Raja R. Sambasivan

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Objective

A tenure-track position in the Computer Science or Computer Engineering Department of a leading university

Research Summary

I am broadly interested in systems and networking with a focus on cloud computing. My research addresses the immense difficulty of diagnosing problems experienced by applications running within and among clouds. It also addresses the unsuitability of the Internet for cloud computing (and other novel uses). To achieve my research goals, I often collaborate with industry (e.g., Google, Red Hat) and academics in other disciplines (e.g., visualization, machine learning). I am published in major conferences, including ATC, FAST, InfoVis, NSDI, SoCC, SIGCOMM, and SIGMETRICS.

Education

Ph.D., Electrical & Computer Engineering, May 2013
Carnegie Mellon University, Pittsburgh, PA
Advisor: Greg Ganger
Dissertation: Diagnosing performance changes in distributed systems by comparing request flows

M.S., Electrical & Computer Engineering, May 2004
Carnegie Mellon University, Pittsburgh, PA

B.S., Electrical & Computer Engineering w/minor in Computer Science, May 2003
Carnegie Mellon University, Pittsburgh, PA

Honours & Awards

Best poster, EMC University Day 2012 (*Diagnosing performance changes by comparing request flows*)

Best paper, SIGMETRICS 2007 (*Modeling the relative fitness of storage*)

Featured in Piled Higher & Deeper (PhDComics), February 14^{th}, 2007 strip

Best paper, FAST 2005 (*Ursa Minor: versatile cluster-based storage*)

Research Summaries

Aug. 2014 – Aug. 2017

Evolvability for inter-domain routing

BGP, the Internet's inter-domain routing protocol, is a foundational part of the Internet's architecture. It is responsible for connecting all the services we hold dear. It is also riddled with critical flaws and limitations. Numerous critical fixes and replacement protocols have been proposed, but almost none have been deployed because BGP is architecturally rigid and cannot facilitate the introduction of new protocols. In this research, we identified the features needed within any inter-domain routing protocol to allow it to bootstrap evolution to new inter-domain routing protocols—i.e., facilitate their deployment and gradually deprecate itself in favor of one or more new protocols. We created a version of BGP (called D-BGP) with these features and showed that it can support a rich Internet composed of any recently-proposed protocols. We demonstrated that D-BGP accelerates the rate at which early adopters see the benefits of several types of new protocols.

Jan. 2014 – Jan. 2016

Resource-aware routing

Content sources (e.g., CDNs), transit ISPs, and eyeball networks have a vested interest in sharing resource demands because of the large amount of traffic they exchange (e.g., in 2009, over 50% of all Internet traffic originated from less than 30 content sources). Since this information is not communicated by BGP, content sources can shift vast amounts of traffic onto unsuspecting ISPs as they search for resource-abundant paths that allow them to meet their goals (e.g., deliver high-quality video). At the same time, ISPs may only advertise

resource-constrained paths to content sources, preventing them from meeting their goals. In this work, we explored a new inter-domain routing protocol that allows ISPs and eyeballs to create routing paths with knowledge of content sources' resource desires.

May 2012 – present

Principled workflow-centric tracing of distributed systems

Workflow-centric tracing (also called end-to-end tracing) captures the workflow of how individual requests are serviced within and among the components of a distributed system. It is an extremely powerful substrate on which to layer future automated-management tools (e.g., for diagnosis or resource provisioning). However, today, there is a lack of clarity with regards to when tracing infrastructure designs need to be different. This has led to both a proliferation of tracing designs and a mistaken belief that a single tracing design can be a "one-size-fits-all" solution for a variety of management tasks. For this research, we used our experiences building workflow-centric tracing infrastructures and building tools on top of them to distill the key design axes of tracing. We described which management tasks require different design choices for these axes. A very interesting result of this research was our realization that certain seemingly innocuous design choices can lead to unexpectedly poor outcomes when used together.

Sept. 2006 – Sept. 2013

Diagnosing performance changes by comparing request flows

Diagnosing problems in large distributed systems and cloud infrastructures is extraordinarily challenging. Sophisticated tools that use systems knowledge, machine learning, statistics, and visualization techniques are needed to help developers with these tasks. My dissertation focused on one such technique, called request-flow comparison, which automatically localizes the source of a performance degradation from the myriad components in a distributed system to just a few potential culprits. We demonstrated request-flow comparison's effectiveness by using it to diagnose real performance problems observed in a distributed storage service called Ursa Minor and in certain Google services. Via a 26-person user study, we found that different visualizations for presenting request-flow comparison's results are best for different problem types. Request-flow comparison builds on workflow-centric tracing.

Jun. 2005 – May 2010

Creating a transparently scalable metadata service for distributed storage

Many object-based storage services, such as the Google File System, are scalable only with regard to data, not metadata. In this work, we explored simple techniques for building a scalable metadata service for Ursa Minor. The key challenge we addressed was how to minimize the complexity of handling multi-server operations, such as RENAMES. Our approach was twofold. We first minimized such occurrences by automatically co-locating metadata for files that resided in similar parts of the filesystem namespace. In cases where the metadata involved resided on multiple servers, we used the migration functionality already present in most systems to move one item to the other item's server. This is a heavy-handed approach, but we found that it worked with little performance impact for many common workloads.

Jul. 2007 – Sept. 2007

Improving the accuracy of query-progress indicators for data warehouses

Queries in business intelligence workloads are often resource intensive and slow to complete. For these queries, accurate query progress estimation is paramount to help operators decide whether to kill a currently long-running query in favor of other more important queries. While an intern at HP Labs, I explored the use of statistical methods for creating a progress indicator for Neoview, HP's data warehousing solution. Our approach involved two steps. First, we utilized linear regression and input transformations to predict the remaining runtime of the individual operators of a query plan. Second, we combined these predictions with knowledge about which operators could execute in parallel to estimate the total remaining runtime.

Jul. 2005 – Dec. 2006

//TRACE: Enabling accurate trace replay for parallel applications

Since company security policies often prohibit explicit application sharing, it is difficult to storage vendors to evaluate their storage systems under a potential client's expected workload. One alternative is trace replay, but the many inter-node dependencies exhibited by most parallel applications make them hard to replay accurately. To address this problem, I helped create //TRACE, a program for extracting and replaying traces of parallel applications to recreate their I/O behavior. Its tracing engine automatically discovers inter-node data dependencies and inter-I/O compute times for each node in a parallel application. //TRACE embeds this

information in per-node annotated I/O traces, allowing its parallel replayer to closely mimic the behavior of a traced application.

Jun. 2003 – Sept. 2005

Evaluating replication policies for layered clustering of NFS servers
Layered clustering (or NAS aggregation) offers cluster-like load balancing for unmodified NFS or CIFS servers. Read requests sent to a busy server can be offloaded to other servers holding replicas of the accessed files. In this research, we explored a key design question for this approach: which files should be replicated? By conducting a trace-based study, we found that the popular policy of replicating read-only files offers little benefit. A policy that replicates read-only portions of read-mostly files, however, implicitly coordinates with client cache invalidations and thereby allows almost all read operations to be offloaded. In a read-heavy trace, we found that 75% of all operations and 52% of all data transfers can be offloaded from a busy server.

Professional Experience

Red Hat Research Fellow **November 2016 – Present**
Boston University, Mass Open Cloud

- Collaborating with Red Hat on research related to diagnosing problems in clouds
- Creating a continuously running instrumentation framework that can automatically enable the instrumentation needed to diagnose newly-observed problems within distributed applications
- Exploring how to automatically identify and label semantic patterns in complex workflow-centric traces to increase these traces' utility for diagnosis tasks
- Advising seven graduate students and undergraduates on various research and engineering projects

Postdoctoral Researcher **June 2013 – September 2016**
Carnegie Mellon University, eXpressive Internet Architecture (XIA) Group

- *Host*: Peter Steenkiste
- Explored mechanisms to enable evolvability for inter-domain routing
- Explored resource-aware routing protocols for use by CDNs and clouds
- Co-wrote NSF annual reports and helped write NSF proposals
- Supervised graduate students on networking-related projects
- Created, developed, and taught a graduate class on cloud computing (15-719, Fall 2013)

Consultant **November 2014 – December 2014**
Huawei, storage group

- Consulted on best practices for problem diagnosis in storage systems
- Provided advice on how to implement request-flow comparison for use in select products
- Helped design a workflow-centric tracing infrastructure for use in select products

Graduate Student **June 2006 – May 2013**
Carnegie Mellon University, Parallel Data Lab

- Developed techniques for tracing distributed systems and automatically localizing problems within them
- Collaborated with fellow graduate students on the following research topics:
  - Building scalable metadata services for distributed storage systems
  - Building an accurate MPI-based trace replayer for HPC applications
  - Applying machine learning to predict workload performance
- Developed and maintained Ursa Minor's NFS server and tracing component

Software Engineering Intern **May 2010 – December 2010**
Google

- *Mentors*: Michael De Rosa and Brian McBarron
- Implemented request-flow comparison on top of Dapper, Google's workflow-centric tracing infrastructure
- Demonstrated request-flow comparison's utility in helping diagnose real performance degradations
- Helped create a Dapper visualization that shows service inter-dependencies annotated with perf. metrics

Research Intern **July 2007 – March 2008**
HP Labs

- *Mentor*: Kivanc Ozonat
- Explored how to create a statistical query-progress indicator for Neoview, HP's enterprise data warehouse
- Created tools for visualizing the complex query execution plans created by Neoview
- Consulted with the statistical learning inference and control (SLIC) team to identify how machine learning could be used to help diagnose performance problems in distributed systems

Systems Programmer **June 2004 – May 2006**
Carnegie Mellon University, Parallel Data Lab

- Core member of the Ursa Minor development team
  - Responsible for the development and maintenance of the NFS server
  - Led an effort to ensure SPEC SFS compatibility with Ursa Minor
  - Developed tools for visualizing Ursa Minor's performance on key benchmarks over time
  - Co-led an effort to improve small-file performance via intelligent metadata prefetching
- Helped implement a tee that compared the responses of a new NFSv3/v4 server to that of a reference
- Created a NFS trace-based simulator for evaluating NAS-replication policies

Student Researcher **January 2003 – May 2003**
Carnegie Mellon University, Advanced Multimedia Processing Lab

- Developed and tested a face detection and tracking algorithm for 3D point-cloud cameras

Technical Support Specialist **September 2000 – May 2001**
Carnegie Mellon University, Computing Services Help Desk

- Provided technical support for members of the campus community

Codeveloper & co-instructor **Fall 2013**
CS 15-719, Advanced Cloud Computing

This class provides an overview of cloud-computing concepts via a curriculum that emphasizes reading research papers, lectures, projects, and exams. It usually consists of 30-40 Master's students and a few PhD students.

- *Co-instructors*: Garth Gibson, Majd Sakr, Greg Ganger
- Drove design of course syllabus
- Created and delivered lectures, created exams, and held regular office hours
- Created and supported a project that involved exploring AWS and implementing Hadoop jobs in it
- Created and supported a project that involved implementing a load balancer for OpenStack

Teaching Assistant **Fall 2005 & Spring 2010**
ECE 18-746, Storage Systems

This class covers a broad range of material, including hard-disk architecture, file-system design and debugging, RAID, and object-based storage. It usually consists of 40-60 Master's students and PhD students.

- Created and supported a project that required students to build a RAID-5 controller for iSCSI
- Created and graded both tests and projects and held regular office hours

Special Skills

Operating systems: Linux, Solaris, Win32, Mac OS X

Programming languages: C, C++, Java, HTML, Perl

Protocols: BGP (advanced), MPI (basic), NFS (expert), RPC (expert)

Technologies: AWS, Hadoop, HDFS, Matlab, OpenStack, R, Quagga

Professional service

Program committee member:

- Transactions on Software Engineering 2017

- Transactions on Services Computing 2015
- HotStorage 2014
- HotStorage 2013

External reviewer: EuroSys 2017

Panel member:

- NSF Cloud Review 2017
- NSF 2016

Session chair:

- NeNS 2017
- SoCC 2016

Reading groups:

- BU diagnosis (2017-present),
- CMU network diagnosis (2013-2014)
- CMU diagnosis (2011-2013)

Volunteer Work

MIT Primes Research Mentor for high-school students (2017, 2018)

- 2017 mentees named Siemens Competition semi-finalists

CS Grand Awards Judge, Intel Science & Engineering Fair Finals (2012, 2015)

Presenter, Carnegie Science Center Buhl Planetarium (2010)

Affiliations

Massachusetts Open Cloud

ACM & USENIX

Raja R. Sambasivan

Refereed Publications

Bootstrapping evolvability for inter-domain routing with D-BGP. Raja R. Sambasivan, David Tran-Lam, Aditya Akella, Peter Steenkiste. In proceedings of the ACM 2017 SIGCOMM Conference (SIGCOMM'17). August 21^{th} to August 25^{th}, 2017. Los Angeles, CA, USA.

Principled workflow-centric tracing of distributed systems. Raja R. Sambasivan, Ilari Shafer, Jonathan Mace, Rodrigo Fonseca, Gregory R. Ganger. In proceedings of the 7^{th} ACM Symposium on Cloud Computing (SoCC'16). October 5^{th} to October 7^{th}, 2016. Santa Clara, CA, USA.

Bootstrapping evolvability for inter-domain routing. Raja R. Sambasivan, David Tran-Lam, Aditya Akella, Peter Steenkiste. In proceedings of the 14^{th} ACM Workshop on Hot Topics in Networks (HotNets'15). November 16^{th} to November 17^{th}, 2015. Philadelphia, PA, USA.

Visualizing request-flow comparison to aid performance diagnosis in distributed systems. Raja R. Sambasivan, Ilari Shafer, Michelle L. Mazurek, Gregory R. Ganger. IEEE Transactions on Visualization and Computer Graphics 19(12), December 2013. In proceedings of Information Visualization 2013.

Specialized storage for big numeric time series. Ilari Shafer, Raja R. Sambasivan, Anthony Rowe, Gregory R. Ganger. In proceedings of the 5^{th} USENIX Workshop on Hot Topics in Storage and File Systems (HotStorage'13). June 27^{th} to June 28^{th}, 2013. San Jose, CA, USA.

Automated diagnosis without predictability is a recipe for failure. Raja R. Sambasivan, Gregory R. Ganger. In proceedings of the 4^{th} USENIX Workshop on Hot Topics in Cloud Computing (HotCloud'12). June 12^{th} to June 13^{th}, 2012. Boston, MA, USA.

Diagnosing performance changes by comparing request flows. Raja R. Sambasivan, Alice X. Zheng, Michael De Rosa, Elie Krevat, Spencer Whitman, Michael Stroucken, William Wang, Lianghong Xu, Gregory R. Ganger. In proceedings of the 8^{th} USENIX Symposium on Network Systems Design and Implementation (NSDI'11). March 30^{th} to April 1^{st}, 2011. Boston, MA, USA.

A transparently-scalable metadata service for the Ursa Minor storage system. Shafeeq Sinnamohideen, Raja R. Sambasivan, Likun Liu, James Hendricks, Gregory R. Ganger. In proceedings of the 2010 USENIX Annual Technical Conference (USENIX ATC'10). June 23^{rd} to 25^{th}, 2010. Boston, MA, USA.

Categorizing and differencing system behaviours. Raja R. Sambasivan, Alice X. Zheng, Eno Thereska, Gregory R. Ganger. Appears in the proceedings of the 2^{nd} International Workshop on Hot Topics in Autonomic Computing (HotAC II). June 15^{th}, 2007. Jacksonville, Florida, USA.

Modeling the relative fitness of storage. Michael Mesnier, Matthew Wachs, Raja R. Sambasivan, Alice X. Zheng, Gregory R. Ganger. In proceedings of the International Conference on Measurement and Modeling of Computer Systems (SIGMETRICS'07). June 12^{th} to 16^{th}, 2007. San Diego, CA, USA.

//Trace: parallel trace replay with approximate causal events. Michael Mesnier, Matthew Wachs, Raja R. Sambasivan, Julio Lopez, James Hendricks, Gregory R. Ganger. In proceedings of the 5^{th} conference on File and Storage Technologies (FAST'07). February 13^{th} to 16^{th}, 2007. San Jose, CA, USA.

Ursa Minor: versatile cluster-based storage. Michael Abd-El-Malek, William V. Courtright II, Chuck Cranor, Gregory R. Ganger, James Hendricks, Andrew J. Klosterman, Michael Mesnier, Manish Prasad, Brandon Salmon, Raja R. Sambasivan, Shafeeq Sinnamohideen, John D. Strunk, Eno Thereska, Matthew Wachs, Jay J. Wylie. In the proceedings of the 4^{th} USENIX conference on File and Storage Technologies (FAST'05). December 13^{th} to 16^{th}, 2005. San Francisco, CA, USA.

Replication policies for layered clustering of NFS servers. Raja R. Sambasivan, Andrew J. Klosterman, Gregory R. Ganger. Appears in the proceedings of the 13^{th} Annual Meeting of the IEEE International Symposium on Modeling, Analysis, and Simulation of Computer and Telecommunication Systems (MASCOTS'05). September 27^{th} to 29^{th}, 2005. Atlanta, Georgia, USA.

Journal Publications

Relative fitness modeling. Michael Mesnier, Matthew Wachs, Raja R. Sambasivan, Alice Zheng, Raja R. Sambasivan, Gregory R. Ganger Research Highlights, Communications of the ACM. April 2009.

Early experiences on the journey towards self-* storage. Michael Abd-El-Malek, William V. Courtright II, Chuck Cranor, Gregory R. Ganger, James Hendricks, Andrew J. Klosterman, Michael Mesnier, Manish Prasad, Brandon Salmon, Raja R. Sambasivan, Shafeeq Sinnamohideen, John D. Strunk, Eno Thereska, Matthew Wachs, Jay J. Wylie. In the Bulletin of the IEEE Computer Society Technical Committee on Data Engineering 29(3). Special issue on self-managing database systems. September 2006.

Technical Reports

Bootstrapping evolvability for inter-domain routing with D-BGP. Raja R. Sambasivan, David Tran-Lam, Aditya Akella, Peter Steenkiste. Carnegie Mellon Computer Science Technical Report CMU-CS-16-117. June 2016.

So, you want to trace your distributed system? Key design insights from years of practical experience. Raja R. Sambasivan, Rodrigo Fonseca, Ilari Shafer, Gregory R. Ganger. Carnegie Mellon University Parallel Data Laboratory Technical Report CMU-PDL-14-102. April 2014.

Visualizing request-flow comparison to aid performance diagnosis in distributed systems. Raja R. Sambasivan, Ilari Shafer, Michelle L. Mazurek. Carnegie Mellon University Parallel Data Laboratory Technical Report CMU-PDL-13-104. May 2013. Supersedes CMU-PDL-12-102.

Visualizing request-flow comparison to aid performance diagnosis in distributed systems. Raja R. Sambasivan, Ilari Shafer, Michelle L. Mazurek. Carnegie Mellon University Parallel Data Laboratory Technical Report CMU-PDL-12-102. May 2012.

Automation without predictability is a recipe for failure. Raja R. Sambasivan, Gregory R. Ganger. Carnegie Mellon University Parallel Data Laboratory Technical Report CMU-PDL-11-101. January 2011.

Diagnosing performance changes by comparing system behaviours. Raja R. Sambasivan, Alice X. Zheng, Elie Krevat, Spencer Whitman, Michael Stroucken, William Wang, Lianghong Xu, Gregory R. Ganger. Carnegie Mellon University Parallel Data Laboratory Technical Report CMU-PDL-10-107. July 2010. Supersedes CMU-PDL-10-103.

A transparently-scalable metadata service for the Ursa Minor storage system. Shafeeq Sinnamohideen, Raja R. Sambasivan, James Hendricks, Likun Liu, Gregory R. Ganger. Carnegie Mellon University Parallel Data Laboratory Technical Report CMU-PDL-10-102. March 2010.

Diagnosing performance problems by visualizing and comparing system behaviours. Raja R. Sambasivan, Alice X. Zheng, Elie Krevat, Spencer Whitman, Gregory R. Ganger. Carnegie Mellon University Parallel Data Lab Technical Report CMU-PDL-10-103. February 2010.

Eliminating cross-server operations in scalable file systems. James Hendricks, Shafeeq Sinnamohideen, Raja R. Sambasivan, Gregory R. Ganger. Carnegie Mellon University Parallel Data Lab Technical Report CMU-PDL-06-105. May 2006.

Improving small file performance in object-based storage. James Hendricks, Raja R. Sambasivan, Shafeeq Sinnamohideen, Gregory R. Ganger. Carnegie Mellon University Parallel Data Lab Technical Report CMU-PDL-06-104. May 2006.

Selected project reports, Spring 2005 Advanced OS & Distributed Systems (15-712). Garth A. Gibson and Hyang-Ah Kim, Editors. Jangwoo Kim, Eriko Nurvitadhi, Eric Chung; Alex Nizhner, Andrew Biggadike, Jad Chamcham; Srinath Sridhar, Jeffrey Stylos, Noam Zeilberger; Gregg Economou, Raja R. Sambasivan, Terrence Wong; Elaine Shi, Yong Lu, Matt Reid; Amber Palekar, Rahul Iyer. Carnegie Mellon Computer Science Technical Report CMU-CS-05-138. May 2005.

Ursa Minor: Versatile cluster-based storage. Michael Abd-El-Malek, William V. Courtright II, Chuck Cranor, Gregory R. Ganger, James Hendricks, Andrew J. Klosterman, Michael Mesnier, Manish Prasad, Brandon Salmon, Raja R. Sambasivan, Shafeeq Sinnamohideen, John D. Strunk, Eno Thereska, Matthew Wachs, Jay J. Wylie. Carnegie Mellon University Parallel Data Laboratory Technical Report CMU-PDL-05-104. April 2005.

Patents

Managing execution of database queries. Stefan Kompress, Harumi Anne Kuno, Umeshwar Dayal, Janet Wiener, Raja Sambasivan. U.S. Patent 9,910,892. March 6^{th}, 2018.

Conference Talks

Bootstrapping evolvability for inter-domain routing with D-BGP. Presented at the ACM 2017 SIGCOMM Conference (SIGCOMM'17). August, 2017.

Principled workflow-centric tracing of distributed systems. Presented at the 7^{th} ACM Symposium on Cloud Computing (SoCC'16). October 2016.

Bootstrapping evolvability for inter-domain routing. Presented at the 14^{th} ACM Workshop on Hot Topics in Networks (HotNets'15). November 2015.

Visualizing request-flow comparison to aid performance diagnosis in distributed systems. Presented at IEEE InfoVis 2013.

Automated diagnosis without predictability is a recipe for failure. Presented at the 4^{th} USENIX Workshop on Hot Topics in Cloud Computing (HotCloud'12). June 2012.

Generalizing request-flow comparison to more systems. WiP talk at 23^{rd} ACM Symposium on Operating Systems Principles (SOSP'11). October 2011.

Diagnosing performance changes by comparing request flows. Presented at the 8^{th} USENIX Symposium on Networked Systems Design and Implementation (NSDI'11). March 2011.

Spectroscope: a tool for categorizing and differencing system behaviours. Presented at the 2^{nd} International Workshop on Hot Topics in Autonomic Computing (HotACII). June 2007.

Replication policies for layered clustering of NFS servers. Presented at the 13^{th} Annual Meeting of the IEEE International Symposium on Modeling, Analysis, and Simulation of Computer and Telecommunication Systems (MASCOTS'05). September 2005.

Invited Talks & Guest Lectures

Toward a diagnosis plane for cloud computing. Presented at LightStep (April 2018), Columbia University (March 2018), Facebook (February 2018), Brown University (February 2018).

Diagnosis and inter-domain support for an Internet of clouds. Presented at Tufts University (October 2017), Yale University (March 2017), AT&T Labs (May 2016), Intel Labs (April 2016), NYU (April 2016).

Diagnosing performance changes by comparing request flows. Presented at UCSD (April 2014), Brown University (April 2012), NetApp RTP (September 2011), Google NYC (June 2011).

Networking at Google: B4 & Jupiter Rising. Guest lecture at BU CS 528 (March 2018, March 2017).

When the cloud fizzles: Outages and how to debug them. Guest lecture at NU CS 6620 (April 2018) and BU CS 528 (April 2017).

A case study of the AWS outage on April 21st, 2011. Guest lecture at CMU 15-719 (Fall 2015, Fall 2014).

Diagnosis via monitoring & tracing. Guest lecture at CMU 15-719 (Fall 2015, Fall 2014).

Raja R. Sambasivan

References

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