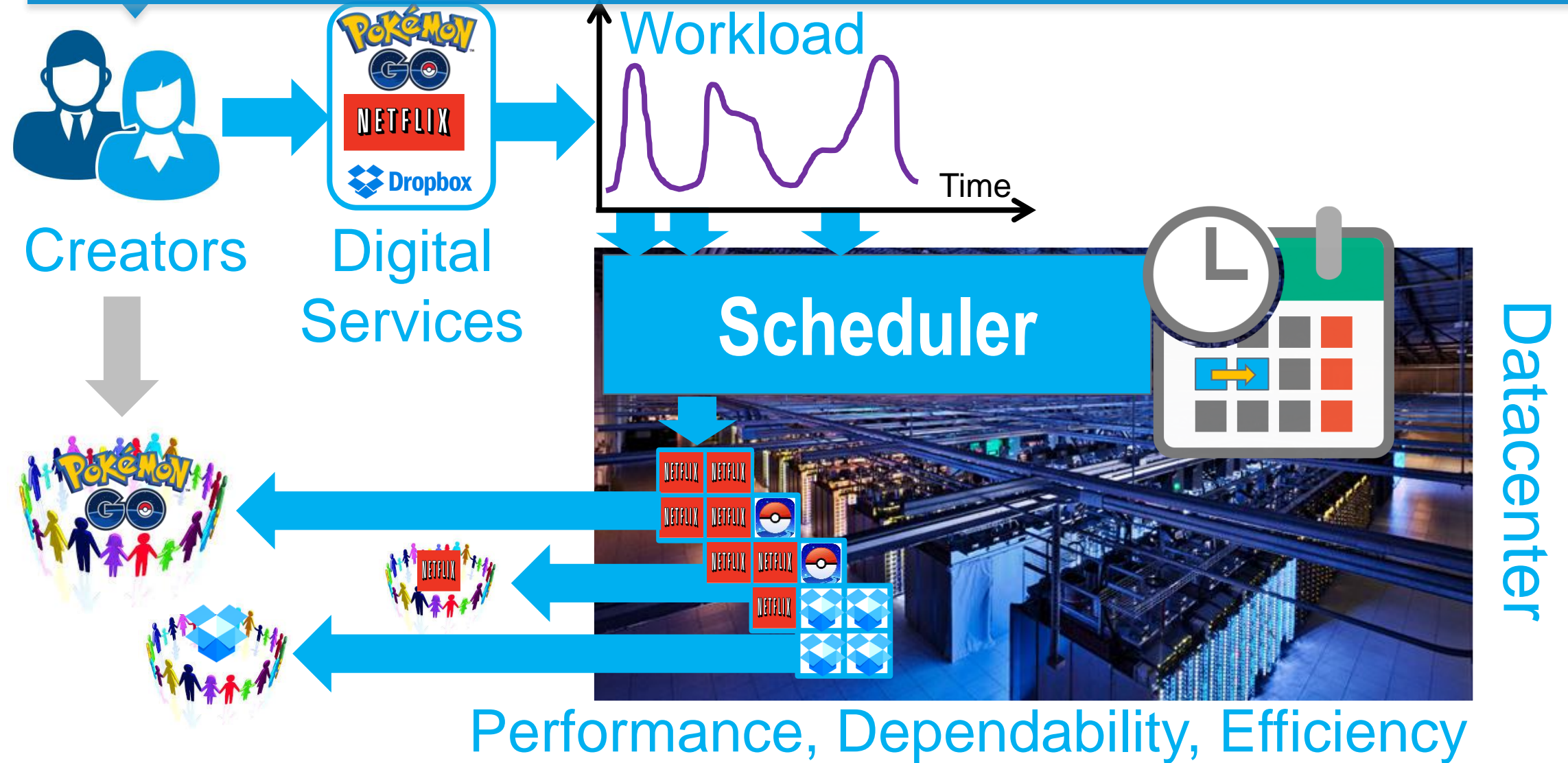
Source: comScore MMX, Worldwide, April 2013, Age 15+



Datacenters



THE CURRENT TECHNOLOGY STACK: DATACENTER, SCHEDULER



VISION: WHAT DOES OUR SOCIETY NEED?





PARTIALLY HAPPENING

“A world where individuals and human-centered organizations are augmented by an automated, sustainable layer of technology. At the core of this technology is ICT, and at the core of ICT are computer ecosystems, interoperating and performing as utilities and services, under human guidance and control.”

- Clients:

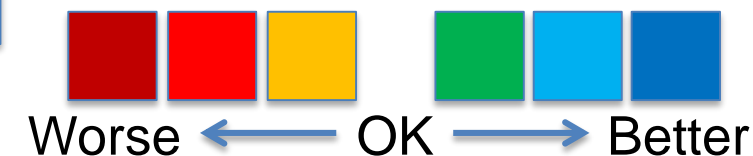
- > Fundamental right to ICT 
- > Understanding 

- Computer **professionals**:

- > Create  
- > Operate 
- > Experiment 
- > ...

- ICT:

- > Utilities/services 
- > Automated 
- > Efficient 
- > Controlled 
- > Ecosystems 
- > Human-guided 



IN THIS DIGITAL ECONOMY, FEW CAN BE SUCCESSFUL!

Why does this happen?



Creator Creator Creator Creator

~~Opportunity To Create
and Operate ICT Services~~

What to do about it?

This Research

NETFLIX



“ICT is vital for SMEs”, “SMEs are 60% GDP”

Sources: Eurostat'15, EC Digital Agenda, IDC'14

THE CRISIS: IN THIS DIGITAL ECONOMY, FEW CAN BE SUCCESSFUL!

THE COMPLEXITY CHALLENGE

1. We Build and Test Isolated Computer Systems, Yet Everything Works in Ecosystems



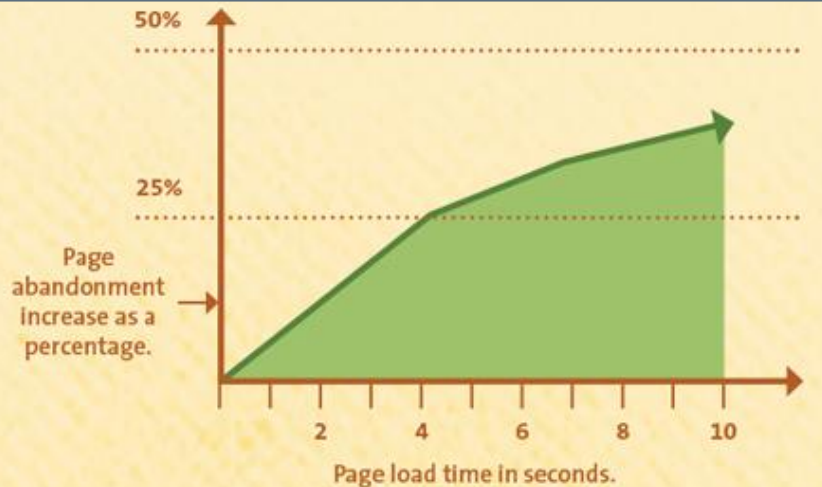
A grid of logos for various data science and technology companies, organized into categories. The categories include: Hadoop On-Premise (Cloudera, Hortonworks, MAPR, Pivot), Hadoop in the Cloud (Amazon, Microsoft Azure), Spark (Databricks), Cluster Services (Amazon, Microsoft), Analyst Platforms (Palantir), Analytics Platforms (Microsoft), Data Science Platforms (ContextRelevant, DataRobot), Visualization (Tableau), Sales & Marketing (Radius, Gainsight, Bloomreach, Zeta), Customer Service (Medallia), Human Capital (Ardent), Legal (Ravel, JUDICATA, Everlaw, Brevia, Premonition), NoSQL (Amazon, Microsoft Azure, MongoDB, Aerospike, SequoiaDB), Graph Databases (Neo4j, OrientDB, InfiniteGraph), Management / Monitoring (New Relic, Dynatrace, AppDynamics, Splunk, Datadog, Driven, Anodot, Code42, DataGravity, Pantheon, NimbleStorage, Coho Data, Quimulo, CRSK, Typesafe, CrowdFlower, Lucidworks, Elastic, ThoughtSpot, MAANA, Swifttype, Algolia, Sinequa, EXL, ClearStory, Cirro, Import.io, Mixpanel, RjMetrics, Amplitude, Granify, SumAll, Retention, Custora, Learning Knewton, Clever, 23andMe, Counsyl, Recombine, Yruus, Flatiron, Zymogen, HealthTop, OPOWER, eHarmony, RetailNext, Stitch Fix, WorkFusion, BlueRiver, Tachyus).

<<1% OF BIG DATA BY MATT TURK (2017)

THE CRISIS: IN THIS DIGITAL ECONOMY, FEW CAN BE SUCCESSFUL!

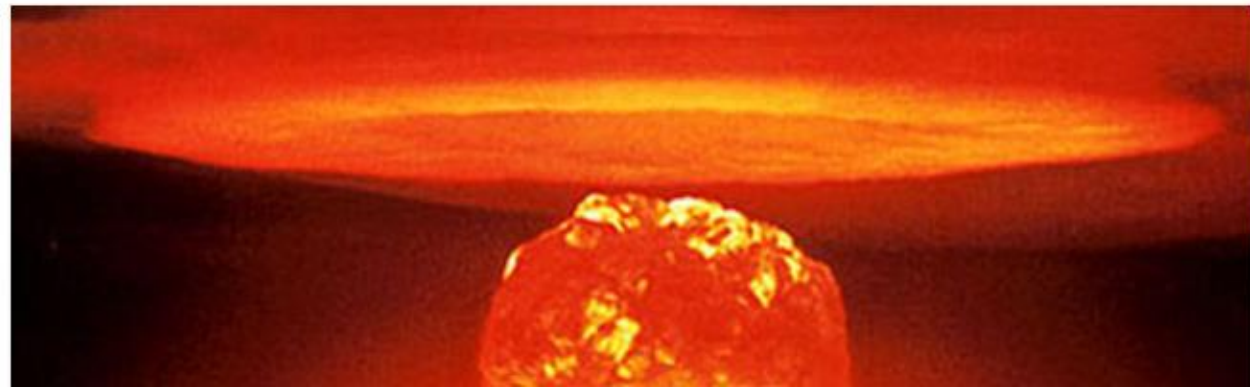
PERFORMANCE, DEPENDABILITY, AND OTHER NON-FUNCTIONAL CHALLENGES

2. We Cannot Even Maintain the Ecosystems we Have Built (and Tested, and Validated)



Google goes dark for 2 minutes, kills 40% of world's net traffic www.theregister.co.uk/2013/08/17/google_outage/

Systemwide outage knocks every service offline



THE CRISIS: IN THIS DIGITAL ECONOMY, FEW CAN BE SUCCESSFUL!

THE RESOURCE MANAGEMENT CHALLENGE

Based on Jav Walker's recent TED talk.

3. Need To Be Much More Efficient,

4. Need to Also Be Ethical, and to Also Educate Our Customers

PSY Gangnam consumed ~500GWh

= more than entire countries* in a year (*41 countries),

= over 50MW of 24/7/365 diesel, 135M liters of oil,

= 100,000 cars running for a year, ...

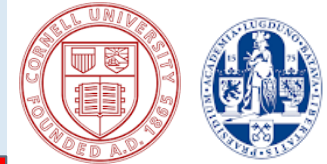
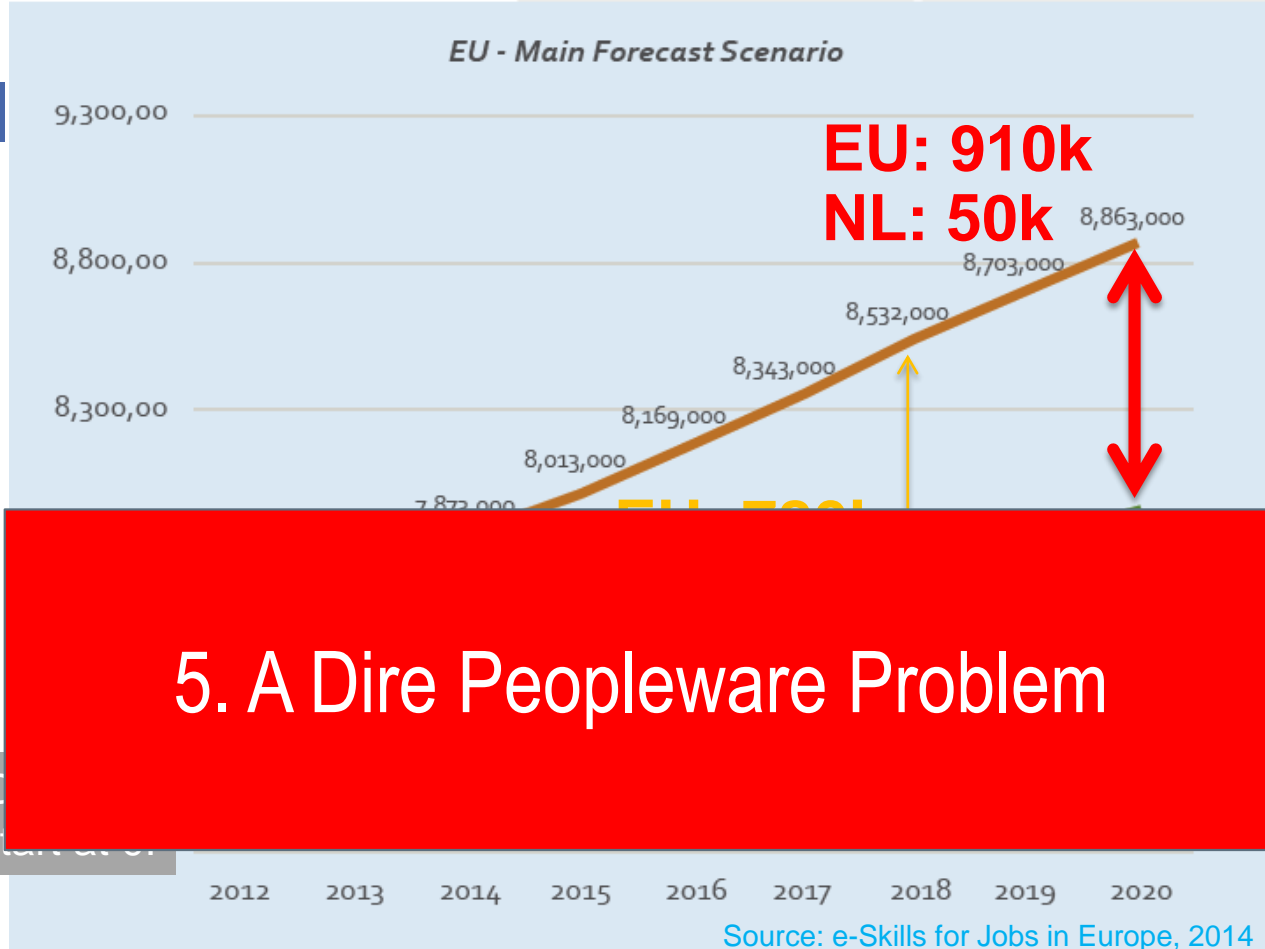
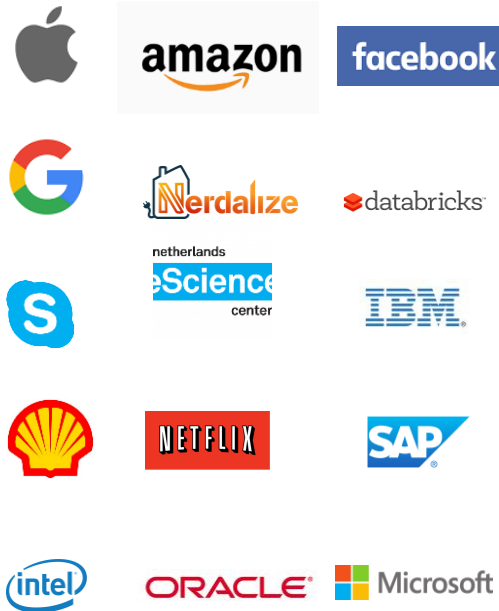
Source: Ian Bitterlin and Jon Summers, UoL, UK, Jul 2013.

Note: Psy has >3.5 billion views (last update, May 2018).



THE CRISIS: IN THIS DIGITAL ECONOMY, FEW CAN BE SUCCESSFUL!

THE WORKFORCE GAP, IN THE NETHERLANDS & IN EUROPE



THIS IS THE GOLDEN AGE OF DISTRIBUTED COMPUTER SYSTEMS

YET WE ARE IN A CRISIS – 5 CORE PROBLEMS

1. The Current Laws and Theories
Are Built and Tested for
Isolated Computer Systems

TRADITIONAL DISTRIBUTED SYSTEMS
COURSES TEACH YOU ALL ABOUT THIS

2. Need to Understand
How to Maintain Ecosystems

3. Need to Understand
How to Make Ecosystems
Automated, Efficient (Smarter)

4. Beyond Tech: Need to
Also Be Ethical

5. Need to Address
the Peopleware Problems

THIS IS THE GOLDEN AGE OF DISTRIBUTED COMPUTER SYSTEMS

YET WE ARE IN A CRISIS

WHICH WE & YOU CAN HELP SOLVE!

Massivizing Computer Systems Tackles The Challenges of Distributed Systems and Ecosystems...

... and Is Relevant, Impactful, and
Inspiring for Many Young Scientists and Engineers

OUR DISTRIBUTED SYSTEMS COURSE



~40'

Massivizing Computer Systems

The Science of Distributed Ecosystems

~10' — Vision, Current Golden Age of Ecosystems, and Crisis →

~5' — Intermezzo: What Is Modern Science? →

~20' — Massivizing Computer Systems →

1. Stakeholders →
2. Meaningful discovery: science + engineering + design →
3. Experimental method for discovery + Reproducibility/Validation →
4. Codified and teachable Science →
5. What's left? →

~2' — Take-home message →

BUT WHAT IS “A SCIENCE”? WHAT IS A MODERN SCIENCE?

Science starts from...

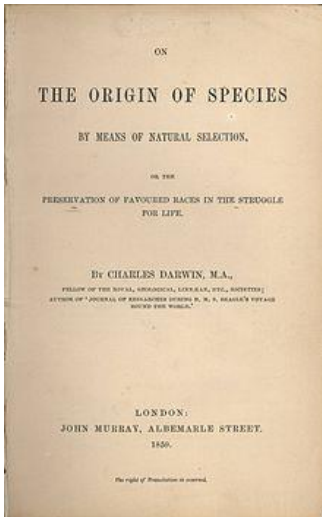
a new
theory

a new
way of thinking

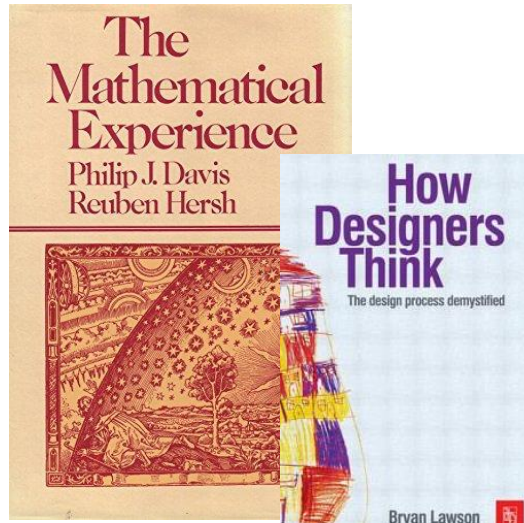
several new
principles

needs arise
from practice

theory-practice
gap too large



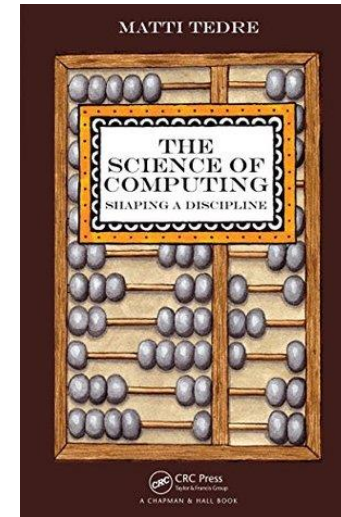
Darwin (1859)
The Origin of Species



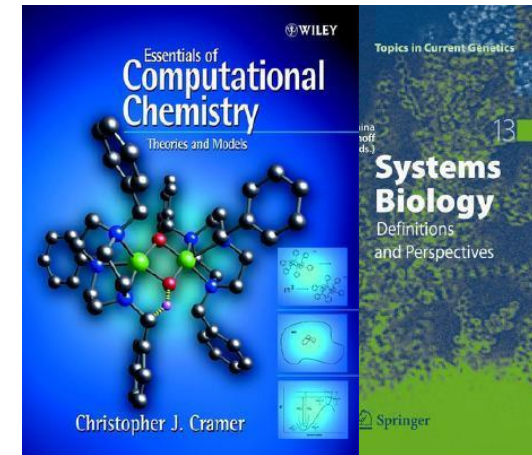
Davis and Hersh (1982)
The Mathematical Experience
Lawson (2005)
How Designers Think



Denning and Martell (2015)
Great Principles of Computing
The Science of Computing



Tedre (2014)
The Science of Computing



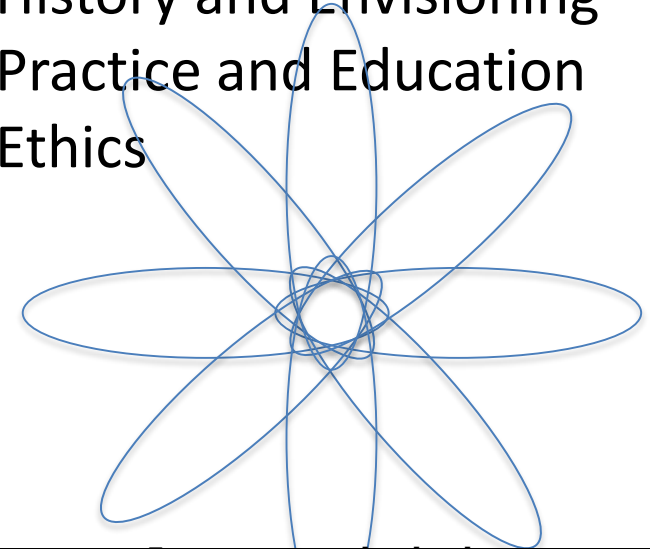
Cramer (2004) Essentials of
Computational Chemistry
Alberghina and Westerhoff (2007)
Systems Biology

BUT WHAT IS “A SCIENCE”? WHAT IS A MODERN SCIENCE?

A SCIENCE OF ECOSYSTEMS

- Denning’s criteria for a new field of science:
 - > Focus on pervasive phenomena
 - > By and for clear stakeholders
 - > Meaningful discovery
 - > Experimental methods of discovery
 - > Methods of validation
 - > Reproducibility of results
 - > Falsifiability of theoretical constructs
 - > Body of knowledge and skills that can be codified and taught

- My definition for a modern field of science:
 - > Fundamentals and Applications
 - > Methodology and Philosophy
 - > History and Envisioning
 - > Practice and Education
 - > Ethics



Denning, The science in computer science, CACM 56, 2013.

Iosup et al., Massivizing Computer Systems, ICDCS 2018. [[online](#)]



~40'

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~2' — Take-home message →

THIS IS THE MODERN SCIENCE OF DISTRIBUTED ECOSYSTEMS

MASSIVIZING COMPUTER SYSTEMS IN A NUTSHELL

WHO?

 SCIENTISTS,  ENGINEERS,  DESIGNERS,  MANAGERS, ETC.

WHAT?
MAIN GOAL

UNDERSTAND AND CONTROL DISTRIBUTED ECOSYSTEMS, TO
TURN THEM INTO EFFICIENT, AUTOMATED UTILITIES

HOW?
CENTRAL PARADIGM

ECOSYSTEM OPERATION AND CHARACTERISTICS DERIVE
NON-TRIVIALY FROM ITS SYSTEMS AND USERS (RECURSIVELY)

WHICH APPROACH?

MODERN DISTRIBUTED SYSTEMS AND PROBLEM-SOLVING





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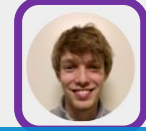

STAKEHOLDERS ALSO INCLUDE: ATLARGE RESEARCH, OUR TEAM

<http://atlarge.science/people.html>

-  Professor
-  Assistant Prof.
-  Teacher
-  Post-doc
-  Ph.D. student
-  Scientist


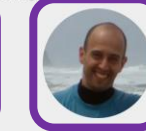

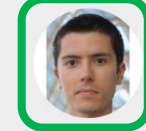
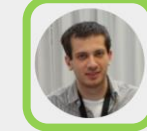

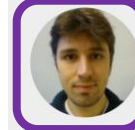

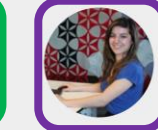


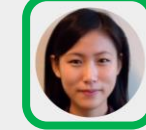




Faculty and Current Team Members

This four, now

 Alexandru Iosup University Research Chair and Full Professor, Vrije Universiteit Amsterdam	 Otto Visser Chief Advisor	 Caroline Wajj Project Manager	 Opening Assistant Professor		
 Georgios Andreadis Project Lead ATLarge Website	 Sietse Au M.Sc. student, TU Delft	 Johannes Bertens M.Sc. student, TU Delft	 Jesse Donkervliet M.Sc. student, TU Delft	 Tim Hegeman M.Sc. student, TU Delft	 Alexey Ilyushkin Ph.D. student, TU Delft
 Chris LeMaire Team Graphalytics	 Fabian S. Mastenbroek Team OpenDC	 Ahmed MUSAafir Researcher, Vrije Universiteit Amsterdam	 Mihai Neacsu M.Sc. student, Vrije Universiteit Amsterdam	 Leon Overweel Product Lead OpenDC	 Sacheendra Talluri M.Sc. student, TU Delft
					

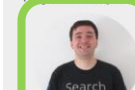





Alumni

They have completed a long-term project in our team.

 Shanny Aneop Team VL-e	 Athanasios Antoniou Team ATLarge	 Marcin Biczak Researcher in graph-processing team	 Mihai Capota Tech Lead Graphalytics	 Bogdan Ghit Ph.D. student, TU Delft	 Yong Guo Graph processing
 Stijn Heldens Researcher, TU Delft	 Adele Lu Jia Social gaming	 Elvan Kula Honors Track	 Shenjun Ma M.Sc. student, TU Delft	 Wing Lung Ngai Researcher, Vrije Universiteit Amsterdam	 Jie Shen Performance modeling
 Sijq Shen Massivizing online gaming	 Ruben Verboon Honors Track	 Nezih Yigitbasi Tech Lead GrenchMark and CMeter	 Ernst van der Hoeven M.Sc. student, TU Delft		

Research Visitors and Interns

They have completed a short-term stay with our team.

					
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WE ARE A DIVERSE GROUP, OF DIFFERENT RACES AND ETHNICITIES, GENDERS AND SEXUAL PREFERENCES, VIEWS OF CULTURE , POLITICS, AND RELIGION. YOU ARE WELCOME TO JOIN!



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~2' — Take-home message →

MASSIVIZING COMPUTER SYSTEMS: MEANINGFUL DISCOVERY

Scheduling

Workflows

Domain-Specific/Agnostic
Portfolio, Auto-scaling*

Dependability

Performance & Failure Analysis*

Space-/Time-Correlation
Availability-On-Demand

New World

Workload Modeling

Serverless
Reference Architectures

Ecosystem Navigator

Performance Variability

Grid*, Cloud, Big Data
Benchmarking*
Longitudinal Studies

Scalability/Elasticity

Delegated Matchmaking*

BTWorld*, POGGI*, AoS
Auto-Scalers*
Heterogeneous Systems

Socially Aware

Collaborative Downloads*

Groups in Online Gaming
Toxicity Detection*
Interaction Graphs

Education

Social Gamification*

Software Artifacts

Graphalytics, OpenDC

Data Artifacts

Distributed Systems Memex*

Fundamental Problems/Research Lines

Our Contribution So Far

* Award-level work

Competitive personal grants



MASSIVIZING COMPUTER SYSTEMS: MEANINGFUL DISCOVERY

Scheduling

Workflows

Dependability

Performance & Failure Analysis*

New World

Workload Modeling

Many thanks to all collaborators* for making this research possible:



Andy



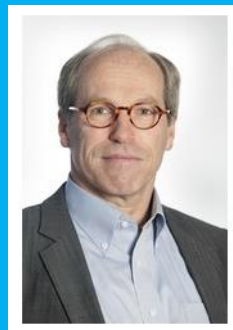
Dror



Sam



Miron



Dick



Fernando Radu



Ion



Ana

* Including all collaborators, I have published with over 180 people. Of them, about 40 were part of the team in the Netherlands.

Education

Social Gamification*

Software Artifacts

Graphalytics, OpenDC

Data Artifacts

Distributed Systems Memex*

Fundamental Problems/Research Lines

Our Contribution So Far

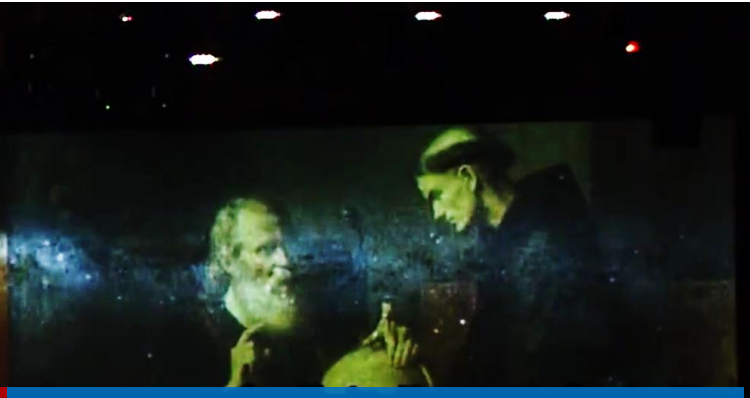
* Award-level work

Competitive personal grants

MEANINGFUL DISCOVERY

UNCOVERING THE MYSTERIES OF OUR UNIVERSE

GALILEO GALILEI, 1608-9, 3-8X TELESCOPE



MERELY AN INSTRUMENT?

FUNDAMENTAL SCIENCE?

Garney. The Inquisition's Semicolon: Punctuation, Translation, and Science in the 1616 Condemnation of the Copernican System, ArXiv document 1402.6168. [[online](#)]

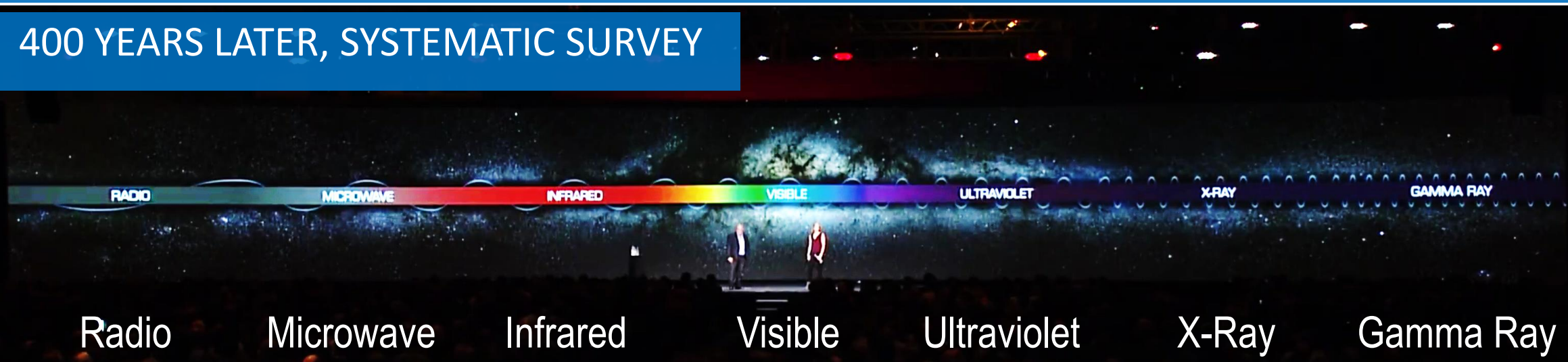
Phil Diamond and Rosie Bolton, Life, the Universe & Computing: The story of the SKA Telescope, SC17 keynote. [[online](#)]



MEANINGFUL DISCOVERY

UNCOVERING THE MYSTERIES OF OUR UNIVERSE

400 YEARS LATER, SYSTEMATIC SURVEY



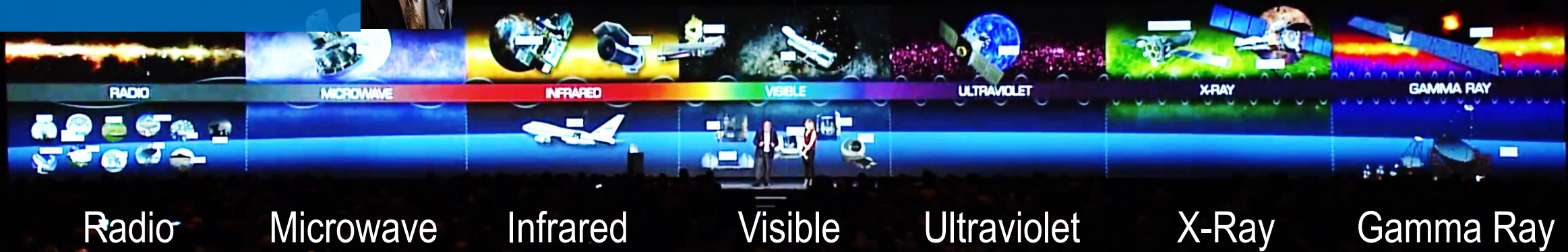
MEANINGFUL DISCOVERY

UNCOVERING THE MYSTERIES OF OUR UNIVERSE

GEORGE SMOOT
NOBEL PRIZE 2006



SKA FUNDING: 500+ FTE, EUR 1.5B



James Cordes, The Square Kilometer Array, Project Description, 2009 [[online](#)]

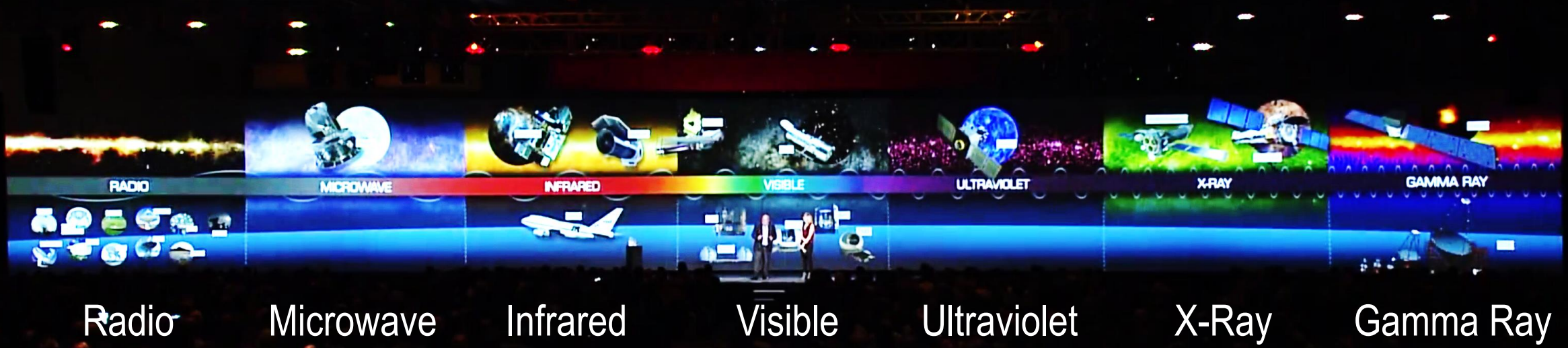
The Square Kilometer Array Factsheet, How much will it cost?, 2012 [[online](#)]

Phil Diamond and Rosie Bolton, Life, the Universe & Computing: The story of the SKA Telescope, SC17 Keynote. [[Online](#)]



MEANINGFUL DISCOVERY

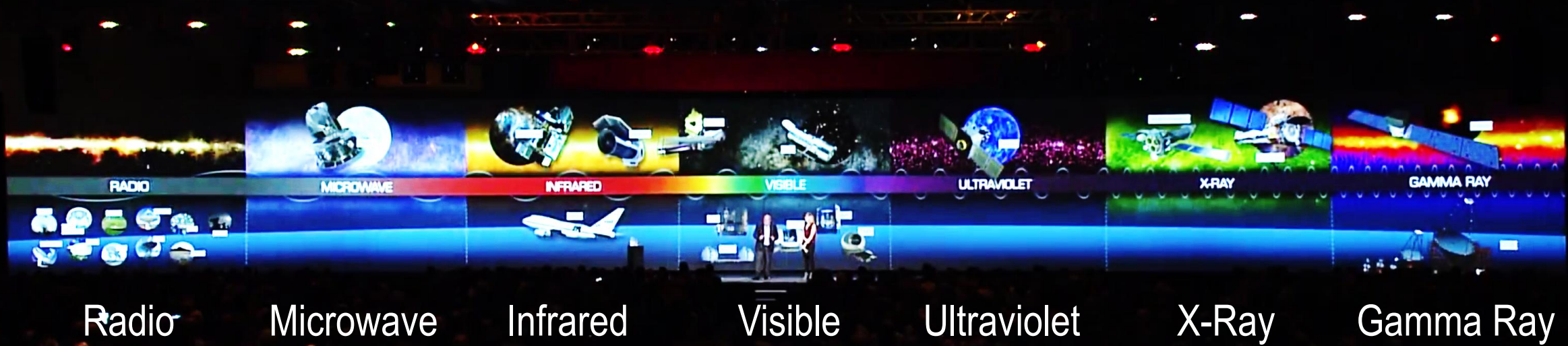
UNCOVERING THE MYSTERIES OF OUR UNIVERSE, PHYSICAL AND DIGITAL



Radio	Microwave	Infrared	Visible	Ultraviolet	X-Ray	Gamma Ray
Cloud, Grid, Edge, Fog, etc.	Big Data	Sci.&Eng. Apps	Consumer Apps	Enterprise Apps	Systems, Ecosystems	Performance, Security, etc.

MEANINGFUL DISCOVERY

UNCOVERING THE MYSTERIES OF OUR UNIVERSE, PHYSICAL AND DIGITAL



Radio

Microwave

Infrared

Visible

Ultraviolet

X-Ray

Gamma Ray

Cloud, Grid, Edge, Fog, etc.

One aspect: BigData, P2P

Sci.&Eng. Apps+Sys.

Consumer Apps+Sys.

Enterprise Sys.

Systems, Ecosystems

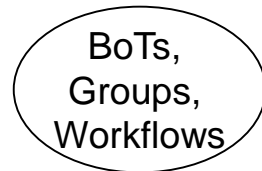
Performance, Availability, etc.



[Iosup et al. FGCS'08]



[Zhang et al. CoNext'10]



[Iosup et al. IEEE IC'11]



[Guo et al. NETGAMES'12]



[Shen et al. CCGRID'15]



[Ghiț et al. CCGRID'14]

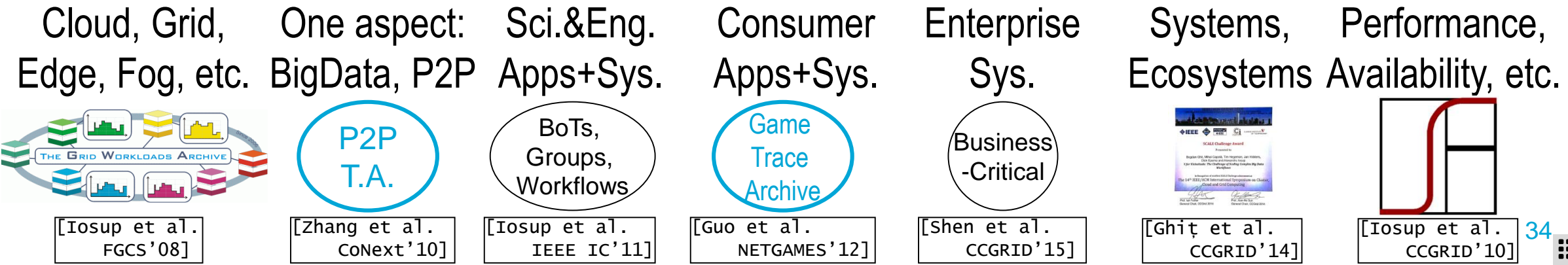


[Iosup et al. CCGRID'10]

MEANINGFUL DISCOVERY

UNCOVERING THE MYSTERIES OF OUR UNIVERSE, PHYSICAL AND DIGITAL

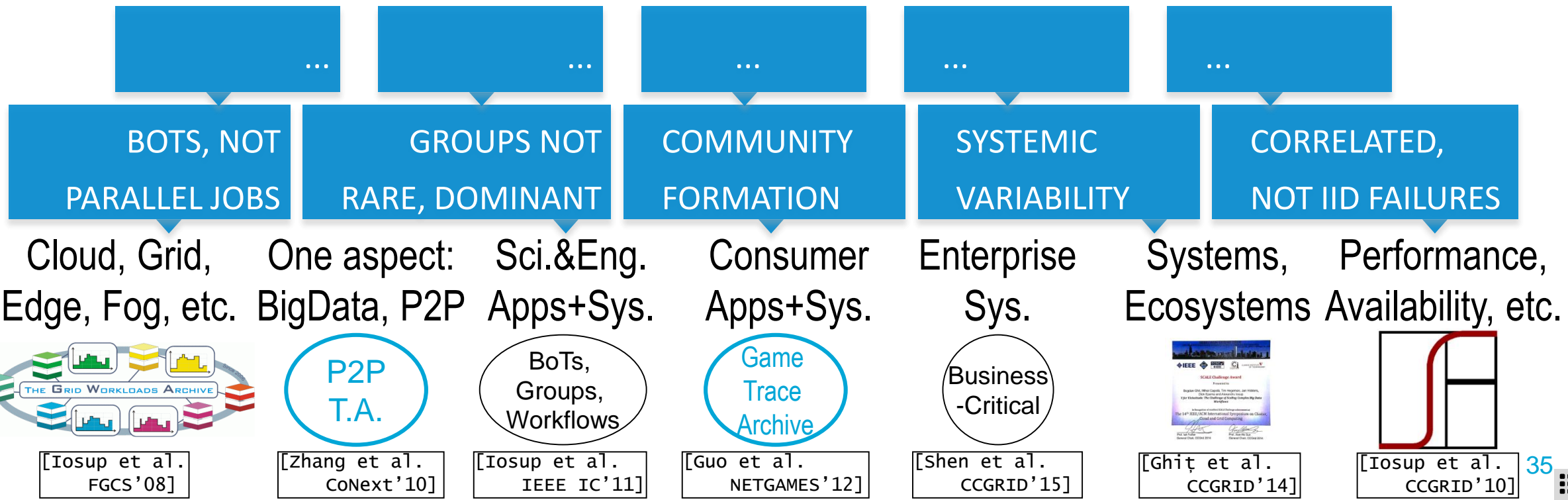
BUT ... WHY WOULD YOU NEED TO UNCOVER AN ARTIFICIAL UNIVERSE?! YOU BUILT IT!



MEANINGFUL DISCOVERY

UNCOVERING THE MYSTERIES OF OUR UNIVERSE, PHYSICAL AND DIGITAL

FOUND MANY UNFORESEEN PHENOMENA: INTERACTION, ADAPTATION, EXAPTATION, ...



MEANINGFUL DISCOVERY

UNCOVERING THE MYSTERIES OF OUR UNIVERSE, PHYSICAL AND DIGITAL

FOUND MANY UNFORESEEN PHENOMENA: INTERACTION, ADAPTATION, EXAPTATION, ...

BUT ... IS THERE A SYSTEMATIC WAY TO APPROACH THESE PHENOMENA?

BOTS, NOT
PARALLEL JOBS

GROUPS NOT
RARE, DOMINANT

COMMUNITY
FORMATION

SYSTEMIC
VARIABILITY

CORRELATED,
NOT IID FAILURES

Cloud, Grid,
Edge, Fog, etc.

One aspect:
BigData, P2P

Sci.&Eng.
Apps+Sys.

Consumer
Apps+Sys.

Enterprise
Sys.

Systems,
Ecosystems

Performance,
Availability, etc.



[Iosup et al.
FGCS'08]



[Zhang et al.
CoNext'10]



[Iosup et al.
IEEE IC'11]



[Guo et al.
NETGAMES'12]



[Shen et al.
CCGRID'15]



[Ghiț et al.
CCGRID'14]



[Iosup et al.
CCGRID'10]

MEANINGFUL DISCOVERY

BUT ... IS THERE A SYSTEMATIC WAY TO APPROACH THESE PHENOMENA?



- The Human Genome Project:
 - > Physical map covering >90% human genome
 - > Sequence data made available open-access
- Big Science:
 - > Took >10 years to complete
 - > Led by US, work by 20 groups in CN, DE, FR, JP, UK, US
- Big impact:
 - > Decrease cost of sequencing
 - > Facilitate biomedical research

FUNDING: > 3B USD

International Human Genome Sequencing Consortium, Initial sequencing and analysis of the human genome, Nature 409, Feb 2011. [\[Online\]](#)

Julie Gould, The Impact of the Human Genome Project, Naturejobs blog, 2015. [\[Online\]](#)



MEANINGFUL DISCOVERY

BUT ... IS THERE A SYSTEMATIC WAY TO APPROACH THESE PHENOMENA?

REMEMBER THE COMPLEXITY CHALLENGE?

The grid contains 44 boxes, each representing a different company or technology. The categories and companies shown include:

- NoSQL Databases:** Amazon DynamoDB, Google Cloud Platform, Oracle, Microsoft Azure, MarkLogic, MongoDB, Databricks, Aerospike, SequoiaDB, Redis Labs, Influxdata.
- NewSQL Databases:** SAP HANA, Clustrix, Pivotal, Paradigm 4, Nuodb, MemSQL, Splice Machine, MariaDB, VoltDB, Citusdata, DeepDB, Trafilabs, Cockroach Labs.
- BI Platforms:** Power BI, Amazon Web Services, Domo, Wave Analytics, GoodData, Kivo Insights, Platforr, Datascale, SAS, Splunk, Sumologic, Netbase, Datasift, Tracx, Bitly, Synthesio, Simple Reach, Log Analytics, Hootsuite.
- Statistical Computing:** SAS, SPSS, MATLAB.
- Log Analytics:** Splunk, Sumologic, Cloud Physics, Loggly.
- Social Analytics:** Hootsuite, Netbase, Datasift, Tracx, Bitly, Synthesio, Simple Reach.
- Ad Optimization:** AppNexus, MediaMath, Criteo, OpenX, Rocketfuel, Integral, The Trade Desk, Ad Algorithms, Distillery, LiveIntent, Tappd, DataXu, Appier, Moat.
- Security:** Cylance, CounterTack, Cybereason, ThreatMetrix, Area 1 Security, SentinelOne, Recorded Future, Guardian Analytics, Fortscale, Sift Science, Keybase, Feedzai, Sionifyd.
- Vertical AI Applications:** Facebook, Clara, Kasisto, Lumiat.
- Graph Databases:** Neo4j, OrientDB, InfiniteGraph.
- MPP Databases:** Vertica, Microsoft Azure, Pivotal, Snowflake, Amazon Redshift, Kognitio, Dremio, Infoworks.
- Cloud EDW:** Amazon Web Services, Google Cloud Platform, Microsoft Azure, Pivotal, Snowflake, Amazon Redshift, Kognitio, Dremio, Infoworks.
- Data Transformation:** Alteryx, Talend, Trifacta, MuleSoft, Snaplogic, Bedrock Data, StreamSets, Alation, Xplenty.
- Data Integration:** MuleSoft, Snaplogic, Bedrock Data, StreamSets, Alation, Xplenty.
- Real-Time:** Amazon Web Services, Metamarkets, Streamio, Confluent, DataTorrent, Data Artisan.
- Machine Learning:** Azure Machine Learning, Amazon SageMaker, Skytree, Rapidminer, DataRPM, Visonze, PredictionIO, Glowfish, Narrative Science, Nuance, Wolfram Alpha, Semantic Machines, ARRIA, Gridspace, Capital Cortex, MindMeld, IDIBON, Yseop.
- Speech & NLP:** Narrative Science, Nuance, Wolfram Alpha, Semantic Machines, ARRIA, Gridspace, Capital Cortex, MindMeld, IDIBON, Yseop.
- Horizontal AI:** IBM Watson, Cortana, Sentient Technologies, Viv, Neovana Systems, Numenta, HyperScience, Dextro, Geometric Intelligence, MetaMind.
- Publisher Tools:** Outbrain, Taboola, Quantcast, Chartbeat, Yieldbot, Yieldmo.
- Govt / Regulation:** Socrata, OpenGov, EN, FiscalNote, Enigma, Predpol, Mark43, OpenDataSoft.
- Finance:** Affirm, LendingClub, OnDeck, Kreditech, Zest Finance, LendUp, Kabbage, Tidemark, Payoff, InsiKT, Zuoora, Dataminr, Lenddo, Kenshco, Aidiya, iSentium, Quantopian.
- Management / Monitoring:** New Relic, Dynatrace, AppDynamics, Actifio, Amazon Web Services, Numerify, Splunk, Datalog, Trocena, Driven, Anodot.
- Security:** Tanium, Illumio, Code 42, DataGravity, Amazon Web Services, Paraspas, Nimble Storage, CipherCloud, Vectra, Sqrrl, BlueTalon, Quumulo, Apigee, Cask, Typesafe, Driven, WorkFusion.
- Storage:** Amazon Web Services, Google Cloud Platform, Microsoft Azure, Paraspas, Nimble Storage, Amazon S3, Coho Data, Quumulo.
- App Dev:** Apigee, Cask, Typesafe, Driven, WorkFusion.
- Crowd-sourcing:** Amazon Mechanical Turk, CrowdFlower, WorkFusion.
- Search:** HP, Oracle, Endeca, Exalead, Lucidworks, Elastic, ThoughtSpot, Maana, Swifttype, Algolia, Sinequa.
- Data Services:** Mu Sigma, Opera, Exl, Data Science, Kaggel, DataScops, DataKind.
- For Business Analysts:** Origami Logic, ClearStory, Cirro, Import.io.
- Web / Mobile / Commerce:** Google Analytics, Mixpanel, Rjmetrics, Bluecore, Amplitude, Granify, Sumall, Airtable, Retention, Custora.
- Education / Learning:** Knewton, Clever, Cleara.
- Life Sciences:** 23andMe, Counsyl, Pathway Genomics, Recombine, Kyruus, Flatiron, Zymogen, HealthTap.
- Industries:** Opower, eHarmony, RetailNext, Stitch Fix, WorkFusion, Tachus, Blue River.



<<1% OF BIG DATA BY MATT TURK (2017)

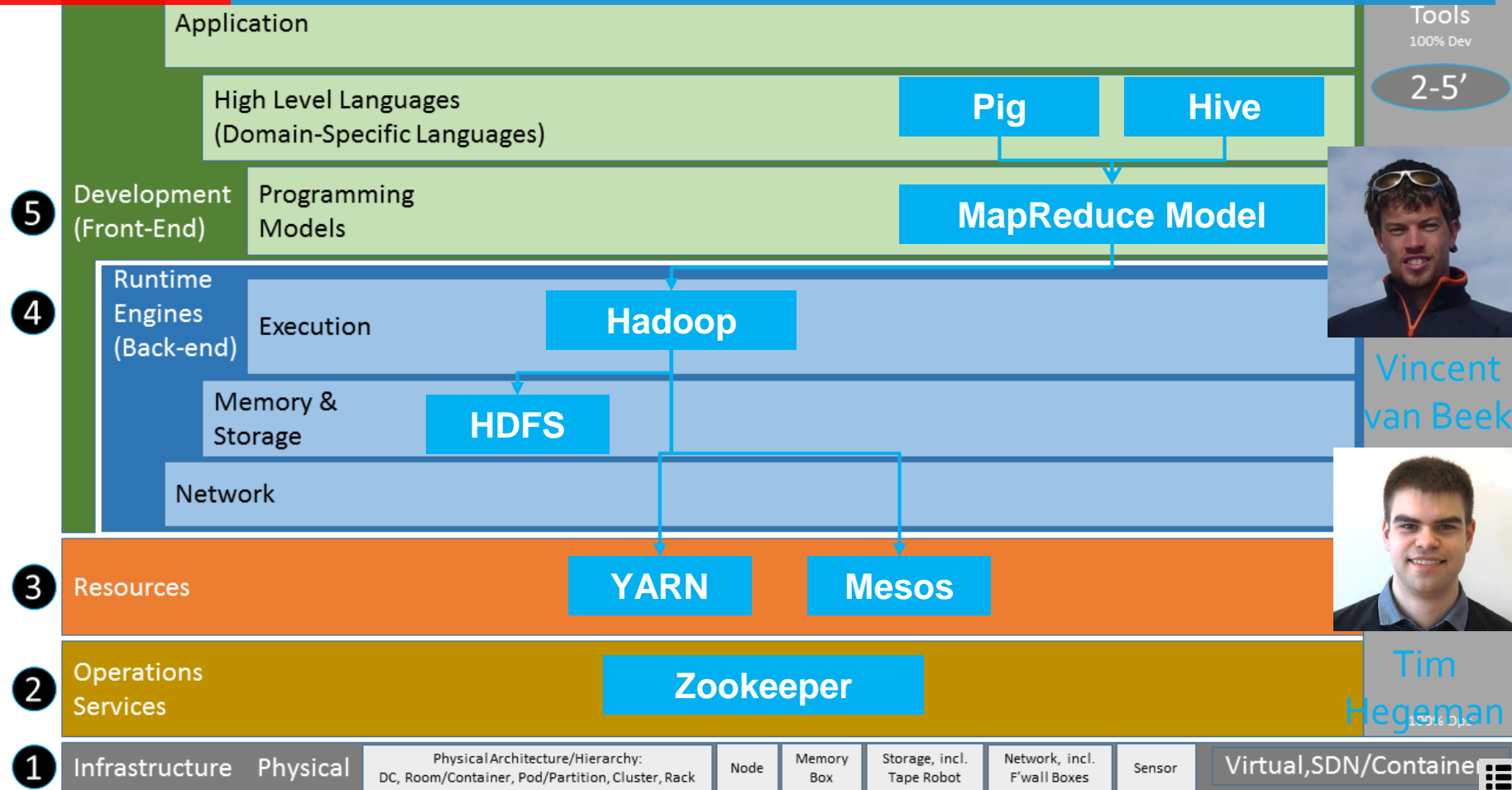
MEANINGFUL DISCOVERY

THE COMPLEXITY CHALLENGE

IOSUP ET AL. REFERENCE ARCHITECTURE FOR DCS

Focus on Applications,
5 Core Layers:

5. Development (Front-end)
4. Runtime Engines (Back-end)
3. Resources
2. Operations Services
1. Infrastructure



[Iosup et al. ICDCS '18]

MEANINGFUL DISCOVERY

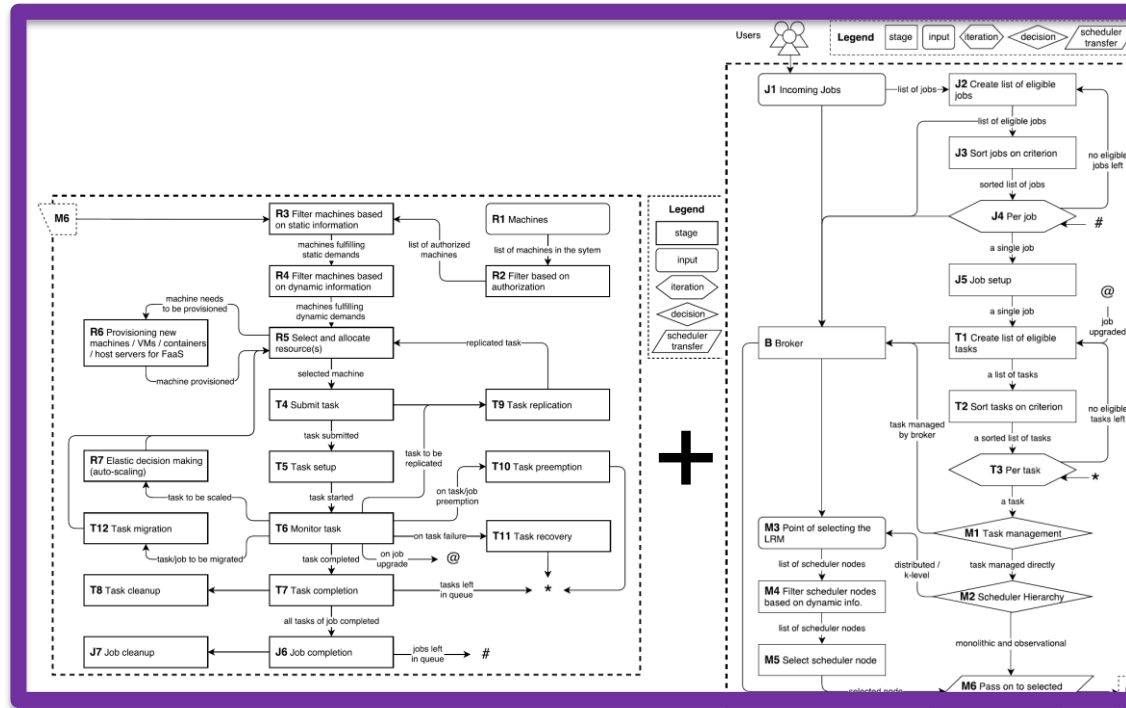
THE COMPLEXITY CHALLENGE

IOSUP ET AL. REFERENCE ARCHITECTURE FOR DCS



Georgios Andreadis

ANDREADIS ET AL. REFERENCE ARCHITECTURE FOR SCHEDULERS IN DCS



Application

High Level Languages

(Domain-Specific Languages)

Development
(Front-End)

Programming
Models

Runtime
Engines
(Back-end)

Execution

Memory &
Storage

Network

Resources

Operations
Services

Infrastructure Physical

Physical Architecture/Hierarchy:
DC, Room/Container, Pod/Partition, Cluster, Rack

Node



Hadoop

HDFS

YARN

Zookeeper

science + engineering + design



MEANINGFUL DISCOVERY

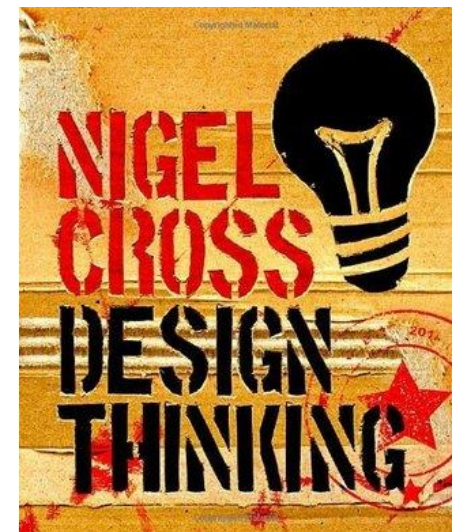
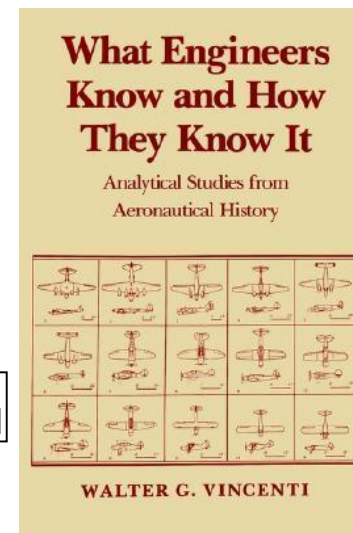
NO SYSTEMATIC PROCESS FOR COMPUTER SYSTEMS

SO I'LL USE EXAMPLES

science + engineering + design

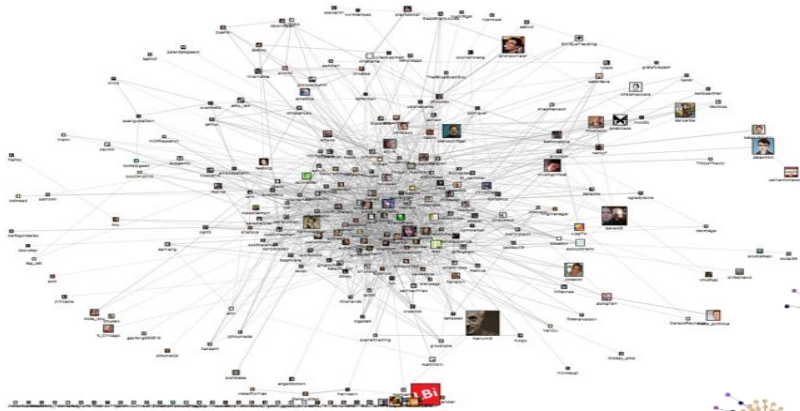
THE COMPUTER SYSTEMS TRIPLET

[Iosup et al.
ICDCS'18]



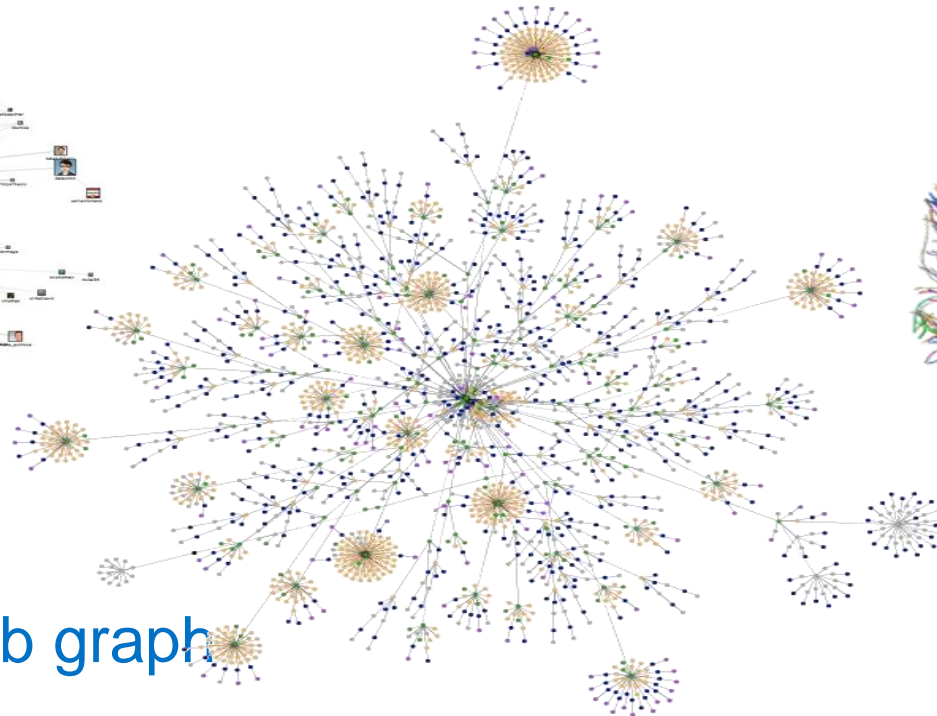
MEANINGFUL DISCOVERY

ENGINEERING LDBC GRAPHALYTICS: THE NEED FOR SPEED ... & GRAPHS!



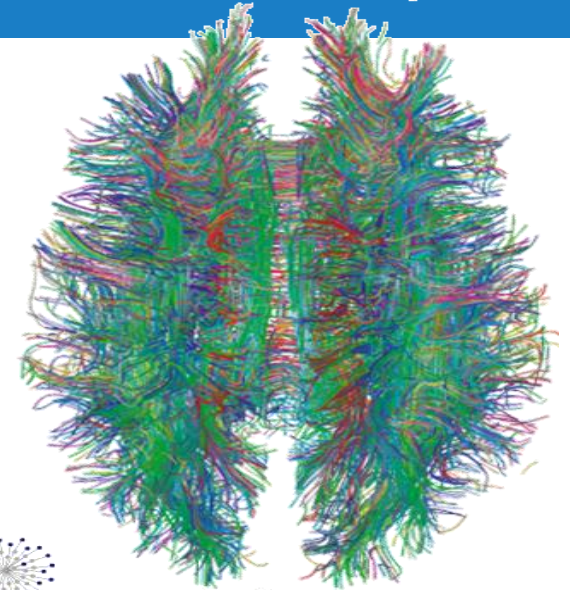
Social network

~1 billion vertices
~100 billion
connections



Web graph

~50 billion pages
~1 trillion hyperlinks

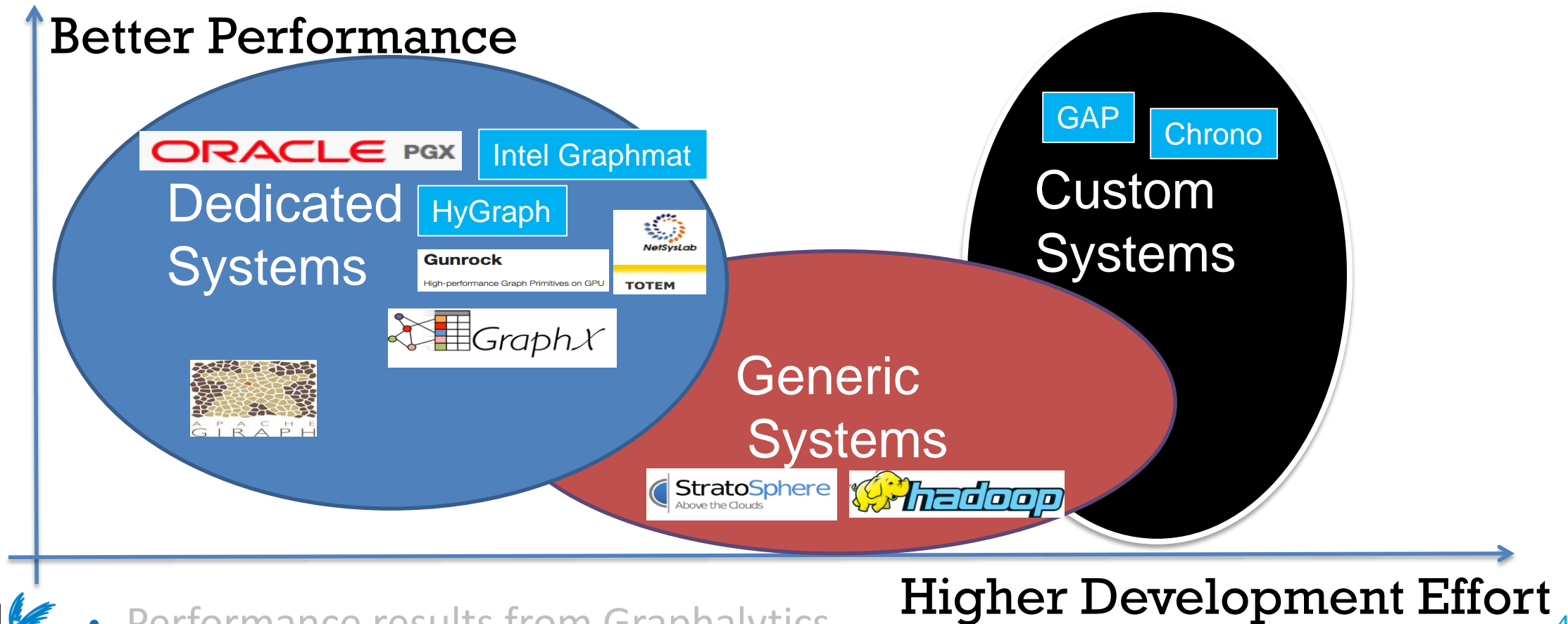


Brain network

~100 billion neurons
~100 trillion
connections

MEANINGFUL DISCOVERY

ENGINEERING LDBC GRAPHALYTICS: THE SYSTEMS LANDSCAPE



MEANINGFUL DISCOVERY

ENGINEERING LDBC GRAPHALYTICS: BENCHMARKING LEADING TO SCIENCE



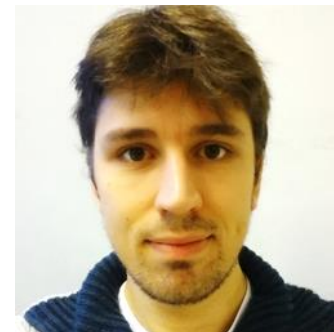
- **Graphalytics:**
 - > **Benchmark**
 - > Many classes of algorithms used in practice
 - > Diverse real and synthetic datasets
 - > Diverse experiments, derived from practice
 - > Renewal process to keep the workload relevant
 - > Enables comparison of many platforms, community-driven and industrial
 - > **Global Competition**



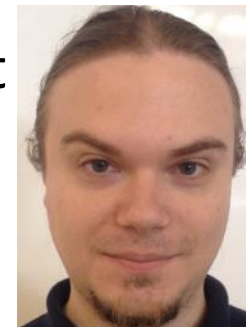
Wing Lung
Ngai



Tim
Hegeman



Stijn
Heldens



Alex
Uță



Ahmed
Musaafir



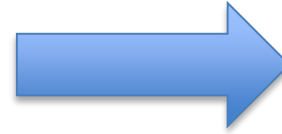
Mihai
Capotă

MEANINGFUL DISCOVERY

ENGINEERING LDBC GRAPHALYTICS: BENCHMARKING LEADING TO SCIENCE



- **Graphalytics:**
 - > Benchmark
 - > Many classes of algorithms used in practice
 - > Diverse real and synthetic datasets
 - > Diverse experiments, representative for practice
 - > Renewal process to keep the workload relevant
 - > Enables comparison of many platforms, community-driven and industrial
 - > Global Competition



- Community endorsed:

graphalytics.org

- Surprising findings:

Performance: orders of magnitude difference due to each of platform, algorithm, dataset, and hardware

- Triggered new research



MEANINGFUL DISCOVERY

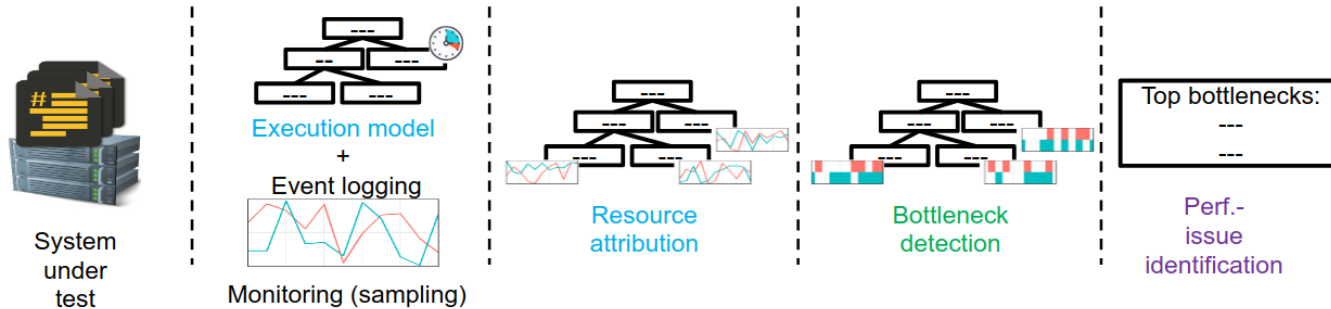
ENGINEERING LDBC GRAPHALYTICS: MODELING LEADS TO PERFORMANCE ANALYSIS



- Graphalytics Grade10:
 - > Automated bottleneck detection
 - > Automated identification of performance issues



Tim
Hegeman



Multi-stage process,
works in ecosystem

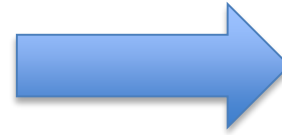


MEANINGFUL DISCOVERY

ENGINEERING LDBC GRAPHALYTICS: MODELING LEADS TO PERFORMANCE ANALYSIS



- **Graphalytics Grade10:**
 - > Automated bottleneck detection
 - > Automated identification of performance issues



- Without Grade10:

No bottleneck at all

- With Grade10:

Always bottleneck

Cause:

- + Message queue full
- + Garbage collector
- + CPU
- + Others



System
under
test



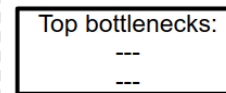
Monitoring (sampling)



Resource
attribution



Bottleneck
detection



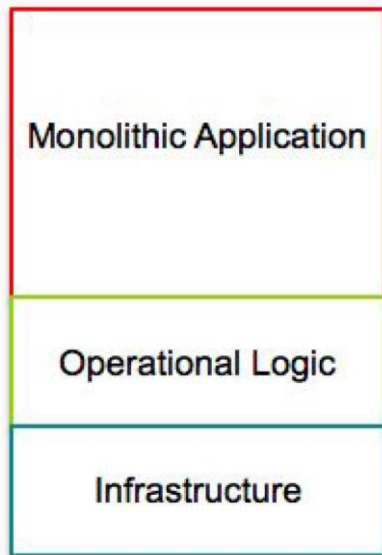
Perf.-
issue
identification

Multi-stage process,
works in ecosystem

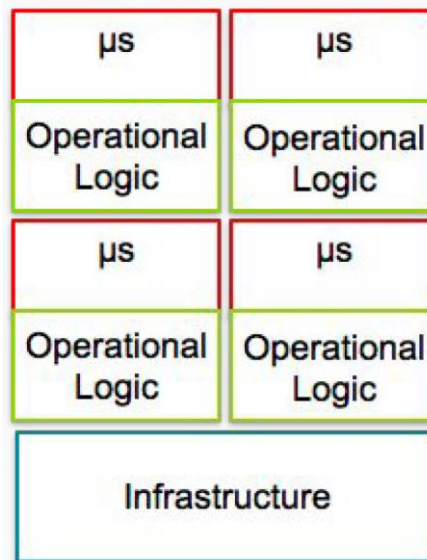
MEANINGFUL DISCOVERY

DESIGNING SERVERLESS ARCHITECTURES

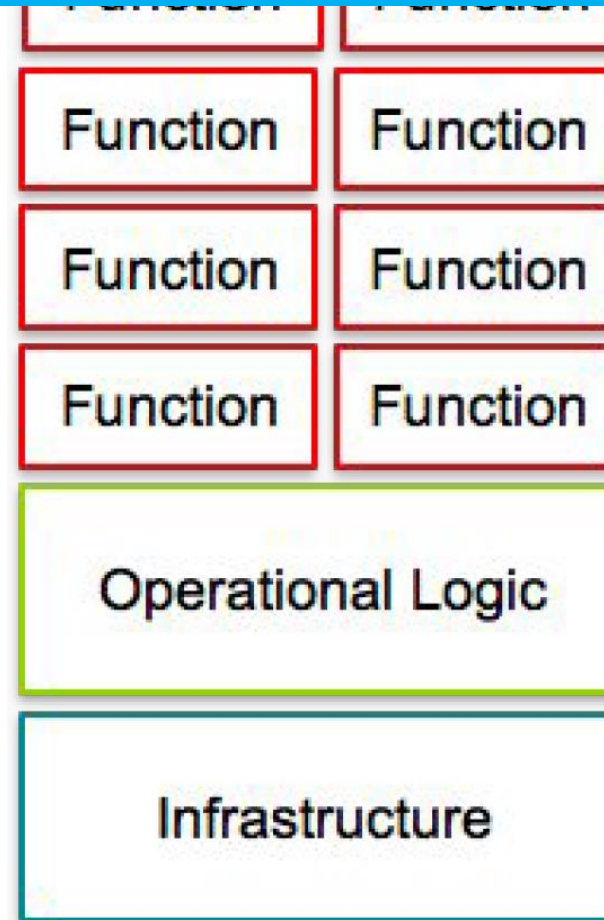
Abstraction: Serverless Design: FaaS systems



Difficult to Scale
Infrequent, Inflexible
Complex deployment
Tightly coupled stack



- Scalable
- Frequent, Flexible
- Complexity: from application logic to operational logic



Erwin
van Eyk



Lucian
Toader

- Scalable
- Frequent, Flexible
- Explicit separation of Business Logic vs. Operational Logic.
- Minimal layer coupling, unit of deployment

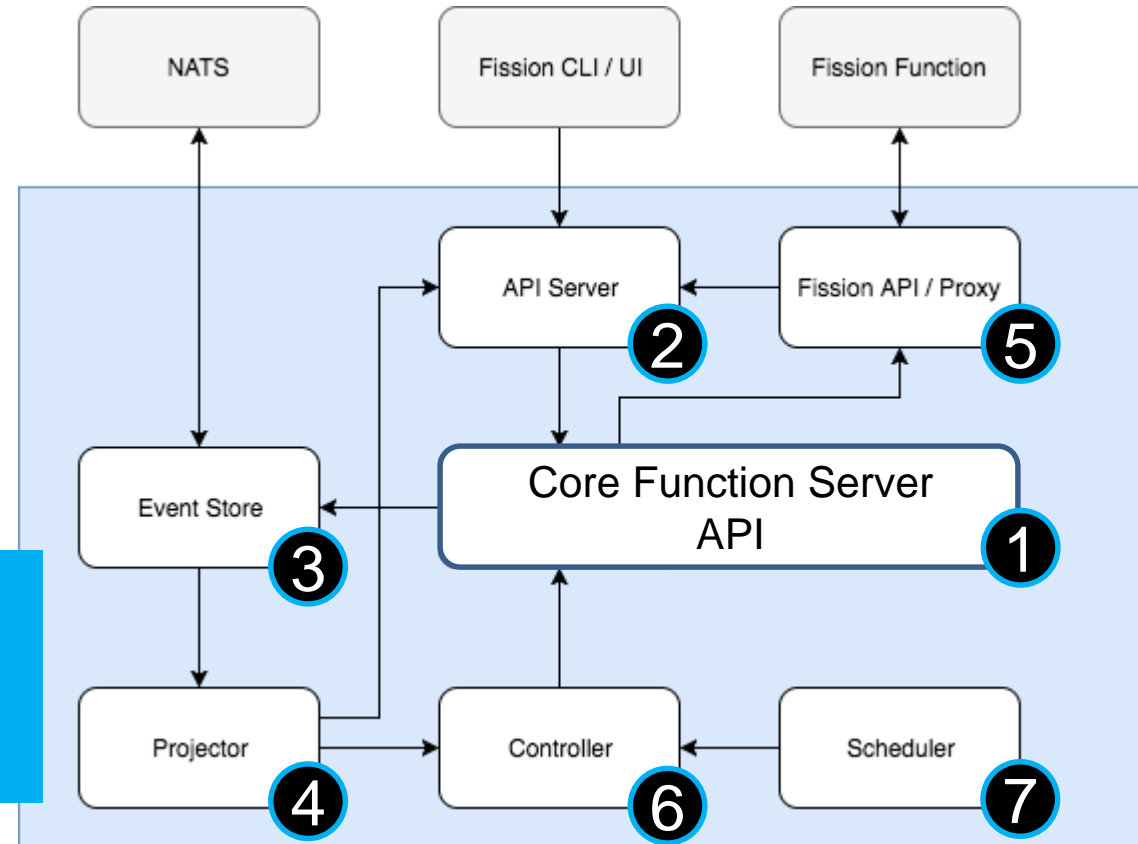
MEANINGFUL DISCOVERY

DESIGNING SERVERLESS ARCHITECTURES



Erwin
van Eyk

The workflow management engine,
part of the Serverless ecosystem
at Fission.io





~40'

Massivizing Computer Systems

The Science of Distributed Ecosystems

~10' — Vision, Current Golden Age of Ecosystems, and Crisis →

~5' — Intermezzo: What Is Modern Science? →

~20' — Massivizing Computer Systems →

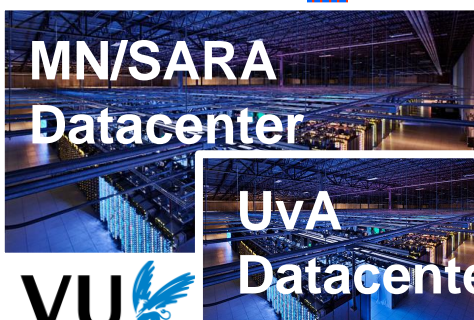
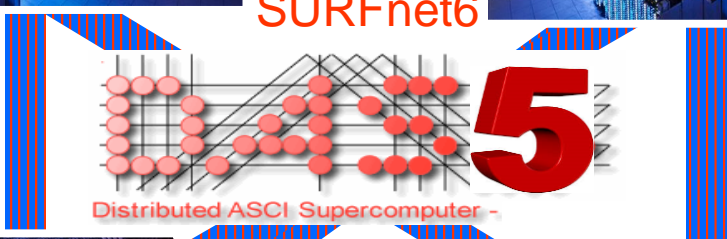
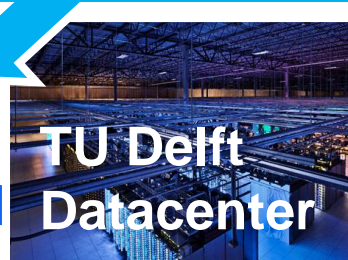
1. Stakeholders →
2. Meaningful discovery: science + engineering + design →
3. Experimental method for discovery + Reproducibility/Validation →
4. Codified and teachable Science →
5. What's left? →

~2' — Take-home message →

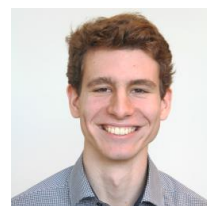
EXPERIMENTAL METHODS OF DISCOVERY

UNIQUE OPPORTUNITY TO VALIDATE: WE DRINK OUR OWN CHAMPAGNE (*IN VIVO*)!

Our Prototypes (*in physico/in vitro*)



Laurens
Versluis



Georgios
Andreadis



Fabian
Mastebroek



Racheendra
Mulluri



Maria Voinea



Alexey Ilyushkin



We also use clouds



And simulators (*in silico*)

REPRODUCIBILITY AND VALIDATION OF DISCOVERY

A PERENNIALY TOUGH PROBLEM, IN COMPUTING BUT ALSO IN ALL OTHER SCIENCES

METHODOLOGY

SHARED PRINCIPLES, METHODS, ETC. ... BUT WHERE*?!

OPEN SCIENCE

FREE OPEN-SOURCE SOFTWARE AND OPEN-ACCESS DATA ...
BUT WHO PAYS/ WHAT INCENTIVES?!

REPORTING &
DISSEMINATION

PROTOCOL AND STUDY CHECKLISTS, PRE-REGISTRATION OF
STUDY AND CONFLICTS-OF-INTEREST ... BUT HOW TO START?!

REPRODUCIBILITY

MODERN ECOSYSTEMS ARE NOT STABLE, PREDICTABLE...

* Conferences do not accept such material... except when they do...

Munafò et al., A manifesto for reproducible science, Nature Human Behaviour, Jan 2017. [[Online](#)]





~40'

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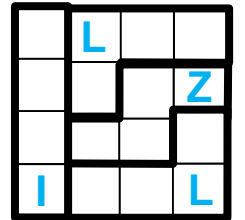
~20' — **Massivizing Computer Systems** →

1. Stakeholders →
2. Meaningful discovery: science + engineering + design →
3. Experimental method for discovery + Reproducibility/Validation →
4. **Codified and teachable Science** →
5. **What's left?** →

~2' — **Take-home message** →

21ST CENTURY NEEDS FOR MASSIVIZING SYSTEMS

AN EDUCATION FRAMEWORK WITH FOUR DIMENSIONS

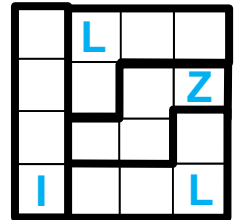


**The Other
Path**

21ST CENTURY NEEDS FOR MASSIVIZING SYSTEMS

AN EDUCATION FRAMEWORK WITH FOUR DIMENSIONS

1. **Curriculum**: what to teach?
2. **Didactics**: how to teach?
3. **Technology**: how to address higher and more diverse expectations?
4. **Management**: how to manage, incentivize also the educators?



**The Other
Path**



21ST CENTURY NEEDS FOR MASSIVIZING SYSTEMS

DIDACTICS: SOCIAL GAMIFICATION AS INTUITION AND METHOD



Gamification = The use of thinking and techniques designed for gaming in non-gaming settings, e.g., in education.

<http://goo.gl/v97zsw>



What is the intuition behind gamification?

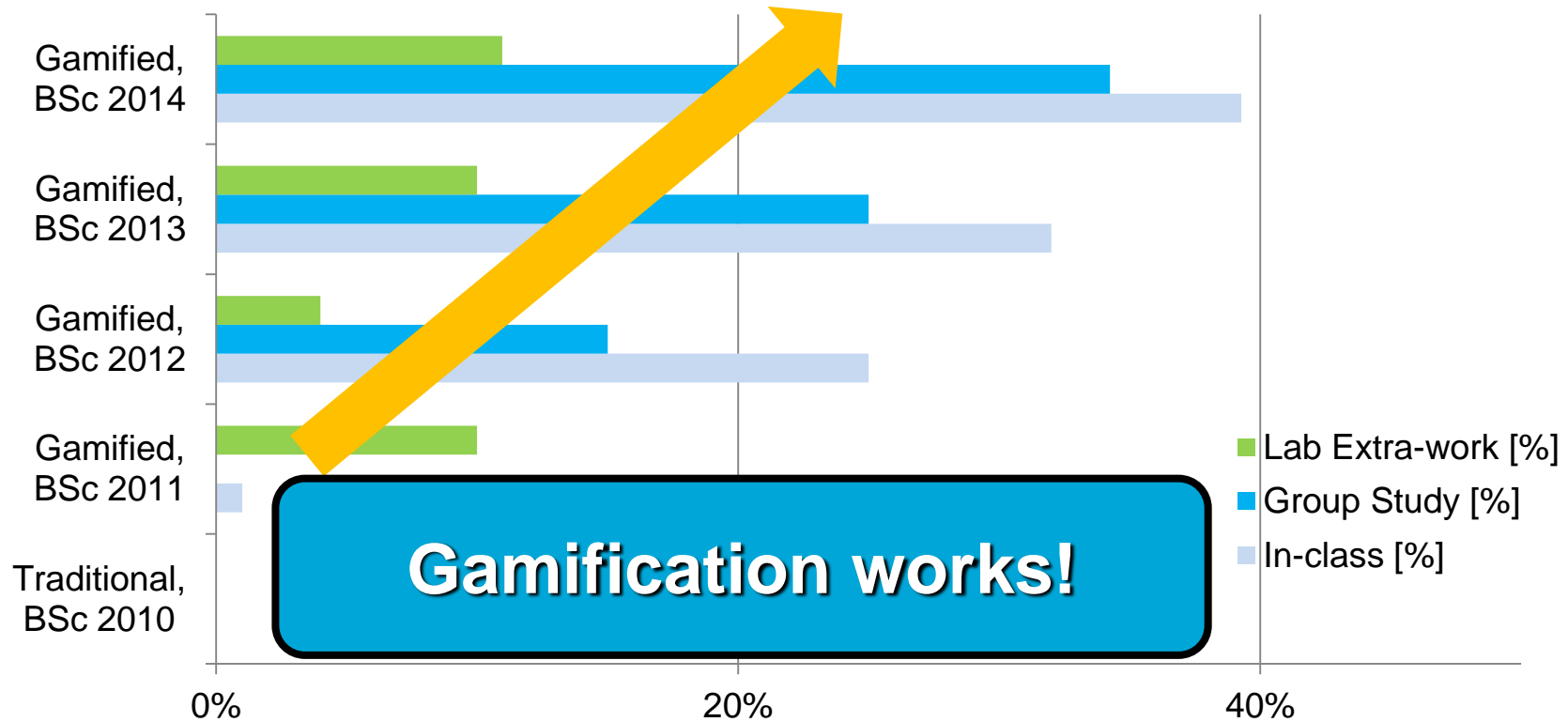
How can gamification be used?

<http://goo.gl/ILSneb>



21ST CENTURY NEEDS FOR MASSIVIZING SYSTEMS

DIDACTICS: SOCIAL GAMIFICATION WORKS!



Extra work due to gamification, relative to traditional
[% all students]

21ST CENTURY NEEDS FOR MASSIVIZING SYSTEMS

IS THIS SCIENCE TEACHABLE? DOING SCIENCE AS BSC + MSC STUDENT

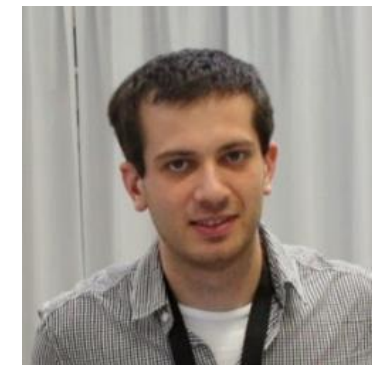
IEEE Big Data 2013

IEEE/ACM SC15 Tutorial

PVLDB 2016



IEEE Scale Challenge Winners 2014



Bogdan
Ghiț

Tim Hegeman
General Chair, CCGrid 2014

Tim Hegeman
General Chair, CCGrid 2014

Tim Hegeman
MSc student



~40'

Massivizing Computer Systems

The Science of Distributed Ecosystems

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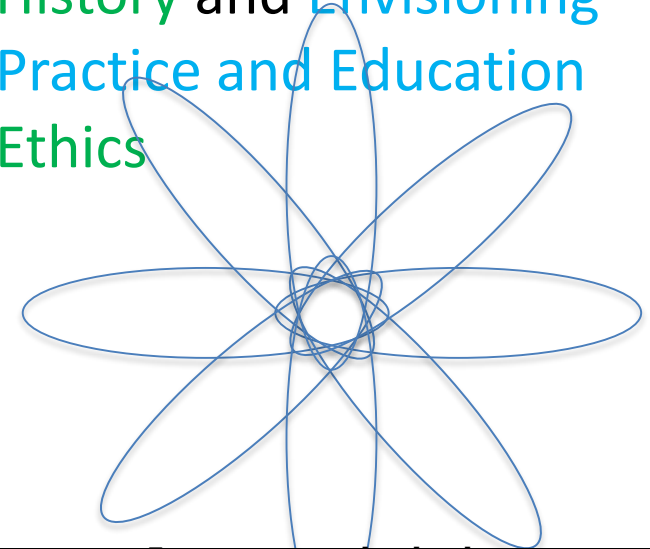
~2' — **Take-home message** →

BUT WHAT IS “A SCIENCE”? WHAT IS A MODERN SCIENCE?

A SCIENCE OF ECOSYSTEMS

- Denning’s criteria for a new field of science:
 - > Focus on pervasive phenomena
 - > By and for clear stakeholders
 - > Meaningful discovery
 - > Experimental methods of discovery
 - > Methods of validation
 - > Reproducibility of results
 - > Falsifiability of theoretical constructs
 - > Body of knowledge and skills that can be codified and taught

- My definition for a modern field of science:
 - > Fundamentals and Applications
 - > Methodology and Philosophy
 - > **History** and Envisioning
 - > Practice and Education
 - > **Ethics**



Denning, The science in computer science, CACM 56, 2013.

Iosup et al., Massivizing Computer Systems, ICDCS 2018. [[online](#)]

MASSIVIZING COMPUTER SYSTEMS: WHAT'S LEFT?

A SCIENCE OF ECOSYSTEMS

THE VISION SEEMS GOOD, AND WE HAVE TAKEN PROMISING INITIAL STEPS

- Clients:

- > Right to ICT



- > Understanding



- Computer **professionals**:

- > Create



- > Operate



- > Experiment



- > Reproducible work



- > Educate and train



- ICT:

- > Automated



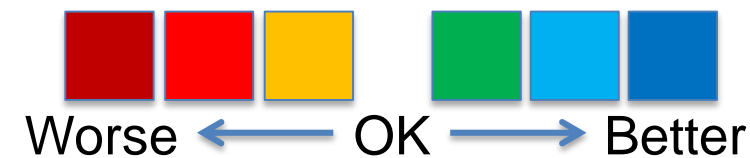
- > Efficient



- > Controlled



- > Ecosystems





~40'

Massivizing Computer Systems

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MASSIVIZING COMPUTER SYSTEMS

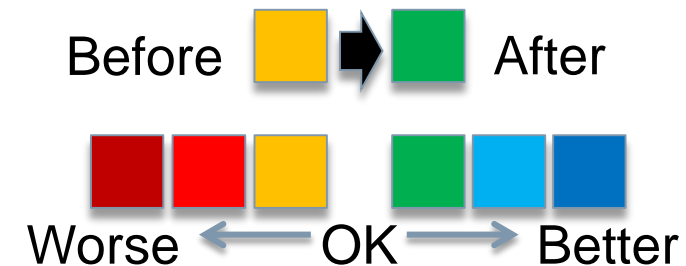
= THE SCIENCE OF MAKING COMPUTER SYSTEMS SCALABLE, RELIABLE, PERFORMANT, ETC., YET ABLE TO FORM EFFICIENT ECOSYSTEMS



- Golden Age of Computer Systems ... Yet crisis Is looming
- Massivizing Computer Systems
 - Think Ecosystems
 - Methods to address key challenges in science, engineering, and design
 - Teaching facilitated by award-winning method
- Much left to do, as we are merely beginning ...


@Large Research
Massivizing Computer Systems

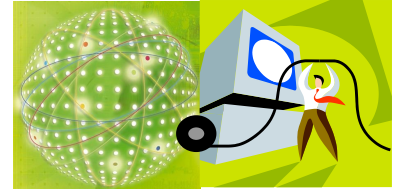
<http://atlarge.science>



MASSIVIZING COMPUTER SYSTEMS

FURTHER READING

1. Iosup et al. Massivizing Computer Systems. ICDCS 2018 (in print)
2. Andreadis et al. A Reference Architecture for Datacenter Scheduling: Design, Validation, and Experiments, SC18 (in print)
3. Van Eyk et al. Serverless is More: From PaaS to Present Cloud Computing, IEEE IC Sep/Oct 2018 (in print)
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Contact Me or Our Team

Collaboration or discussion about Massivizing Computer Systems:

Understanding, designing, deploying, tuning, analyzing, benchmarking distributed systems and ecosystems, including cloud computing and big data systems. Other topics in large-scale distributed systems and performance engineering are welcome.

A.losup@vu.nl 


+31-20 59 89468 (Amsterdam) 

@Alosup 

<https://atlarge-research.com/aiosup/> 

<https://www.linkedin.com/in/aiosup> 



VU University, Faculty FEW/building W&N, Room P4.14 

De Boelelaan 1081, 1081HV [Amsterdam](#),

The Netherlands

