History of the mainframe

From S/360 to Linux

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IBM

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Overview

- Historic background and birth of the mainframe
- S/360 hardware features
- S/360 software
- S/370 hardware and software – virtual memory and virtualization
- S/390 – CMOS mainframes
- z/Architecture – modern 64-bit
- Linux on the mainframe

State of the art in the 50s

- Many different incompatible systems, even from the same vendor
- Each system had only few small variations
  - Amount of memory, speed, number of I/O peripherals
- Each system had its own incompatible operating system
  - Closely modelled after the hardware
  - Drivers often rewritten from scratch
- Moving software between different systems required rewriting it
  - Different OS interfaces, programming languages, machine code
- Vendors had to support several different platforms

Bet the company

- Strong competition, need for innovation
    - IBM risked to become “a company that sells computers” like many others
- A task group was created to address the issue
    - It recommended developing five compatible systems spanning a 200-fold performance range
- IBM followed the advice and replaced the whole product line with **compatible machines**
- Estimated total cost 675 millions, of which 30 millions for software

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- Estimated total cost 675 millions, of which 30 millions for software
- Ended up costing 5 billions! (500 millions of which for software)
- Toward the end of the project, IBM was in financial difficulties

Innovations

- 8-bit bytes
- Instruction Set Architecture (ISA)
- Microcode for commercial computers
- Solid Logic Technology (SLT)
- Hardware abstraction in the OS

S/360 architecture

- Big endian
- 24-bit addresses
- Consistent instruction formats
  - 2, 4, or 6 bytes long; first 2 bits of instruction indicate length
- Registers:

16	32-bit	General purpose	
1	64-bit	Program Status Word	
4	64-bit	Floating point	(optional)

- Channel I/O
- Interrupts (with classes and subclasses)
- Protection (storage keys, optional)
- Floating point (not IEEE, optional)
- Decimal (BCD) arithmetic (optional)
- Dynamic Address Translation (virtual memory, S/360-67)
- Multiprocessing (S/360-65)

Protection (Storage keys)

Storage keys are 4-bit values, optionally with a 5th bit for fetch protection.

Two instructions allow to set and get the storage keys for each *2kB* block of real (physical) memory.

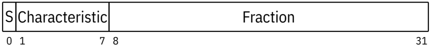
The PSW also has a key. At each memory access the key of the accessed memory block is compared with the key in the PSW.

	Storage key x		Storage key y no fetch protection		Storage key y fetch protection*	
	read	write	read	write	read	write
PSW key 0	√	√	√	√	√	√
PSW key x	√	√	√	X	X	X

* only with Fetch-protection feature

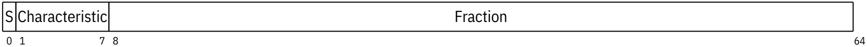
Hexadecimal floating point

Short Floating-point


S | Characteristic | Fraction

0 1 7 8 31

Long Floating-point


S | Characteristic | Fraction

0 1 7 8 64

- Not IEEE compatible
  - The IEEE 754 standard was released only in 1985, 20 years after S/360!
- Long and short only differ in size of fraction
- Characteristic: Biased exponent (0..127 = -64..+63)
- Base 16: $value = 16^{exponent} \cdot 0.fraction$
- No NaNs, no infinities
- Some special conditions can raise (maskable) program interrupts

S/360

Model	Shipped	kIPS	Memory (kiB)	Weight (kg)
30	1965	10	8–64	771
		⋮		
195	1971	10000	1024–4096	6101–12859

Performance calculated (not measured) based on a mix of instructions typical of scientific (*Gibson Mix*).

S/360-67

- New PSW Format
- Control registers
- Virtual memory (24 and 32 bit)
  - 4kB pages
  - TLB

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  - TLB (8 entries!)

S/360 Operating systems

1965	BOS/360	Basic Operating System
1965	TOS/360	Tape Operating System
1966	DOS/360	Disk Operating System
1966	OS/360	Operating System (PCP and MFT)
1966	RAX	Remote Access Computing
1967	CMS	Cambridge Monitor System
1967	CP-40, CP-67	Control Program
1967	TSS/360	Time Sharing System
1967	OS/360	Operating System (MVT)
1967	ORVYL	
1968	CALL/360	
1968	ACP	Airline Control Program
1968	VP/CSS	

BPS/BOS/TOS/DOS

- The development of OS/360 was lagging behind due to complexity
- Interim smaller OSs developed to fill the gaps
- OS/360 would not run on smaller systems, contrary to stated goals
- The smaller OSs were needed for smaller machines
- Customers invested in DOS and did not want to switch to OS/360

OS	Memory	Tape	Disk	Year	Notes
BPS	8kB	(opt)	–	1964	not an actual OS
BOS/360	8kB	–	yes	1965	
TOS/360	16kB	yes	–	1965	
DOS/360	16kB	–	yes	1966	

BPS	IBM Basic Programming Support/360
BOS	Basic Operating System/360
TOS	Tape Operating System/360
DOS	Disk Operating System/360

OS/360

- The flagship OS for S/360 mainframes
- Three variants, sharing API, ABI, and Job Control Language
  - PCP – single task (48kB)
  - MFT – fixed number of tasks (256kB)
  - MVT – variable number of tasks (512kB)
- Memory partitions for user programs
- File name structure, allowing for hierarchies
- Various forms of remote access
- Sub-tasks (not PCP) – threads within one job
- Toleration for S/370

CP/CMS

Cambridge Monitor System

- Single user
- Can run on a bare-metal S/360

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Control Program (CP-40)

- Virtual machine (Trap and emulate)
- Ran only on one specially modified S/360-40
- Research prototype for the upcoming S/360-67
- Multiuser support for CMS!

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- Support more VMs
- Used in production
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VM/370

- Re-implementation of CP for S/370

ACP – Airline Control Program

- PARS – Programmed Airline Reservations System (1968)
  - Consolidate existing airline reservation systems
  - SABRE, Deltamatic, PANAMAC
- ACP split from PARS (1969)
- Real-time
- Transaction-oriented
- Not a general purpose OS
- Later also used by banks
- TPF — Transaction Processing Facility
  - z/TPF — 64-bit extension

S/370 architecture

Base S/370 architecture (1970)

- **Translation (virtual memory)**
  - Different and incompatible with S/360-67!
  - 2kB and 4kB page sizes
- Extended-precision floating point
- Dual address space
- Support for multiprocessing

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S/370-XA (Extended Architecture, 1983)

- Switchable per-process 31-bit mode (new PSW bit)
- Only 4kB supported for storage keys and virtual memory pages
- Channel I/O completely rehauled
- Vector instructions (3090 only)

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ESA/370 architecture (Enterprise Systems Architecture, 1988)

- Access register mode
- Home address space
- LPAR – Logical partitions

Virtualization

IBM starts to recognize the importance of virtualization.

Virtual-Machine Assist (1980)

- For S/370 without XA
- A collection of 6 assists for VM/370

START INTERPRETIVE EXECUTION (1984)

- For S/370-XA
- Nested paging supported since the beginning
- Almost all instructions execute without exit
- A control block in memory describes a guest CPU
- Still there today!

Clones

Most S/360 clones were not drop-in replacements

- Mostly copying the instruction set, or subsets
- Not aiming to perfect compatibility
  - Except for the Soviet ES EVM

S/370 clones were meant as drop-in replacements

- Amdahl Corporation
  - Gene Amdahl, former IBMer
  - Started selling drop-in replacements for IBM mainframes
- Many companies followed suit
  - Fujitsu, Hitachi, ES EVM, Magnuson Computer Systems, Mitsubishi, Siemens, Univac
- Some competitors at times sold better hardware than IBM!

Operating systems overview

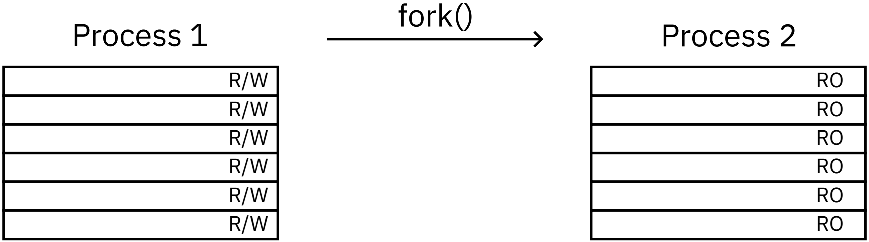
1965	DOS/360			
1966		OS/360 PCP, MFT		
1967		OS/360 MVT	CP/CMS	ACP
1968		OS/360 MFT II	VP/CSS	
1972	DOS/VS	OS/VS1	VM/370	
1972		OS/VS2R1 (SVS)		
1974		OS/VS2R2 (MVS)		
1978		MVS/SE		
1979	DOS/VSE			TPF
1980		MVS/SP	VM/SP	
1983		MVS/XA		
1984			VM/XA	
1986	VSE/SP			
1988		MVS/ESA		
1990	VSE/ESA		VM/ESA	
1995		OS/390		
2000		z/OS	z/VM	
2005	z/VSE			z/TPF
2021	VSE^n			

1980	Unix	[tss]
1980	UTS$^{(amdahl)}$	[vm]
1984	IX/370	[tss,vm]
1985	VM/IX	[vm]
1988	AIX/370	[vm]
1991	AIX/ESA	
1993	MVS/ESA OpenEdition	[os]
1999	Linux	
2001	z/OS UNIX System Services	[os]
2008	OpenSolaris	[vm]

S/390 architecture

- Additional floating point registers (16 in total)
- Binary floating point (IEEE 754)
- Instructions to load and work with immediate values and relative addresses
- Suppression on protection

AIX/ESA - Suppression on Protection



Process 1

R/W
R/W
R/W
R/W
R/W
R/W

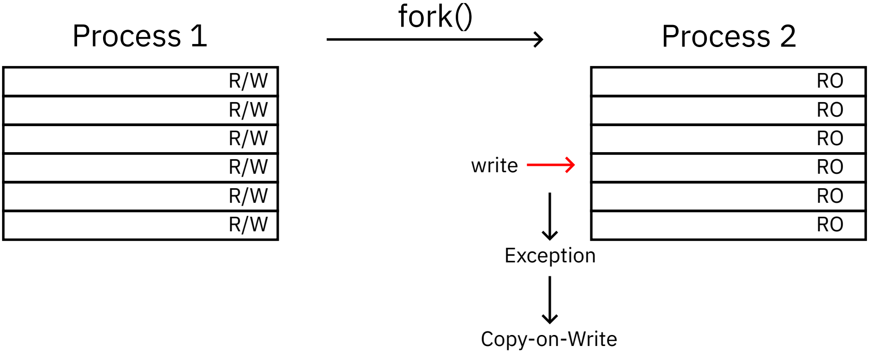
fork()

Process 2

RO
RO
RO
RO
RO
RO

- `fork()` creates identical copy of process
- memory is not copied → all pages read-only

AIX/ESA - Suppression on Protection



- write to read-only page of process 2 causes exception → page copied
- Instruction causing exception must not have had any side-effects
- s390: write crossing page boundary may execute partly!
- Feb 1993: *Suppression-on-protection* for AIX/ESA to solve issue

Bipolar vs CMOS

ES/9000 – 1990

- first series of S/390
- bipolar logic
- fast but very hot (biggest models water cooled)

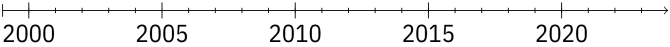
9672 – 1994

- CMOS
- Many optional features removed (e.g. vector instructions)
- Slower but cooler
    - g1 and g2 – mostly prototypes, used in very low end products
    - g3 and g4 – catching up
    - g5 and g6 – faster than bipolar

z/Architecture

Move to 64 bits in 2000.

- Registers extended to 64-bit, new instructions
- Backwards compatibility with 31-bit.
- Expanded storage not needed anymore to use more than 2 GiB.
- Page tables with variable number of levels, full 64-bit virtual address space
- Clone manufacturers did not keep up with the switch to 64 bits.



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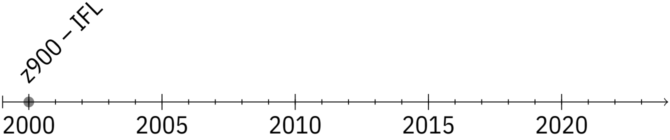

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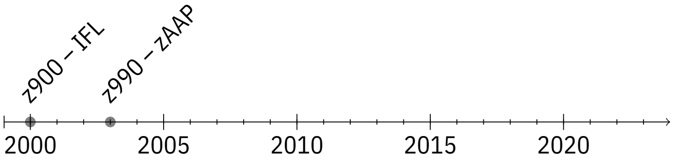

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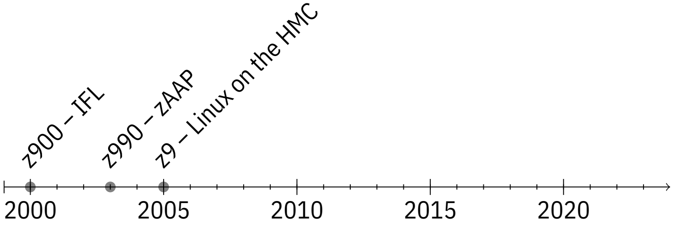

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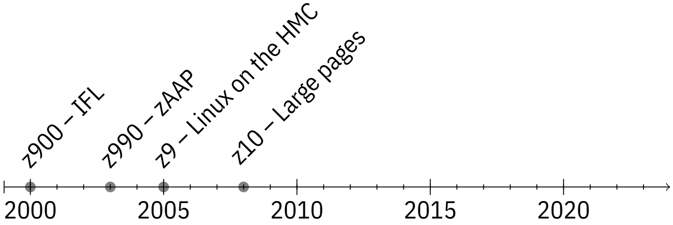

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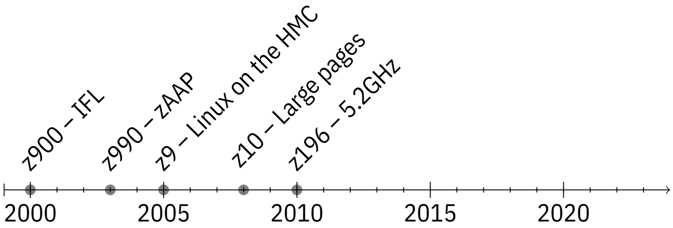

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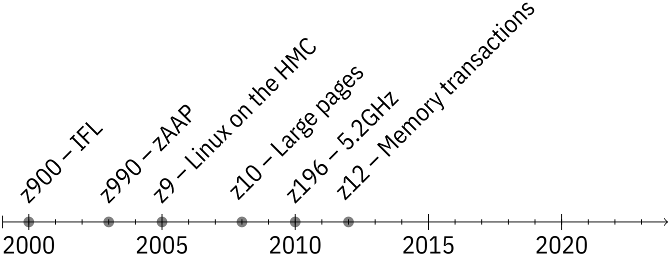

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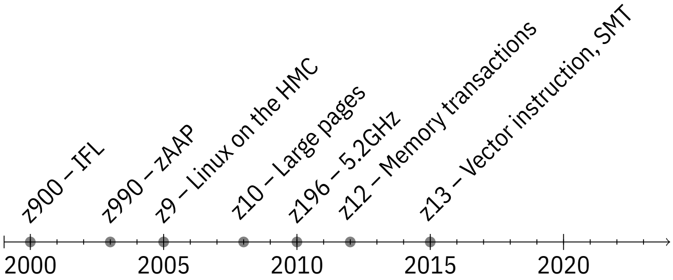

z900 – IFL

z990 – zAAP

z9 – Linux on the HMC

z10 – Large pages

z196 – 5.2GHz

z12 – Memory transactions

z13 – Vector instruction, SMT

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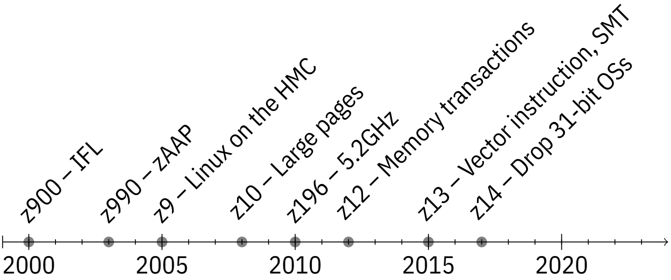

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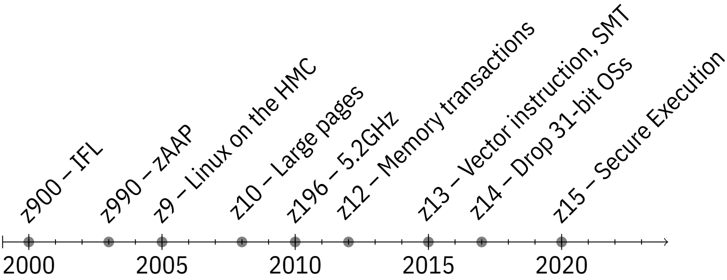

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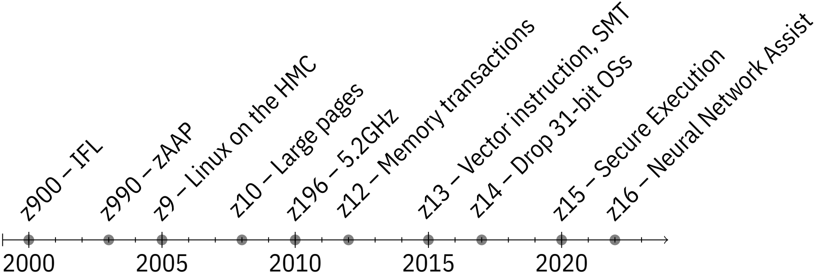

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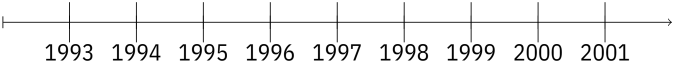
z15 – Secure Execution

z16 – Neural Network Assist

Linux for the mainframe - The compiler



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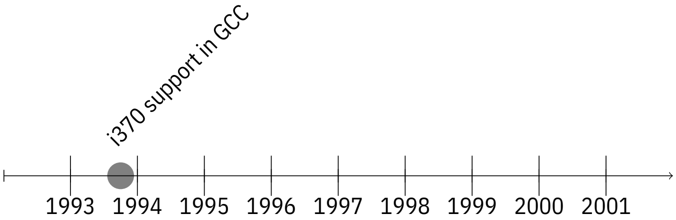
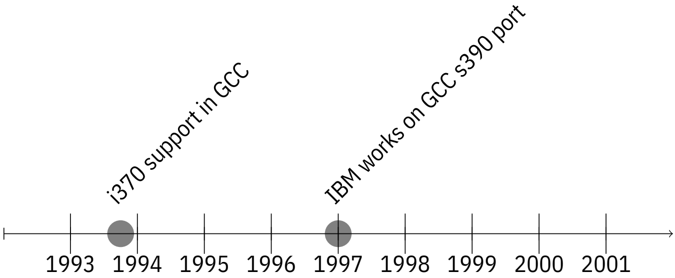


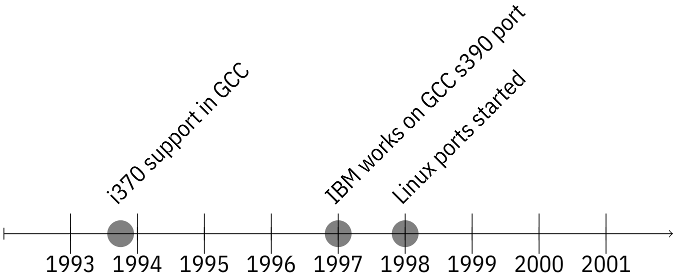
- October 1993: Code for the i370 backend appears in GCC repository
  - Developed outside IBM
  - Main objective: compile applications for MVS

Linux for the mainframe - The compiler



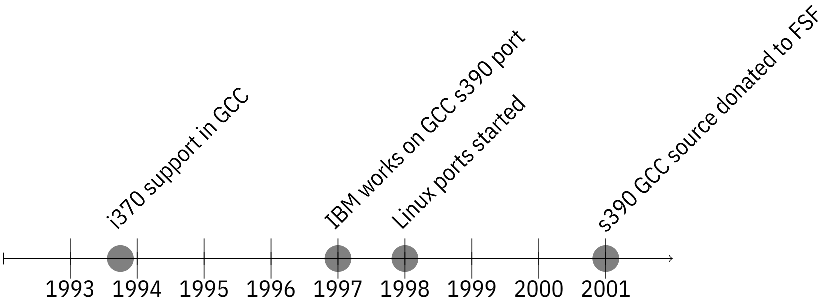
- 1997: IBM S/390 Firmware looking for a C compiler
    - Existing i370 backend for GCC is evaluated
    - S/390 port with less backward compatibility starts

Linux for the mainframe - The compiler



- 1998: Linux ports to the mainframe start
- Accelerates further development of compiler (i.e. ELF support)

Linux for the mainframe - The compiler



- 2001: GCC source code donated to Free Software Foundation

Linux for s390 - The IBM port `s390`

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- 1998: IBM engineers prototype a Linux port to S/390 in their free time
- 18 December 1999: IBM releases source of Linux for S/390 on their FTP server

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- January 2000: Code appears in Linux 2.2.14
- January 2000: First Linux Distro appears (Marist Linux by Marist College)

Linux for `s390` - `s390` and `i370`

- i370 also compatible with older machines
- i370 uses classical HLASM Assembly style, s390 does not
- Different toolchain
- i370 was less stable
- i370 developed by volunteers, s390 by IBM employees
- Linux i370 was abandoned when s390 port was published

Linux for s390 - Why it was interesting

Consolidation In 2000s datacenters consist of many physical boxes, with z/VM and Linux they can run on a single mainframe

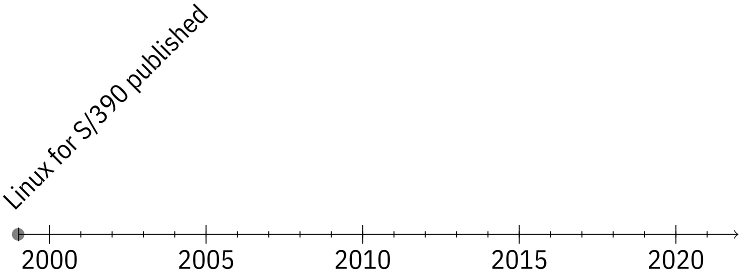
Java Java worked well on Linux

Unix Applications wanted a Unix-like OS

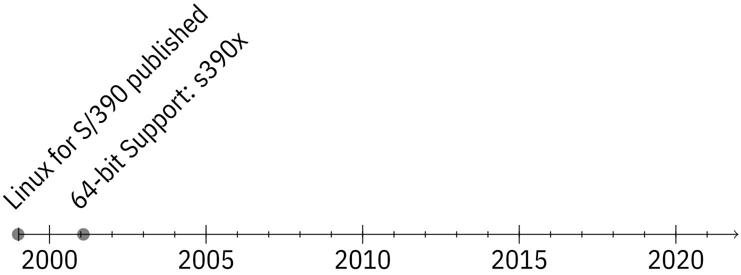
Save costs Comparatively cheap OS, later: cheaper CPUs for Linux (IFLs)

It was cool Many people just liked Linux

Linux for s390 - Evolution

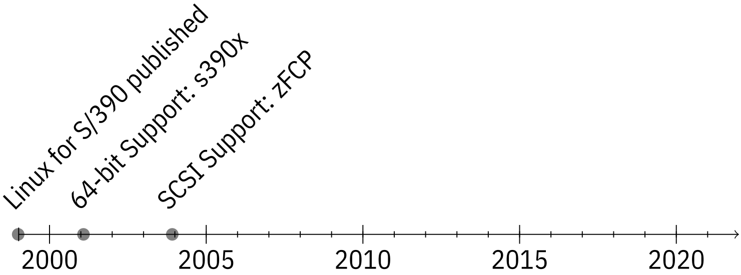


Linux for s390 - Evolution



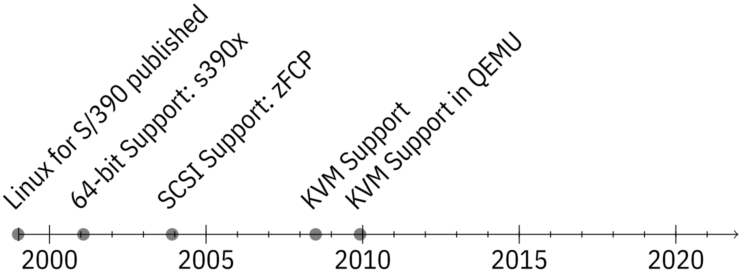
- 64-bit z/Architecture (s390x) supported since Linux 2.4.2 (Feb 2001)
  - 64-bit Kernels can run a 31-bit userspace fine (and still do so today)

Linux for s390 - Evolution



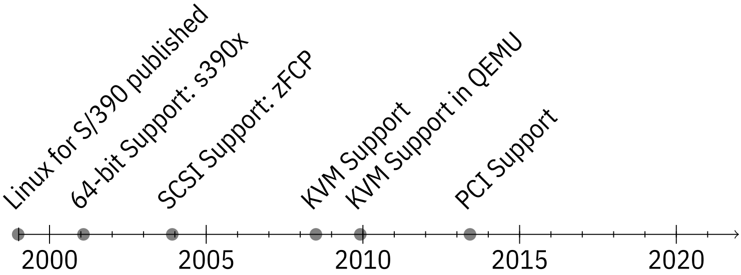
- SCSI Support (zFCP) since Linux 2.6.0 (Dec 2003)
  - Before that only DASD disks could be used, need special storage systems
  - Motivation: cheaper, more common storage

Linux for s390 - Evolution



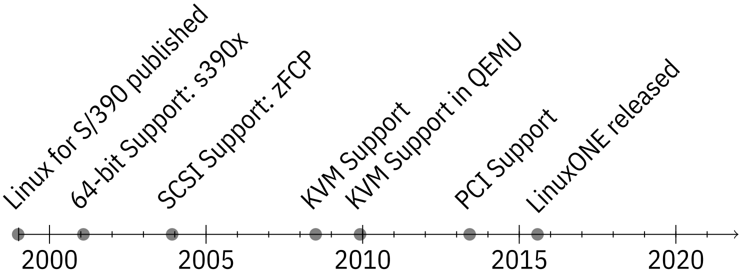
- KVM Support since Linux 2.6.26 (Jul 2008)
  - Initially with custom userspace `kuli`
  - Since December 2009, QEMU includes support for KVM
  - KVM Forum 2008: IBM shows 200 Linux VMs on a single Linux host

Linux for s390 - Evolution



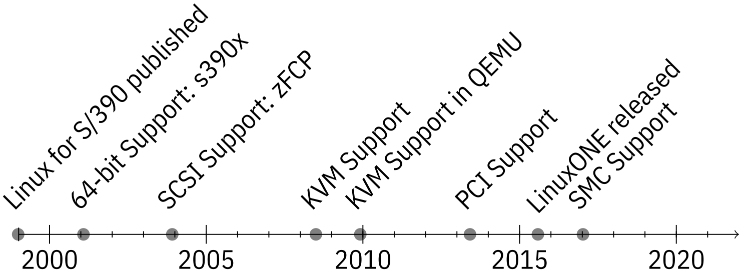
- PCI Support since Linux 3.10 (Jun 2013)
  - Standard interface to hardware (today: NVMe, network, HSMs, ...)
  - Can’t interface everything, you need custom hardware most of the time

Linux for s390 - Evolution



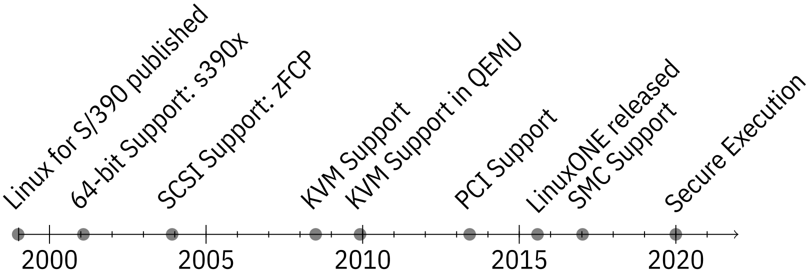
- LinuxONE: Linux-only system (Aug 2015)
  - Cheaper system which only runs Linux

Linux for s390 - Evolution



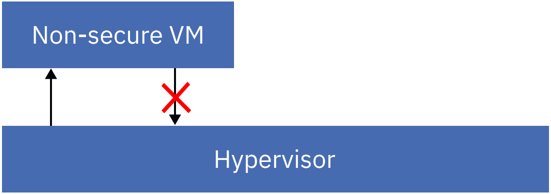
- SMC: Shared Memory Communications (Jan 2017)
  - Applications can establish a socket-like connection
  - Uses shared memory in the background
  - Works locally (i.e. between partitions) and remotely (between zSystems)

Linux for s390 - Evolution

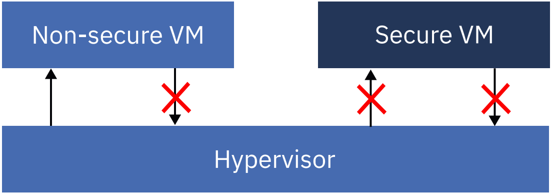


- Secure Execution: Confidential VMs (2020)

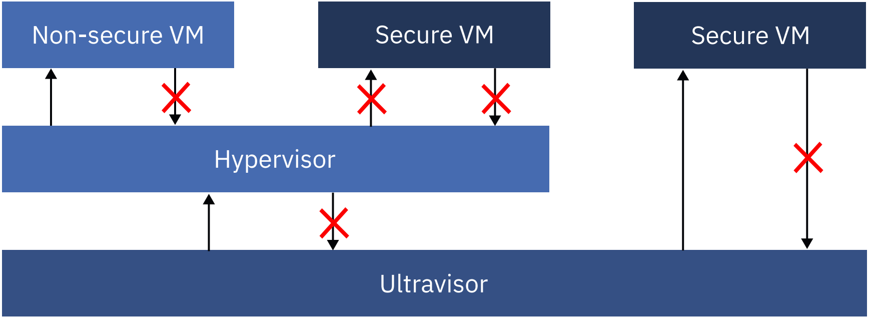
Linux for s390 - Secure Execution



Linux for s390 - Secure Execution



Linux for s390 - Secure Execution



References

Year	Reference	Title
1965	C24-3420-0	IBM System/360 Basic Programming Support and IBM Basic Operating System/360 Programming Systems Summary
1968	A22-6821-7	IBM System/360 Principles of Operation
1979	GA22-7070-0	IBM 4300 Processors Principles of Operation for ECPS:VSE Mode
1980	GA22-7074-0	Virtual-Machine Assist and Shadow-Table-Bypass Assist
1981	GA22-7000-7	IBM System/370 Principles of Operation
1984	SA22-7095-0	IBM System/370 Extended Architecture Interpretive Execution
1987	SA22-7085-1	IBM System/370 Extended Architecture Principles of Operation
1988	SA22-7200-0	IBM Enterprise Systems Architecture/370
2003	SA22-7201-08	Enterprise Systems Architecture/390 Principles of Operation
2022	SA22-7832-13	z/Architecture Principles of Operation

I want to play with this!

Hardware:

- Buy a mainframe (uhhhh.... yeah, right)
- Want to try your software on Big Endian? IBM LinuxONE Community Cloud: `https://linuxone.cloud.marist.edu/`
- zPDT
- Qemu for newer hardware
- Other emulators for older hardware

Software:

- OS/360
- DOS/360 and TOS/360
- CP-67/CMS and VM/370
- TSS/370

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