Institution:
University of Cambridge

Unit of Assessment:
UoA11

Title of case study:
Xen

1. Summary of the impact (indicative maximum 100 words)

Research in machine virtualisation conducted in the Cambridge Computer Laboratory from 1999 onwards provides the basis for much of the present day Cloud.

Xen is a virtual machine monitor that supports execution of multiple guest operating systems consuming little overhead and providing resource isolation. This was prototyped in the Laboratory and led to XenSource, a spin-out company, which was founded in 2005. XenSource was acquired in 2007 by Citrix Systems for US$500M, and products that were launched from December 2007 onwards have had a profound impact throughout the period. Xen is now used on millions of machines around the world, providing deployment flexibility and savings on power. It forms the basis of Citrix XenServer and Amazon's Elastic Cloud 2.

2. Underpinning research (indicative maximum 500 words)

In 1999, researchers in the Computer Laboratory, University of Cambridge, postulated a world in which anyone could run any software, anywhere – providing they paid for the resources they used. Originally referred to as XenoServers (servicing "guest" applications), today this concept is known as the Cloud.

A virtual machine monitor (VMM) allows the division of a single powerful computer into a number of smaller, less powerful computers called virtual machines. Each virtual machine runs its own operating system and applications, and is strongly isolated from other virtual machines.

Previous systems had used a "trap-and-emulate" approach in which the VMM ran hosted operating systems in an unprivileged operating mode ("user mode"). Most of the time, the software ran exactly as it would on a real machine, but if the operating system (OS) attempted to perform a privileged operation, a hardware trap would occur, serviced by VMM-provided emulation. Such an approach tends to have a high overhead.

The Xen approach, developed at the Computer Laboratory, was an architecture that allowed guest operating systems to run in a more privileged mode, initially by exploiting multiple protection levels (i.e., more than two), and then by exploiting virtualisation hardware that was a direct result of interaction with processor manufacturers. The result, in 2003, was an efficient system with less than 2% performance degradation.

The key researchers were Dr Steven Hand and Dr Ian Pratt. Dr Hand joined the University in 1996 as a Research Assistant, becoming a Lecturer in October 1998, a Senior Lecturer in October 2005 and Reader in Computer Systems since October 2009. Dr Pratt joined the University in 1998 as a Lecturer, becoming a Senior Lecturer in October 2001. He left the University in December 2007 to join XenSource. Drs Hand and Pratt were joined by Dr Keir Fraser following completion of his PhD, when he joined the University as an EPSRC Academic Fellow in January 2005. Dr Fraser also left the University in December 2007 to join XenSource.

The concept of running software on a rented machine (with rental agreements lasting minutes) was postulated by Pratt in 1999 [1]. A subsequent proposal to EPSRC was successful, resulting in the award of a three-year grant for the research into the enhancement of Xen 1.0, which had been released as open source software in 2003 [3].

The primary technique designed by Hand, Pratt and Fraser used by Xen is "para-virtualization" [3] – in essence, the operating systems running in the virtual machines are slightly modified to deal with the fact that they are running on top of a VMM. Specifically, alterations are made to the way in which the "guest" operating systems manage page tables and segment registers, as well as how they interact with I/O devices. Doing this means that trap-and-emulate is not required, and considerable efficiency is gained.

3. References to the research (indicative maximum of six references)

* Denotes references that best indicate the quality of the research

[1]. D Reed, I Pratt, P Menage, S Early, N Stratford. Xenoservers: accountable execution of untrusted code. In IEEE Hot Topics in Operating Systems (HotOS) VII, March 1999
DOI: 10.1109/HOTOS.1999.798390

[2]. S Hand, T Harris, E Kotsovinos, and I Pratt. Controlling the XenoServer Open Platform. In Proceedings of the 6th International Conference on Open Architectures and Network Programming (OPENARCH'03), April 2003.
DOI: 10.1109/OPNARC.2003.1196368

*[3]. P Barham, B Dragovic, K Fraser, S Hand, T Harris, A Ho, R Neugebauer, I Pratt, and A Warfield. Xen and the Art of Virtualization. In Proceedings of the 19th ACM Symposium on Operating Systems Principles, pages 164–177, October 2003.
DOI: 10.1145/945445.945462

*[4]. C Clark, K Fraser, S Hand, J G Hansen, E Jul, C Limpach, I Pratt, and A Warfield. Live Migration of Virtual Machines. In Proceedings of the 2nd Annual ACM/USENIX Symposium on Networked System Design and Implementation (NSDI'05), May 2005
URL: http://dl.acm.org/citation.cfm?id=1251223

*[5]. A Ho, M Fetterman, C Clark, A Warfield, and S Hand. Practical Taint-Based Protection using Demand Emulation. In Proceedings of EuroSys 2006, April 2006.
DOI: 10.1145/1217935.1217939

[6]. G. Milos, D Murray, S Hand, and M Fetterman. Satori: Enlightened Page Sharing. In Proceedings of the USENIX Annual Technical Conference, June 2009. [Awarded best paper]. (Submitted to REF 2 by Dr Hand.)
URL: http://dl.acm.org/citation.cfm?id=1855808

"XenoServers for Ubiquitous Execution", EPSRC project GR/S01894/01, January 2003 – February 2006, PI Dr I. Pratt. £283,680.00

"Supporting Flexible End-to-End Services", EPSRC project GR/S68934/01, January 2004 – December 2006, PI Dr S. Hand. £174,164.00

4. Details of the impact (indicative maximum 750 words)

Xen, both as open source software and as a paradigm, has had a significant, transformative effect both on the national and international economy and, owing to the energy saving afforded by virtualisation, on the environment.

In addition to Xen's broad impact, the Cambridge team founded a successful company to exploit the research. In 2005, Pratt, Hand and Fraser co-founded XenSource as a vehicle to provide a robust open source version of Xen. Pratt and Fraser joined XenSource in 2007 on a permanent basis; Hand took sabbatical leave to work at XenSource in 2006/7.

XenSource was acquired by Citrix Systems in 2007 for US$500M. Since then, Xen has become a key technology in Citrix's product portfolio. Xen is the hypervisor at the core of Citrix's *XenServer* virtualisation product and also underpins the Citrix XenDesktop, XenApp, Netscaler SDX and Cloud Platform solutions. Xen is also used in the Citrix internal cloud on which many of the Citrix Online SaaS products are hosted. As of early 2013 there are over 100,000 unique customers using XenServer. XenServer runs workloads in over half of the businesses in the Fortune 50. Combining the sales of all Citrix Xen-based products and solutions, Citrix estimate that Xen is an active component in over $1billion of Citrix business annually.[7,8] Citrix employs around 100 engineers in the XenServer team, many of whom are active contributors to the OpenSource Xen code base. If all Citrix staff in Xen-related roles are taken into account, they total approximately 150 FTE.[7]

Xen has also had an impact on the environment through CO_2 reductions. For example, in March 2009, Tesco announced it had implemented Citrix XenServer to increase the capacity of its Real Time Sales system by 75%, enabling the handling of 1,500 sales-related messages per second.

Tesco's IT Director also commented that the virtualised Real Time Sales environment used 'less than half of the energy of the physical bare metal equivalents', supporting the company in achieving its CO_2 targets.[9]

In 2010, Citrix commissioned a report from Forrester Consulting (FC) into the 'total economic impact' of Citrix XenServer Enterprise Edition. FC reported that organisations purchasing XenServer could expect reduced energy requirements, lower labour costs for managing the server environment and avoidance of maintenance costs. FC found that the particular company they interviewed in depth gained a return on investment of 136%, and that increased return on investment was a probable outcome for other organizations needing to virtualize a greater number of physical servers.[10]

Xen is available as open source, so that Xen has made contributions beyond Citrix. It remains the dominant virtualisation platform in the public cloud.[8] Xen is the hypervisor in the world's largest OpenStack cloud, operated by RackSpace, as well as in Amazon EC2.[12,13] In March 2012 it was reported that Accenture Technology Labs had used a probe methodology to estimate that Amazon EC2 was running on up to 454,000 servers(14) across 7,100 racks, an impossibility in pre-Xen times. Significant services offered over the EC2 infrastructure include NASDAQs FinCloud, Netflix, and Zynga.

Citrix estimate that there are 10 million distinct users of OpenSource Xen [7], including many large enterprises. Xen's recent move to the Linux Foundation demonstrates continued strength and vibrancy, with industry partners including Amazon, Google, Intel, AMD, Verizon, CA Technologies and Samsung joining Citrix on the advisory board of the Linux Foundation Collaborative Project. This Poject is based around OpenSource, using the same scheme that started with the original Xen 1.0 GPLv2 release from the Computer Lab.

Oracle is one company that have made use of the open source availability: "*Oracle VM Server for x86 is based on the Xen kernel and underlying hypervisor technology, and it capitalizes on the Xen paradigm for management of Oracle VM guests"*.[16]

Xen's impact on processor design, which originates from 2006 [15], remains in force today: the Intel hardware-based virtual machine (HVM) processor feature is a direct consequence of Intel supporting the Xen architecture. HVM is in turn now used by all virtualisation systems that run on Intel processors, which means that the original Cambridge research on Xen has had impact even on Xen's competitors.

5. Sources to corroborate the impact (indicative maximum of 10 references)

[7]. Statement from Vice President, Product Development, Cloud Platforms Group, Citrix Systems for information on: Citrix products and statistics; Xen applications from RackSpace, Amazon, Linux Foundation: Product Development, Cloud Platforms Group, Citrix Systems UK Ltd. [Statement on File]

[8]. 100,000 customers, four out of top five public clouds, Fortune 50: Cambridge IP Presentation [Document on File]

[9]. Tesco use of XenServer: http://www.citrix.com/wsdm/restServe/skb/attachments/RDY2453/Citirx_XenServer_Product_Overview.pdf

[10]. Savings on energy, server management and maintenance: *Forrester Consulting Report: The Total Economic Impact of Citrix XenServer Enterprise Edition* [Document on File]

[11]. Rackspace: http://www.rackspace.com/cloud/cloud_hosting_faq/

[12]. Amazon EC2: Statement from Director of EC2 Fleet, Amazon [Statement on File]

[13]. Amazon presentation about EC2 and Xen: http://www.slideshare.net/xen_com_mgr/3-pradeep-vartofusingxenatscale

[14]. Report on Accenture estimate of the size of EC2: http://servicesangle.com/blog/2012/03/14/just-how-big-is-the-amazon-ec2-cloud/

[15]. Intel HVM and Xen
http://noggin.intel.com/content/extending-xen-with-intel%C2%AE-virtualization-technology

[16]. Oracle VM based on Xen:
http://www.oracle.com/technetwork/articles/servers-storage-admin/networking-ovm-x86-1873548.html