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The VoltDB Codeline

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I was hired by Mike Stonebraker to commercialize the H-Store[1] research [Stonebraker et al. 2007b] in early 2008. For the first year, I collaborated with academic researchers building the prototype, with close oversight from Mike Stonebraker.[2] Andy Pavlo and I presented our early results at VLDB 2008 [Kallman et al. 2008] in August of that year. I then helped lead the efforts to commercialize VoltDB, ultimately spending the next ten years developing VoltDB with a team I was privileged to work with. In my time at VoltDB, Inc., Mike Stonebraker served as our CTO and then advisor, offering wisdom and direction for the team.

VoltDB was conceived after the success of Vertica[3]; if, Vertica, a system dedicated to analytical data, could beat a general-purpose system by an order of magnitude at analytical workloads, could a system dedicated to operational data do the same for operational workloads? This was the next step in Mike Stonebraker's crusade against the one-size-fits-all database.

VoltDB was to be a shared-nothing, distributed OLTP database. Rethinking assumptions about traditional systems, VoltDB threw out shared-memory concurrency, buffer pools and traditional disk persistence, and client-side transaction control. It assumed that high-volume OLTP workloads were mostly horizontally partitionable, and that analytics would migrate to special-purpose systems, keeping queries short.

The proposed system would dramatically reduce scaling issues, support native replication and high availability, and reduce costs for operational workloads without sacrificing transactions and strong consistency.

1. For more on H-Store see Chapter 19: H-Store/VoltDB.

2. See https://dl.acm.org/citation.cfm?id=1454211 for the list of collaborators.

3. For more on Vertica see Chapters 18 and 27.

VoltDB 1.0 was originally released in April 2010, after nearly two years of internal development. Work on the H-Store academic project continued in parallel. Over the years, many ideas and experimental results were shared between the researchers and the VoltDB engineering team, but code diverged as the two systems had different purposes. VoltDB also hired a number of graduate students who worked on the H-Store project.

Compaction[4]

In the Fall of 2010, the very first customer, who was equal parts brave and foolish, was using VoltDB 1.x in production and was running into challenges with memory usage.

This customer was using the resident set size (RSS) for the VoltDB process as reported by the OS as the key metric. While memory usage monitoring is more complex than disk usage monitoring, this is a good metric to use in most cases.

The problem was that the RSS was increasing with use, even though the data was not growing. Yes, records were being updated, deleted, and added, but the total number of records and the size of the logical data they represented was not growing. However, eventually, VoltDB would use all of the memory on the machine. This early customer was forced to restart VoltDB on a periodic basis—not great for a system designed for uptime. Needless to say, this was unacceptable for an in-memory database focused on operational workloads.

The problem was quickly identified as allocator fragmentation. Under it all, VoltDB was using GNU LibC malloc, which allocated big slabs of virtual address space and doled out smaller chunks on request. Allocator fragmentation happens when a slab is logically only half used, but the "holes" that can be used to service new allocations are too small to be useful.

There are two main ways to deal with this problem. The most common approach is to use a custom allocator. The two most common alternatives are JEMalloc and TCMalloc. Both are substantially more sophisticated at avoiding fragmentation waste than the default GLibC malloc.

The VoltDB team tried these options first but ran into challenges because VoltDB mixed C++ and Java in the same process. Using these allocators with the in-process JVM was challenging at the time.

4. Compaction, which is critical to running VoltDB for more than a few hours, didn't come up in the initial design or research because academics don't always run things the way one might in production. It ended up being critical to success.

The second approach, which is both more challenging and more effective, is do all the allocation yourself. You don't actually have to manage 100% of allocations. Short-lived allocations and permanent allocations tend not to contribute to allocator fragmentation. You primarily have to worry about data with unknown and variable life cycles, which is really critical for any in-memory database.

The team focused on three main types of memory usage that fit this profile.

- Tuple storage—a logical array of fixed size tuples per table.
- Blob storage—a set of variable-sized binary objects linked from tuples.
- Index storage—trees and hash tables that provide fast access to tuples by key.

Two teams set about implementing two different approaches to see which might work best.

The first team took on indexes and blob storage. The plan was to remake these data structures in such a way that they never had any "holes" at all. For indexes, all allocations for a specific index with a specific key width would be done sequentially into a linked list of memory-mapped slabs. Whenever a tree node or hash entry was deleted, the record at the very end of the set of allocations would be moved into the hole, and the pointers in the data structure would be reconfigured for the new address. Blob storage was managed similarly, but with pools for various size blobs.

There was a concern that the extra pointer fixups would impact performance, but measurements showed this was not significant. Now indexes and blobs *could not fragment.* This came at an engineering cost of several engineer-months, but without much performance impact to the product.

Tuple storage took a different approach. Tuples would be allocated into a linked list of memory-mapped slabs, much like index data, but holes from deletion would be tracked, rather than filled. Whenever the number of holes exceeded a threshold (e.g., 5%), a compaction process would be initiated that would rearrange tuples and merge blocks. This would bind fragmentation to a fixed amount, which met the requirements of VoltDB and the customer.

In the end, we didn't pick a winner; we used both schemes in different places. Both prototypes were sufficient and with an early product, there were many other things to improve. The anti-fragmentation work was a huge success and is considered a competitive advantage of VoltDB compared to other in-memory stores that often use memory less efficiently.[5] Without it, it would be hard to use VoltDB in any production workloads.

5. The competition catch-up is a long story. Most systems can't do what VoltDB does because they use shared-memory multi-threading and even lock-free or wait-free data structures. These are

These kinds of problems can really illustrate the gulf between research and production.

It turns out compaction is critical to running VoltDB for more than a few hours, but this didn't come up because of the research results. We previously assumed that if a steady state workload worked for an hour, it would work forever, but this is absolutely not the case.

Lesson. Memory usage should closely track the actual data stored, and systems should be tested for much longer periods of time.

Latency

Version 1.0 of the VoltDB database, like the H-Store prototype it was based on, used a transaction ordering and consensus scheme that was based on the ideas described in the original H-Store paper [Stonebraker et al. 2007b], but with additional safety. Oversimplifying a bit, nodes would collect all candidate work in a 5 ms epoch and then exchange between all nodes the work inside the cluster for that 5 ms. This work would then be ordered based on a scheme similar to Twitter Snowflake.[6]

This scheme guaranteed a total, global pre-order for all submitted transactions. That is, before a transaction was run, its serializable order with respect to all other transactions was known.

Compared to contemporary transaction ordering schemes, VoltDB offered more fault tolerance than two-phase-commit and was dramatically simpler than using a schema like Paxos for ordering. It also supported significantly higher throughput than either.

Having a global pre-ordering of all transactions required less coordination between cluster nodes when the work itself was being done [Stonebraker et al. 2007b]. In theory, participants have broad leeway to re-order work, so it can be executed more efficiently, provided it produces results effectively equivalent to the specified order. This was all part of the original H-Store research [Stonebraker et al. 2007b].

So, what's the catch? This scheme used wall clocks to order transactions. That meant transactions must wait up to 5 ms for the epoch to close, plus network round trip time, plus any clock skew. In a single data center, Network Time Protocol (NTP)

much harder to compact. Other systems *can* use TCMalloc or JEMalloc because they don't embed the JVM.

6. "Announcing Snowflake," the Twitter blog, June 1, 2010. https://blog.twitter.com/engineering/en_us/a/2010/announcing-snowflake.html. Last accessed March 29, 2018.

is capable of synchronizing clocks to about 1 ms, but that configuration isn't trivial to get right. Network skew is also typically low but can be affected by common things like background network copies or garbage collections.

To put it more clearly, on a single-node VoltDB instance, client operations would take at least 5 ms even if it did no actual work. That means a synchronous benchmark client could do 200 trivial transactions per second, substantially slower than MySQL for most workloads.

In a cluster, it was worse. Getting NTP set up well in order to evaluate VoltDB was a stumbling block, especially in the new world of the cloud. This meant the delay might be 10–20 ms. The original VoltDB paper assumes achieving clock synchronization is trivial, but we found that to be just false *enough* to cause problems. We didn't just need synced-clocks, we needed them to stay synced for days, months, or even years without issue.

None of this affected throughput. The VoltDB client was fully asynchronous by design and could processes responses in the order they arrived. A proper parallel workload could achieve millions of transactions per second on the right cluster, but asking prospective users to build fully asynchronous apps proved too much of a challenge. Users were not used to developing that way and changing user habits is difficult.

VoltDB needed to be faster than MySQL without application wizardry.

Many months of disagreement and thought from the engineering team culminated in a small meeting where a decision had to be made.

A rough plan was hashed out to replace VoltDB consensus with a post-order system that would slash latency to near zero while keeping throughput. The new system would limit some performance improvements to cross-partition transactions (which are typically rare for VoltDB use cases) and it would require several engineers working for almost a year, time that could be spent on more visible features.

Engineering came out of that meeting resolved to fix the latency issues. As part of the plan, the VoltDB 1.0 consensus scheme would be kept, but only to bootstrap a new system of elected partition leaders that serialized all per-partition work and a single, global cross-partition serializer that determined the order of cross-partition work.

This scheme was launched with version 3.0, and average cluster latency was reduced to nearly nothing now that we did not have to hold transactions for clock skew and the all-to-all exchange. Typical response latencies were less than a millisecond with a good network.

This directly led to VoltDB use in low-latency industries like ad-tech and personalization.

Lesson. Response time is as important as throughput.

Disk Persistence

When VoltDB launched, the high-availability story was 100% redundancy through clustering. There were periodic disk snapshots, so you would see data loss only if you lost multiple nodes, and then you might only lose minutes of recent data. The argument was that servers were more reliable, and per-machine UPSs (uninterruptive power supplies) were increasingly common, so multiple failures weren't a likely occurrence.

The argument didn't land.

VoltDB technical marketing and sales spent too much time countering the idea that VoltDB wouldn't keep your data safe. Competitors reinforced this narrative. In early 2011, it got to the point where lack of disk persistence was severely limiting customer growth.

VoltDB needed per-transaction disk persistence without compromising the performance it was known for. Part of the original H-Store/VoltDB thesis was that logging was one of the things holding traditional RDBMSs back when they moved to memory [Harizopoulos et al. 2008], so this posed quite a challenge.

To address this problem, Engineering added an inter-snapshot log to VoltDB but broke with the ARIES (Algorithms for Recovery and isolation Exploiting Semantics) style logs used by traditional RDBMSs. VoltDB already heavily relied on determinism and logical descriptions of operations to replicate between nodes. Engineering chose to leverage that work to write a logical log to disk that described procedure calls and SQL statements, rather than mutated data.

This approach had a huge technical advantage for VoltDB. As soon as transactions were ordered for a given partition (but before they were executed), they could be written to disk. This meant disk writes *and* the actual computation could be done *simultaneously*. As soon as both were completed, the transaction could be confirmed to the caller. Other systems performed operations and *then* wrote binary change-logs to disk. The logical approach and VoltDB implementation meant disk persistence didn't have substantial impact on throughput, and only minimal impact on latency.

Per-transaction disk-persistence was added in VoltDB 2.5 in Fall 2011 and almost immediately silenced persistence-based criticism of VoltDB. It's clear that without this feature, VoltDB would have seen much more limited use.

As an addendum, we have a lot more data today about how common complete cluster failure is with VoltDB. Cluster failures for well-run VoltDB instances are rare, but not always 100% unavoidable, and not all VoltDB clusters are well run. Disk persistence is a feature that not only cut off a line of criticism, but also gets exercised by users from time to time.

Lesson. People don't trust in-memory systems as system of record.

Latency Redux

In 2013, within a year of reducing average latency in VoltDB to nil, VoltDB was courted by a major telecommunications OEM (original equipment manufacturer) looking to replace Oracle across their stack. Oracle's pricing made it hard for them to compete with upstart Asian vendors who had built their stacks without Oracle, and Oracle's deployment model was poorly suited to virtualization and data-center orchestration.

Replacing Oracle would be a substantial boost to competitiveness.

During the OEM's VoltDB evaluation, latency quickly became an issue. While average latency met requirements, long tail latency did not. For a typical call authorization application, the service level agreement might dictate that any decision not made in 50 ms can't be billed to the customer, forcing the authorization provider to pay the call cost.

VoltDB created a new automated test to measure long tail latency. Rather than measure average latency or measure at the common 99th percentile or even the 99.999th percentile, Engineering set out to specifically count the number of transactions that took longer than 50 ms in a given window. The goal was to reduce that number to zero for a long-term run in our lab so the customer could support P99.999 latency under 50 ms in their deployments.

Once you start measuring the right things, the problem is mostly solved, but there was still code to write. We moved more of the statistics collection and health monitoring code out of blocking paths. We changed how objects were allocated and used to nearly eliminate the need for stop-the-world garbage collection events. We also tuned buffer sizes and Java virtual machine parameters to get everything running nice and "boring."

If there's one thing VoltDB Engineering learned over the course of ten years of development, it's that customers want their operational databases to be as boring and unsurprising as possible. This was the final piece of the puzzle that closed the first major telecommunications customer, with more coming right on their heels.

Today, a significant portion of the world's mobile calls and texts are authorized through a VoltDB-based system.

Lesson. P50 is a bad measure—P99 is better—P99.999 is best.

Conclusion

Of course, the incidents described here are just a tiny sliver of the challenges and adventures we encountered building VoltDB into the mature and trusted system it is today. Building a system from a research paper, to a prototype, to a 1.0, and to a robust platform deployed around the world is an unparalleled learning experience.

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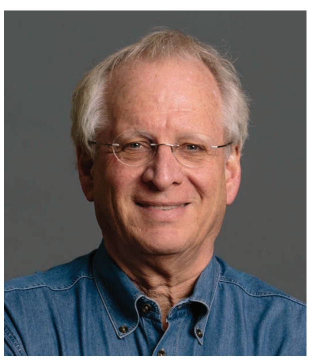

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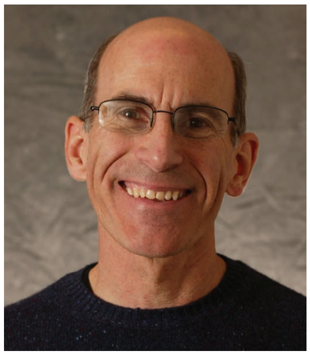
Janice L. Brown is president and founder of Janice Brown & Associates, Inc., a communications consulting firm. She uses strategic communications to help entrepreneurs and visionary thinkers launch technology companies, products, and ventures, as well as sell their products and ideas. She has been involved in three ventures (so far) with 2014 Turing Award-winner Michael Stonebraker: Vertica Systems, Tamr, and the Intel Science and Technology Center for Big Data. Her background includes positions at several public relations and advertising agencies, and product PR positions at two large technology companies. Her work for the Open Software Foundation won the PRSA's Silver Anvil Award, the "Oscar" of the PR industry. Brown has a B.A. from Simmons College. Visit www.janicebrown.com.

Paul Brown

Paul Brown first met Mike Stonebraker in early 1992 at Brewed Awakening coffee shop on Euclid Avenue in Berkeley, CA. Mike and John Forrest were interviewing Paul to take over the job Mike Olson had just left. Paul had a latte. Mike had tea. Since then, Paul has worked for two of Mike's startups: Illustra Information Technologies and SciDB / Paradigm4. He was co-author with Mike of a book and a number of research papers. Paul has worked for a series of DBMS companies all starting with the letter "I": Ingres, Illustra, Informix, and IBM. Alliterative ennui setting in, Paul joined Paradigm4 as SciDB's Chief Architect. He has since moved on to work for Teradata. Paul likes dogs, DBMSs, and (void *). He hopes he might have just picked up sufficient gravitas in this industry to pull off the beard.

Paul Butterworth



Paul Butterworth served as Chief Systems Architect at Ingres from 1980–1990. He is currently co-founder and Chief Technology Officer (CTO) at VANTIQ, Inc. His past roles include Executive Vice President, Engineering at You Technology Inc., and co-founder and CTO of Emotive Communications, where he conceived and designed the Emotive Cloud Platform for enterprise mobile computing. Before that, Paul was an architect at Oracle and a founder & CTO at AmberPoint, where he directed the technical strategy for the AmberPoint SOA governance products. Prior to AmberPoint, Paul was a Distinguished Engineer and Chief Technologist for the Developer Tools Group at Sun Microsystems and a founder, Chief Architect, and Senior Vice President of Forte Software. Paul holds undergraduate and graduate degrees in Computer Science from UC Irvine.

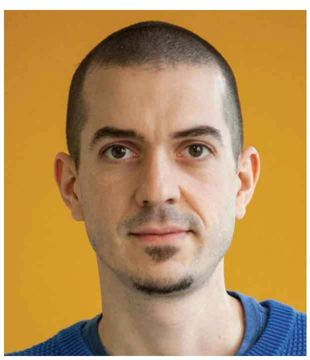
Michael J. Carey

Michael J. Carey received his B.S. and M.S. from Carnegie-Mellon University and his Ph.D. from the University of California, Berkeley, in 1979, 1981, and 1983, respectively. He is currently a Bren Professor of Information and Computer Sciences at the University of California, Irvine (UCI) and a consulting architect at Couchbase, Inc. Before joining UCI in 2008, Mike worked at BEA Systems for seven years and led the development of BEA's AquaLogic Data Services Platform product for virtual data integration. He also spent a dozen years teaching at the University of Wisconsin-Madison, five years at the IBM Almaden Research Center working on object-relational databases, and a year and a half at Propel Software, an e-commerce platform startup, during the infamous 2000–2001 Internet bubble. He is an ACM Fellow, an IEEE Fellow, a member of the National Academy of Engineering, and a recipient of the ACM SIGMOD E.F. Codd Innovations Award. His current interests center on data-intensive computing and scalable data management (a.k.a. Big Data).

Fred Carter

Fred Carter , a software architect in a variety of software areas, worked at Ingres Corporation in several senior positions, including Principal Scientist/Chief Architect. He is currently a principal architect at VANTIQ, Inc. Prior to VANTIQ, Fred was the runtime architect for AmberPoint, which was subsequently purchased by Oracle. At Oracle, he continued in that role, moving the AmberPoint system to a cloud-based, application performance monitoring service. Past roles included architect for EAI products at Forte (continuing at Sun Microsystems) and technical leadership positions at Oracle, where he designed distributed object services for interactive TV, online services, and content management, and chaired the Technical Committee for the Object Definition Alliance to foster standardization in the area of network-based multimedia systems. Fred has an undergraduate degree in Computer Science from Northwestern University and received his M.S. in Computer Science from UC Berkeley.

Raul Castro Fernandez



Raul Castro Fernandez is a postdoc at MIT, working with Samuel Madden and Michael Stonebraker on data discovery—how to help people find relevant data among databases, data lakes, and the cloud. Raul built Aurum, a data discovery system, to identify relevant data sets among structured data. Among other research lines, he is looking at how to incorporate unstructured data sources, such as PDFs and emails. More generally, he is interested in data-related problems, from efficient data processing to machine learning engineering. Before MIT, Raul completed his Ph.D. at Imperial College London, where he focused on designing new abstractions and building systems for large-scale data processing.

Ugur Çetintemel

Ugur Çetintemel is a professor in the department of Computer Science at Brown University. His research is on the design and engineering of high-performance, user-friendly data management and processing systems that allow users to analyze large data sets interactively. Ugur chaired SIGMOD '09 and served on the editorial boards of *VLDB Journal*, *Distributed and Parallel Databases*, and *SIGMOD Record*. He is the recipient of a National Science Foundation Career Award and an IEEE 10-year test of time award in Data Engineering, among others. Ugur was a co-founder and a senior architect of StreamBase, a company that specializes in high-performance data processing. He was also a Brown Manning Assistant Professor and has been serving as the Chair of the Computer Science Department at Brown since July 2014.

Xuedong Chen

Xuedong Chen is currently an Amazon.com Web Services software developer in Andover, Massachusetts. From 2002–2007 he was a Ph.D. candidate at UMass Boston, advised by Pat and Betty O'Neil. He, along with Pat O'Neil and others, were coauthors with Mike Stonebraker.

Mitch Cherniack

Mitch Cherniack is an Associate Professor at Brandeis University. He is a previous winner of an NSF Career Award and co-founder of Vertica Systems and StreamBase Systems. His research in Database Systems has focused on query optimization, streaming data systems, and column-based database architectures. Mitch received his Ph.D. from Brown University in 1999, an M.S. from Concordia University in 1992, and a B.Ed. from McGill University in 1984.

David J. DeWitt

David J. DeWitt joined the Computer Sciences Department at the University of Wisconsin in September 1976 after receiving his Ph.D. from the University of Michigan. He served as department chair from July 1999 to July 2004. He held the title of John P. Morgridge Professor of Computer Sciences when he retired from the University of Wisconsin in 2008. In 2008, he joined Microsoft as a Technical Fellow to establish and manage the Jim Gray Systems Lab in Madison. In 2016, he moved to Boston to join the MIT Computer Science and AI Laboratory as an Adjunct Professor. Professor DeWitt is a member of the National Academy of Engineering (1998), a fellow of the American Academy of Arts and Sciences (2007), and an ACM Fellow (1995). He received the 1995 Ted Codd SIGMOD Innovations Award. His pioneering contributions to the field of scalable database systems for "big data" were recognized by ACM with the 2009 Software Systems Award.

Aaron J. Elmore

Aaron J. Elmore is an assistant professor in the Department of Computer Science and the College of the University of Chicago. Aaron was previously a postdoctoral associate at MIT working with Mike Stonebraker and Sam Madden. Aaron's thesis on *Elasticity Primitives for Database-as-a-Service* was completed at the University of California, Santa Barbara under the supervision of Divy Agrawal and Amr El Abbadi. Prior to receiving a Ph.D., Aaron spent several years in industry and completed an M.S. at the University of Chicago.

Miguel Ferreira

Miguel Ferreira is an alumnus of MIT. He was coauthor of the paper, "Integrating Compression and Execution in Column-Oriented Database Systems," while working with Samuel Madden and Daniel Abadi, and "C-store: A Column-Oriented DBMS," with Mike Stonebraker, Daniel Abadi, and others.

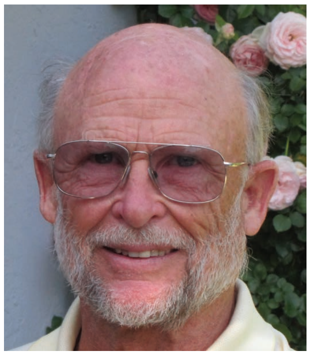
Vijay Gadepally

Vijay Gadepally is a senior member of the technical staff at the Massachusetts Institute of Technology (MIT) Lincoln Laboratory and works closely with the Computer Science and Artificial Intelligence Laboratory (CSAIL). Vijay holds an M.Sc. and Ph.D. in Electrical and Computer Engineering from The Ohio State University and a B.Tech in Electrical Engineering from the Indian Institute of Technology, Kanpur. In 2011, Vijay received an Outstanding Graduate Student Award at The Ohio State University. In 2016, Vijay received the MIT Lincoln Laboratory's Early Career Technical Achievement Award and in 2017 was named to AFCEA's inaugural 40 under 40 list. Vijay's research interests are in high-performance computing, machine learning, graph algorithms, and high-performance databases.

Nabil Hachem

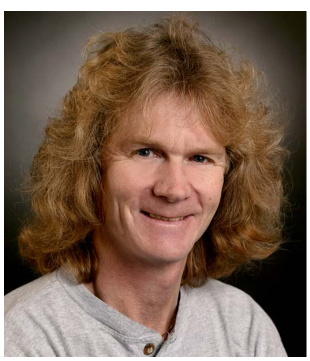
Nabil Hachem is currently Vice President, Head of Data Architecture, Technology, and Standards at MassMutual. He was formerly Global Head of Data Engineering at Novartis Institute for Biomedical Research, Inc. He also held senior data engineering posts at Vertica Systems, Inc., Infinity Pharmaceuticals, Upromise Inc., Fidelity Investments Corp., and Ask Jeeves Inc. Nabil began his career as an electrical engineer and operations department manager for a data telecommunications firm in Lebanon. In addition to his commercial career, Nabil taught computer science at Worcester Polytechnic Institute. He co-authored dozens of papers on scientific databases, file structures, and join algorithms, among others. Nabil received a degree in Electrical Engineering from the American University of Beirut and earned his Ph.D. in Computer Engineering from Syracuse University.

Don Haderle



Don Haderle joined IBM in 1968 as a software developer and retired in 2005 as the software executive operating as Chief Technology Officer (CTO) for Information Management. He consulted with venture capitalists and advised startups. He currently sits on technical advisory boards for a number of companies and consults independently. Considered the father of commercial high-performance, industrial-strength relational database systems, he was the technical leader and chief architect of DB2 from 1977–1998. He led DB2's overall architecture and development, making key personal contributions to and holding fundamental patents in all key elements, including: logging primitives, memory management, transaction fail-save and recovery techniques, query processing, data integrity, sorting, and indexing. As CTO, Haderle collaborated with researchers to incubate new product directions for the information management industry. Don was appointed an IBM Fellow in 1989 and Vice President of Advanced Technology in 1991; named an ACM Fellow in 2000; and elected to the National Academy of Engineering in 2008. He is a graduate of UC Berkeley (B.A., Economics, 1967).

James Hamilton



James Hamilton is Vice President and Distinguished Engineer on the Amazon Web Services team, where he focuses on infrastructure efficiency, reliability, and scaling. He has spent more than 20 years working on high-scale services, database management systems, and compilers. Prior to joining AWS, James was architect on the Microsoft Data Center Futures team and the Windows Live Platform Services team. He was General Manager of the Microsoft Exchange Hosted Services team and has led many of the SQL Server engineering teams through numerous releases. Before joining Microsoft, James was Lead Architect on the IBM DB2 UDB team. He holds a B.Sc. inComputer Science from the University of Victoria and a Master's in Math, Computer Science from the University of Waterloo.

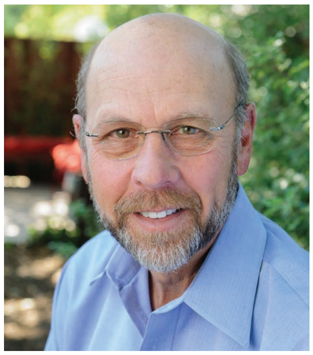
Stavros Harizopoulos

Stavros Harizopoulos is currently a Software Engineer at Facebook, where he leads initiatives on Realtime Analytics. Before that, he was a Principal Engineer at AWS Redshift, a petabyte-scale columnar Data Warehouse in the cloud, where he was leading efforts on performance and scalability. In 2011, he co-founded Amiato, a fully managed real-time ETL cloud service, which was later acquired by Amazon. In the past, Stavros has held research-scientist positions at HP Labs and MIT CSAIL, working on characterizing the energy efficiency of database servers, as well as dissecting the performance characteristics of modern in-memory and column-store databases. He is a Carnegie Mellon Ph.D. and a Y Combinator alumnus.

Marti Hearst

Marti Hearst is a professor in the School of Information and the EECS Department at UC Berkeley. She was formerly a member of the research staff at Xerox PARC and received her Ph.D. from the CS Division at UC Berkeley. Her primary research interests are user interfaces for search engines, information visualization, natural language processing, and improving education. Her book *Search User Interfaces* was the first of its kind in academics. Prof. Hearst was named a Fellow of the ACM in 2013 and a member of the CHI Academy in 2017, and is president of the Association for Computational Linguistics. She has received four student-initiated Excellence in Teaching Awards.

Jerry Held



Jerry Held has been a successful Silicon Valley entrepreneur, executive, and investor for over 40 years. He has managed all growth stages of companies, from conception to multi-billion-dollar global enterprise. He is currently chairman of Tamr and Madaket Health and serves on the boards of NetApp, Informatica, and Copia Global. His past board service includes roles as executive chairman of Vertica Systems and MemSQL and lead independent director of Business Objects. Previously, Dr. Held was "CEO-in-residence" at venture capital firm Kleiner Perkins Caufield & Byers. He was senior vice president of Oracle Corporation's server product division and a member of the executive team that grew Tandem Computers from pre-revenue to multi-billion-dollar company. Among many other roles, he led pioneering work in fault-tolerant, shared-nothing, and scale-out relational database systems. He received his Ph.D. in Computer Science from the University of California, Berkeley, where he led the initial development of the Ingres relational database management system.

Pat Helland

Pat Helland has been building databases, transaction systems, distributed systems, messaging systems, multiprocessor hardware, and scalable cloud systems since 1978. At Tandem Computers, he was Chief Architect of the transaction engine for NonStop SQL. At Microsoft, he architected Microsoft Transaction Server, Distributed Transaction Coordinator, SQL Service Broker, and evolved the Cosmos big data infrastructure to include optimizing database features as well as petabyt-scale transactionally correct event processing. While at Amazon, Pat contributed to the design of the Dynamo eventually consistent store and also the Product Catalog. Pat attended the University of California, Irvine from 1973–1976 and was in the inaugural UC Irvine Information and Computer Science Hall of Fame. Pat chairs the Dean's Leadership Council of the Donald Bren School of Information and Computer Sciences (ICS), UC Irvine.

Joseph M. Hellerstein

Joseph M. Hellerstein is the Jim Gray Professor of Computer Science at the University of California, Berkeley, whose work focuses on data-centric systems and the way they drive computing. He is an ACM Fellow, an Alfred P. Sloan Research Fellow, and the recipient of three ACM-SIGMOD "Test of Time" awards for his research. In 2010, *Fortune Magazine* included him in their list of 50 smartest people in technology, and MIT's *Technology Review* magazine included his work on their TR10 list of the 10 technologies "most likely to change our world." Hellerstein is the co-founder and Chief Strategy Officer of Trifacta, a software vendor providing intelligent interactive solutions to the messy problem of wrangling data. He serves on the technical advisory boards of a number of computing and Internet companies including Dell EMC, SurveyMonkey, Captricity, and Datometry, and previously served as the Director of Intel Research, Berkeley.

Wei Hong

Wei Hong is an engineering director in Google's Data Infrastructure and Analysis (DIA) group, responsible for the streaming data processing area including building and maintaining the infrastructure for some of Google's most revenue-critical data pipelines in Ads and Commerce. Prior to joining Google, he cofounded and led three startup companies: Illustra and Cohera with Mike Stonebraker in database systems and Arch Rock in Internet of Things. He also held senior engineering leadership positions at Informix, PeopleSoft, Cisco, and Nest. He was a senior researcher at Intel Research Berkeley working on sensor networks and streaming database systems and won an ACM SIGMOD Test of Time Award. He is a co-inventor of 80 patents. He received his Ph.D. from UC Berkeley and hos ME, BE, and BS from Tsinghua University.

John Hugg

John Hugg has had a deep love for problems relating to data. He's worked at three database product startups and worked on database problems within larger organizations as well. Although John dabbled in statistics in graduate school, Dr. Stonebraker lured him back to databases using the nascent VoltDB project. Working with the very special VoltDB team was an unmatched opportunity to learn and be challenged. John received an M.S in 2007 and a B.S. in 2005 from Tufts University.

Ihab Ilyas

Ihab Ilyas is a professor in the Cheriton School of Computer Science at the University of Waterloo, where his main research focuses on the areas of big data and database systems, with special interest in data quality and integration, managing uncertain data, rank-aware query processing, and information extraction. Ihab is also a co-founder of Tamr, a startup focusing on large-scale data integration and cleaning. He is a recipient of the Ontario Early Researcher Award (2009), a Cheriton Faculty Fellowship (2013), an NSERC Discovery Accelerator Award (2014), and a Google Faculty Award (2014), and he is an ACM Distinguished Scientist. Ihab is an elected member of the VLDB Endowment board of trustees, elected SIGMOD vice chair, and an associate editor of *ACM Transactions on Database Systems* (TODS). He holds a Ph.D. in Computer Science from Purdue University and a B.Sc. and an M.Sc. from Alexandria University.

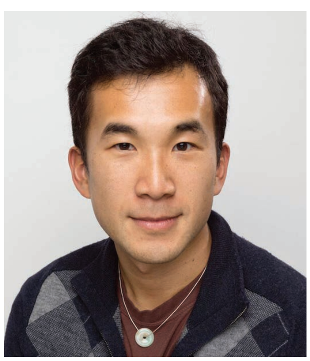
Jason Kinchen

Jason Kinchen , Paradigm4's V.P. of Engineering, is a software professional with over 30 years' experience in delivering highly complex products to life science, automotive, aerospace, and other engineering markets. He is an expert in leading technical teams in all facets of a project life cycle from feasibility analysis to requirements to functional design to delivery and enhancement, and experienced in developing quality-driven processes improving the software development life cycle and driving strategic planning. Jason is an avid cyclist and a Red Cross disaster action team volunteer.

Moshe Tov Kreps

Moshe Tov Kreps (formerly known as Peter Kreps) is a former researcher at the University of California at Berkeley and the Lawrence Berkeley National Laboratory. He was coauthor, with Mike Stonebraker, Eugene Wong, and Gerald Held, of the seminal paper, "The Design and Implementation of INGRES," published in the ACM Transactions on Database Systems in September 1976.

Edmond Lau



Edmond Lau is the co-founder of Co Leadership, where his mission is to transform engineers into leaders. He runs leadership experiences, multi-week programs, and online courses to bridge people from where they are to the lives and careers they dream of. He's the author of *The Effective Engineer*, the now the de facto onboarding guide for many engineering teams. He's spent his career leading engineering teams across Silicon Valley at Quip, Quora, Google, and Ooyala. As a leadership coach, Edmond also works directly with CTO's, directors, managers, and other emerging leaders to unlock what's possible for them. Edmond has been featured in the *New York Times*, *Forbes*, *Time*, *Slate*, *Inc.*, *Fortune*, and *Wired*. He blogs at coleadership.com, has a website (www.theeffectiveengineer.com), and tweets at @edmondlau.

Shilpa Lawande

Shilpa Lawande is CEO and co-founder of postscript .us, an AI startup on a mission to free doctors from clinical paperwork. Previously, she was VP/GM HPE Big Data Platform, including its flagship Vertica Analytics Platform. Shilpa was a founding engineer at Vertica and led its Engineering and Customer Success teams from startup through the company's acquisition by HP. Shilpa has several patents and books on data warehousing to her name, and was named to the 2012 Mass High Tech Women to Watch list and Rev Boston 20 in 2015. Shilpa serves as an advisor at Tamr, and as mentor/volunteer at two educational initiatives, Year Up (Boston) and CSPathshala (India). Shilpa has a M.S. in Computer Science from the University of Wisconsin-Madison and a B.S in Computer Science and Engineering from the Indian Institute of Technology, Mumbai.

Amerson Lin

Amerson Lin received his B.S. and M.Eng both in Computer Science at MIT, the latter in 2005. He returned to Singapore to serve in the military and government before returning to the world of software. He was a consultant at Pivotal and then a business development lead at Palantir in both Singapore and the U.S. Amerson currently runs his own Insurtech startup—Gigacover—which delivers digital insurance to Southeast Asia.

Samuel Madden

Samuel Madden is a professor of Electrical Engineering and Computer Science in MIT's Computer Science and Artificial Intelligence Laboratory. His research interests include databases, distributed computing, and networking. He is known for his work on sensor networks, column-oriented database, high-performance transaction processing, and cloud databases. Madden received his Ph.D. in 2003 from the University of California at Berkeley, where he worked on the TinyDB system for data collection from sensor networks. Madden was named one of Technology Review's Top 35 Under 35 (2005), and is the recipient of several awards, including an NSF CAREER Award (2004), a Sloan Foundation Fellowship (2007), VLDB best paper awards (2004, 2007), and a MobiCom 2006 best paper award. He also received "test of time" awards in SIGMOD 2013 and 2017 (for his work on Acquisitional Query Processing in SIGMOD 2003 and on Fault Tolerance in the Borealis system in SIGMOD 2007), and a ten-year best paper award in VLDB 2015 (for his work on the C-Store system).

Tim Mattson

Tim Mattson is a parallel programmer. He earned his Ph.D. in Chemistry from the University of California, Santa Cruz for his work in molecular scattering theory. Since 1993, Tim has been with Intel Corporation, where he has worked on High Performance Computing: both software (OpenMP, OpenCL, RCCE, and OCR) and hardware/software co-design (ASCI Red, 80-core TFLOP chip, and the 48 core SCC). Tim's academic collaborations include work on the fundamental design patterns of parallel programming, the BigDAWG polystore system, the TileDB array storage manager, and building blocks for graphs "in the language of linear algebra" (the GraphBLAS). Currently, he leads a team of researchers at Intel working on technologies that help application programmers write highly optimized code that runs on future parallel systems. Outside of computing, Tim fills his time with coastal sea kayaking. He is an ACA-certified kayaking coach (level 5, advanced open ocean) and instructor trainer (level three, basic coastal).

Felix Naumann

Felix Naumann studied Mathematics, Economics, and Computer Science at the University of Technology in Berlin. He completed his Ph.D. thesis on "Quality-driven Query Answering" in 2000. In 2001 and 2002, he worked at the IBM Almaden Research Center on topics of data integration. From 2003–2006, he was assistant professor for information integration at the Humboldt-University of Berlin. Since then, he has held the chair for information systems at the Hasso Plattner Institute at the University of Potsdam in Germany. He is Editor-in-Chief of *Information Systems*, and his research interests are in data profiling, data cleansing, and text mining.

Mike Olson

Mike Olson co-founded Cloudera in 2008 and served as its CEO until 2013 when he took on his current role of chief strategy officer (CSO). As CSO, Mike is responsible for Cloudera's product strategy, open-source leadership, engineering alignment, and direct engagement with customers. Prior to Cloudera, Mike was CEO of Sleepycat Software, makers of Berkeley DB, the open-source embedded database engine. Mike spent two years at Oracle Corporation as Vice President for Embedded Technologies after Oracle's acquisition of Sleepycat in 2006. Prior to joining Sleepycat, Mike held technical and business positions at database vendors Britton Lee, Illustra Information Technologies, and Informix Software. Mike has a B.S. and an M.S. in Computer Science from the University of California, Berkeley. Mike tweets at @mikeolson.

Elizabeth O'Neil

Elizabeth O'Neil (Betty) is a Professor of Computer Science at the University of Massachusetts, Boston. Her focus is research, teaching, and software development in database engines: performance analysis, transactions, XML support, Unicode support, buffering methods. In addition to her work for UMass Boston, she was, among other pursuits, a long-term (1977–1996) part-time Senior Scientist for Bolt, Beranek, and Newman, Inc., and during two sabbaticals was a full-time consultant for Microsoft Corporation. She is the owner of two patents owned by Microsoft.

Patrick O'Neil

Patrick O'Neil is Professor Emeritus at the University of Massachusetts, Boston. His research has focused on database system cost-performance, transaction isolation, data warehousing, variations of bitmap indexing, and multi-dimensional databases/OLAP. In addition to his research, teaching, and service activities, he is the coauthor—with his wife Elizabeth (Betty)—of a database management textbook, and has been active in developing database performance benchmarks and corporate database consulting. He holds several patents.

Mourad Ouzzani

Mourad Ouzzani is a principal scientist with the Qatar Computing Research Institute, HBKU. Before joining QCRI, he was a research associate professor at Purdue University. His current research interests include data integration, data cleaning, and building large-scale systems to enable science and engineering. He is the lead PI of Rayyan, a system for supporting the creation of systematic reviews, which had more than 11,000 users as of March 2017. He has extensively published in top-tier venues including SIGMOD, PVLDB, ICDE, and TKDE. He received Purdue University Seed for Success Awards in 2009 and 2012. He received his Ph.D. from Virginia Tech and his M.S. and B.S. from USTHB, Algeria.

Andy Palmer

Andy Palmer is co-founder and CEO of Tamr, Inc., the enterprise-scale data unification company that he founded with fellow serial entrepreneur and 2014 Turing Award winner Michael Stonebraker, Ph.D., and others. Previously, Palmer was co-founder and founding CEO of Vertica Systems (also with Mike Stonebraker), a pioneering analytics database company (acquired by HP). He founded Koa Labs, a seed fund supporting the Boston/Cambridge entrepreneurial ecosystem, is a founder-partner at The Founder Collective, and holds a research affiliate position at MIT CSAIL. During his career as an entrepreneur, Palmer has served as Founder, founding investor, BoD member, or advisor to more than 60 startup companies in technology, healthcare, and the life sciences. He also served as Global Head of Software and Data Engineering at Novartis Institutes for BioMedical Research (NIBR) and as a member of the start-up team and Chief Information and Administrative Officer at Infinity Pharmaceuticals (NASDAQ: INFI). Previously, he held positions at innovative technology companies Bowstreet, pcOrder.com, and Trilogy. He holds a BA from Bowdoin (1988) and an MBA from the Tuck School of Business at Dartmouth (1994).

Andy Pavlo

Andy Pavlo is an assistant professor of Databaseology in the Computer Science Department at Carnegie Mellon University. He also used to raise clams. Andy received a Ph,D, in 2013 and an M.Sc. in 2009, both from Brown University, and an M.Sc. in 2006 and a B.Sc., both from Rochester Institute of Technology.

Alex Poliakov

Alex Poliakov has over a decade of experience developing distributed database internals. At Paradigm4, he helps set the vision for the SciDB product and leads a team of Customer Solutions experts who help researchers in scientific and commercial applications make optimal use of SciDB to create new insights, products, and services for their companies. Alex previously worked at Netezza, after graduating from MIT's Course 6. Alex is into flying drones and producing drone videos.

Alexander Rasin

Alexander Rasin is an Associate Professor in the College of Computing and Digital Media (CDM) at DePaul University. He received his Ph.D. and M.Sc. in Computer Science from Brown University, Providence, RI. He is a co-Director of Data Systems and Optimization Lab at CDM and his primary research interest is in database forensics and cybersecurity applications of forensic analysis. Dr. Rasin's other research projects focus on building and tuning performance of domain-specific data management systems—currently in the areas of computer-aided diagnosis and software analytics. Several of his current research projects are supported by NSF.

Jennie Rogers

Jennie Rogers is the Lisa Wissner-Slivka and Benjamin Slivka Junior Professor in Computer Science and an Assistant Professor at Northwestern University. Before that she was a postdoctoral associate in the Database Group at MIT CSAIL where she worked with Mike Stonebraker and Sam Madden. She received her Ph.D. from Brown University under the guidance of Ugur Çetintemel. Her research interests include the management of science data, federated databases, cloud computing, and database performance modeling. Her Erdös number is 3.

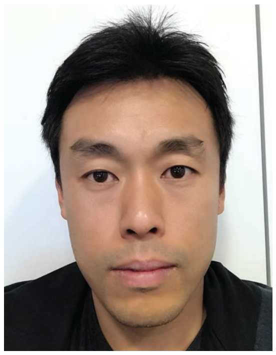
Lawrence A. Rowe

Lawrence A. Rowe is an Emeritus Professor of Electrical Engineering and Computer Science at U.C. Berkeley. His research interests are software systems and applications. His group developed the Berkeley Lecture Webcasting System that produced 30 course lecture webcasts each week viewed by over 500,000 people per month. His publications received three "best paper" and two "test of time" awards. He is an investor/advisor in The Batchery a Berkeley-based seed-stage incubator. Rowe is an ACM Fellow, a co-recipient of the 2002 U.C. Technology Leadership Council Award for IT Innovation, the recipient of the 2007 U.C. Irvine Donald Bren School of ICS Distinguished Alumni Award, the 2009 recipient of the ACM SIGMM Technical Achievement Award, and a co-recipient of the Inaugural ACM SIGMOD Systems Award for the development of modern object-relational DBMS. Larry and his wife Jean produce and sell award-winning premium wines using Napa Valley grapes under the Greyscale Wines brand.

Kriti Sen Sharma

Kriti Sen Sharma is a Customer Solutions Architect at Paradigm4. He works on projects spanning multiple domains (genomics, imaging, wearables, finance, etc.). Using his skills in collaborative problem-solving, algorithm development, and programming, he builds end-to-end applications that address customers' big-data needs and enable them to gain business insights rapidly. Kriti is an avid blogger and also loves biking and hiking. Kriti received a Ph.D. in 2013 and an M.Sc. in 2009, both from Virginia Polytechnic Institute and State University, and an a B.Tech. from Indian Institute of Technology, Kharagpur, in 2005.

Nan Tang



Nan Tang is a senior scientist at Qatar Computing Research Institute, HBKU, Qatar Foundation, Qatar. He received his Ph.D. from the Chinese University of Hong Kong in 2007. He worked as a research staff member at CWI, the Netherlands, from 2008–2010. He was a research fellow at University of Edinburgh from 2010–2012. His current research interests include data curation, data visualization, and intelligent and immersive data analytics.

Jo Tango

Jo Tango founded Kepha Partners. He has invested in the e-commerce, search engine, Internet ad network, wireless, supply chain software, storage, database, security, on-line payments, and data center virtualization spaces. He has been a founding investor in many Stonebraker companies: Goby (acquired by NAVTEQ), Paradigm4, StreamBase Systems (acquired by TIBCO), Vertica Systems (acquired by Hewlett-Packard), and VoltDB. Jo previously was at Highland Capital Partners for nearly nine years, where he was a General Partner. He also spent five years with Bain & Company, where he was based in Singapore, Hong Kong, and Boston, and focused on technology and startup projects. Jo attended Yale University (B.A., *summa cum laude* and Phi Beta Kappa) and Harvard Business School (M.B.A., Baker Scholar). He writes a personal blog at jtangoVC.com.

Nesime Tatbul

Nesime Tatbul is a senior research scientist at the Intel Science and Technology Center at MIT CSAIL. Before joining Intel Labs, she was a faculty member at the Computer Science Department of ETH Zurich. She received her B.S. and M.S. in Computer Engineering from the Middle East Technical University (METU) and her M.S. and Ph.D. in Computer Science from Brown University. Her primary research area is database systems. She is the recipient of an IBM Faculty Award in 2008, a Best System Demonstration Award at SIGMOD 2005, and the Best Poster and the Grand Challenge awards at DEBS 2011. She has served on the organization and program committees for various conferences including SIGMOD (as an industrial program co-chair in 2014 and a group leader in 2011), VLDB, and ICDE (as a PC track chair for Streams, Sensor Networks, and Complex Event Processing in 2013).

Nga Tran

Nga Tran is currently the Director of Engineering in the server development team at Vertica, where she has worked for the last 14 years. Previously, she was a Ph.D. candidate at Brandeis University, where she participated in research that contributed to Mike Stonebraker's research.

Marianne Winslett

Marianne Winslett has been a professor in the Department of Computer Science at the University of Illinois since 1987, and served as the Director of Illinois's research center in Singapore, the Advanced Digital Sciences Center, from 2009–2013. Her research interests lie in information management and security, from the infrastructure level on up to the application level. She is an ACM Fellow and the recipient of a Presidential Young Investigator Award from the U.S. National Science Foundation. She is the former Vice-Chair of ACM SIGMOD and the former co-Editor-in-Chief of *ACM Transactions on the Web*, and has served on the editorial boards of *ACM Transactions on Database Systems*, *IEEE*

Transactions on Knowledge and Data Engineering, *ACM Transactions on Information and System Security*, *The Very Large Data Bases Journal*, and *ACM Transactions on the Web*. She has received two best paper awards for research on managing regulatory compliance data (VLDB, SSS), one best paper award for research on analyzing browser extensions to detect security vulnerabilities (USENIX Security), and one for keyword search (ICDE). Her Ph.D. is from Stanford University.

Eugene Wong

Eugene Wong is Professor Emeritus at the University of California, Berkeley. His distinguished career includes contributions to academia, business, and public service. As Department Chair of EECS, he led the department through its greatest period of growth and into one of the highest ranked departments in its field. In 2004, the Wireless Foundation was established in Cory Hall upon completion of the Eugene and Joan C. Wong Center for Communications Research. He authored or co-authored over 100 scholarly articles and published 4 books, mentored students, and supervised over 20 dissertations. In 1980, he co-founded (with Michael Stonebraker and Lawrence A. Rowe) the INGRES Corporation. He was the Associate Director of the Office of Science and Technology Policy, under George H. Bush; from 1994–1996, he was Vice President for Research and Development for Hong Kong University of Science and Technology. He received the ACM Software System Award in 1988 for his work on INGRES, and was awarded the 2005 IEEE Founders Medal, with the apt citation: "For leadership in national and international engineering research and technology policy, for pioneering contributions in relational databases."

Stan Zdonik

Stan Zdonik is a tenured professor of Computer Science at Brown University and a noted researcher in database management systems. Much of his work involves applying data management techniques to novel database architectures, to enable new applications. He is co-developer of the Aurora and Borealis stream processing engines, C-Store column store DBMS, and H-Store NewSQL DBMS, and has contributed to other systems including SciDB and the BigDAWG polystore system. He co-founded (with Michael Stonebraker) two startup companies: StreamBase Systems and Vertica Systems. Earlier, while at Bolt Beranek and Newman Inc., Dr. Zdonik worked on the Prophet System, a data management tool for pharmacologists. He has more than 150 peer-reviewed papers in the database field and was named an ACM Fellow in 2006. Dr. Zdonik has a B.S in Computer Science and one in Industrial Management, an M.S. in Computer Science, and the degree of Electrical Engineer, all from MIT, where he went on to receive his Ph.D. in database management under Prof. Michael Hammer.