Introduction to SOC Verification

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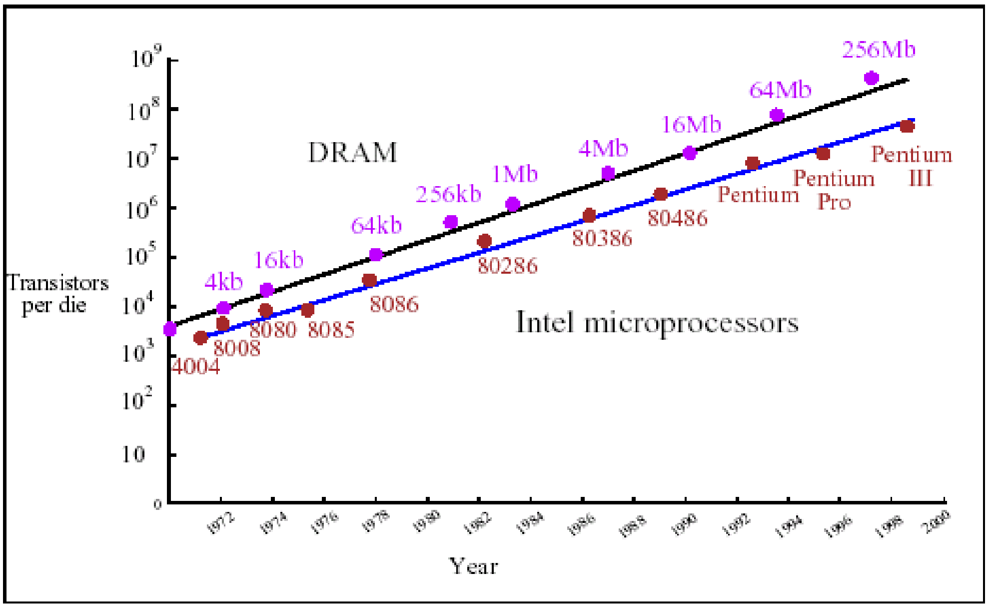
DAT 聯盟

Outline

- Moving to SOC
- What is Verification?
- Functional Verification Solutions
- System Verification Solutions

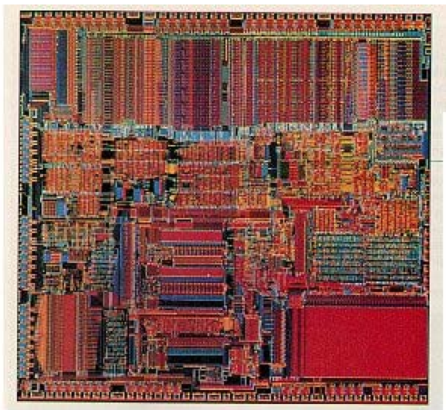
Moore's Law

- Logic capacity doubles per IC per year at regular intervals (1965)
- Logic capacity doubles per IC every 18 months (1975)



The Dies of Intel CPUs

Pentium Pro



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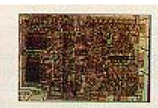

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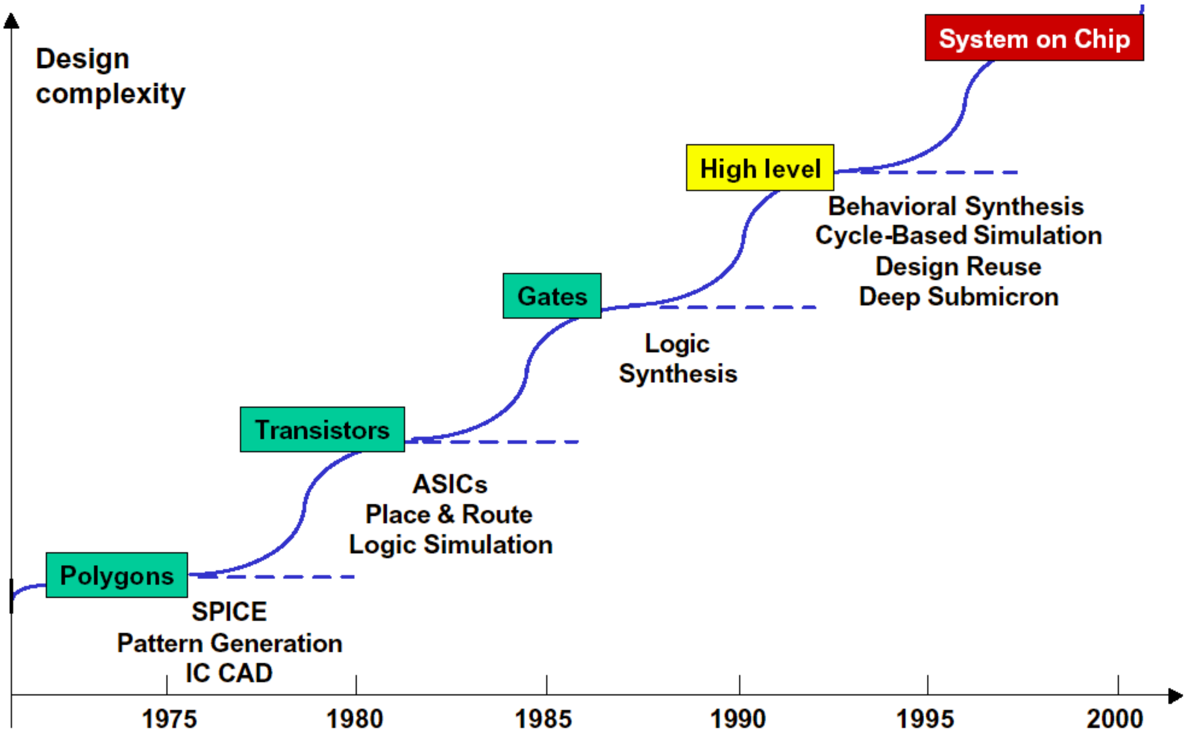
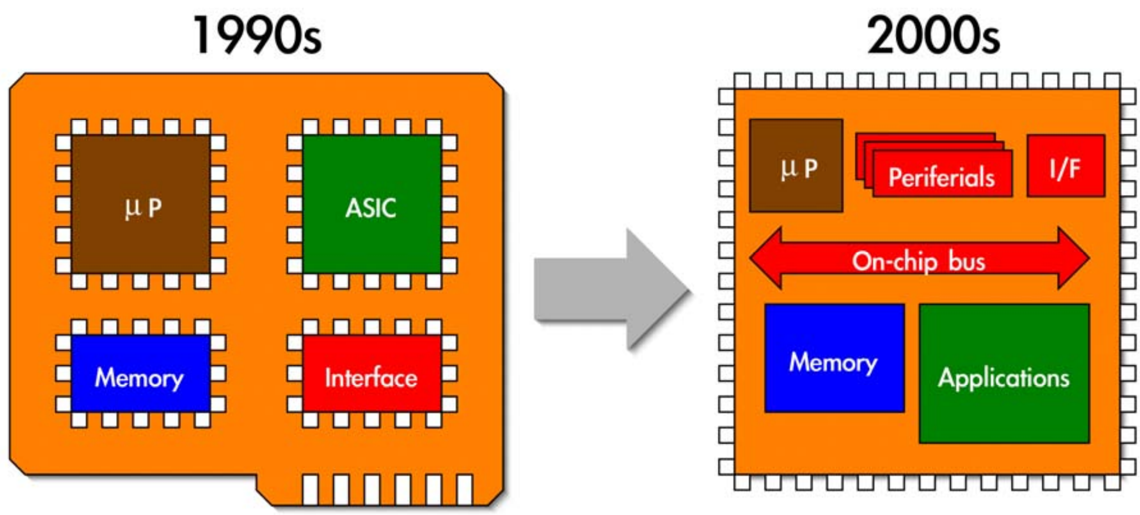
Trends of VLSI Design



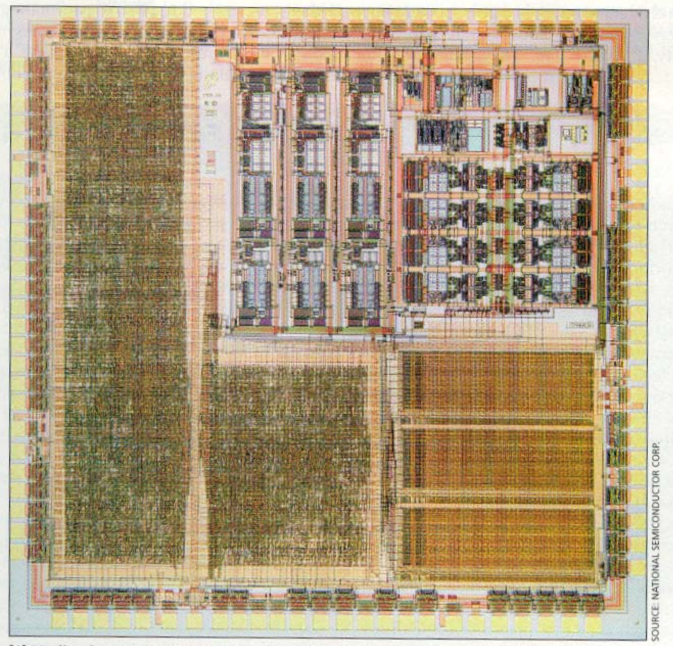
Reference : www.doulos.com

What is SoC?

- System-on-Chip
- An IC that integrates the major functional elements of a complete end-product into a single chip



Scanner on a Chip



[1] Merlin, the scanner-on-a-chip just introduced by National Semiconductor Corp., Santa Clara, Calif., includes an analog front end, sensor clock generation, motor control, data buffering, and parallel port interface, all in a dime-sized area. Chips like this one, which load up with components in much the same way as boards load up with chips, are being dragged into existence by the demands of consumer electronics.

National Semiconductor
IEEE Spectrum
Jan. 1999, p.57

An SoC …

- Usually contains
  - Reusable IP
  - Embedded processor, memory
  - Real-world interface
  - Mixed-signal blocks
  - Programmable hardware
  - RTOS and embedded software
- Has more than 500 K gates,
- Use .25 μm technology or below
- Is not an ASIC …

Why SoC ? (from System View)

- Lower power than discrete implementations
- Increased functionality/performance in reduced footprint
- Simplified PCB design
- Lower system cost
- Increased product mechanical robustness
- And more and more advantages ……

SoC Challenges

- Increasing complexity
  - Time-to-market pressure
  - Verification bottleneck
- Integration 硬體、軟體、製程的整合問題
  - Hardware v.s. software
  - Digital circuits v.s. analog circuits
  - Testing issues
- Deep submicron effects 製程微縮後帶來的物理效應
  - Timing closure problem
  - Signal integrity problem
  - Reliability problem

SoC（System on Chip）是一種集成電路，它將多個計算機系統的組件集成到單一芯片上。這些組件通常包括處理器核心、記憶體、輸入/輸出（I/O）控制器和其他周邊設備。以下是 SoC 的一些主要特點和應用：

主要特點
集成度高：
SoC 將處理器、記憶體、I/O 接口、以及其他功能模塊集成到一個芯片上，這樣可以減少系統的物理空間需求和功耗。

節能：
由於所有組件都在一個芯片上，它們之間的通信延遲較小，功耗也比多芯片系統低。

尺寸小：
SoC 的集成度高，使得整個系統的尺寸大幅度減少，這對於移動設備（如智能手機、平板電腦）非常重要。

成本效益：
高度集成的設計可以降低生產成本，因為它減少了需要的芯片數量和板上空間。

性能：
SoC 通常設計為支持高效的數據處理和快速的數據傳輸，因此它們在性能上往往能夠滿足現代應用的需求。

常見組件
處理器核心：通常包含 CPU 和/或 GPU，用於計算和圖形處理。
記憶體：包括 RAM 和快取記憶體，用於存儲數據和指令。
I/O 控制器：管理和控制外部設備的接口，如 USB、SPI、I2C 等。
網絡模組：如 Wi-Fi、藍牙、以太網等，用於網絡連接。
音頻和視頻處理單元：處理音頻和視頻數據的專用硬體。
儲存模組：如 Flash 記憶體，用於長期儲存數據。
應用範圍
智能手機和平板電腦：SoC 提供了高效的處理能力和低功耗特性，非常適合這些便攜設備。
嵌入式系統：用於各種嵌入式應用，如家用電器、汽車電子系統、工業控制等。
物聯網設備：許多 IoT 設備使用 SoC 來實現連接和處理功能。
智能穿戴設備：如智能手錶、健身追蹤器等，這些設備需要高效能和低功耗的集成電路。
SoC 的設計和使用可以顯著提高系統的整體性能和效能，並且是許多現代電子設備的核心組件。

Time-to-Market Pressure

- A lot of pressure from
  - Shorter product lifespan
  - Shrinking design cycles

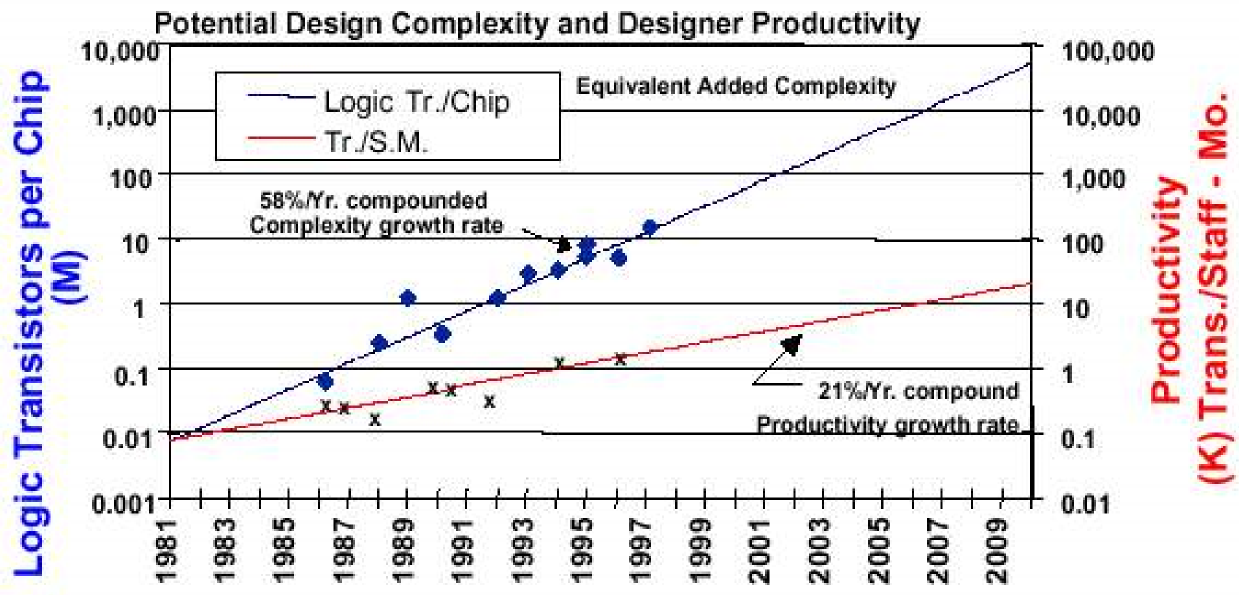
	1997	1998	1999	2002
Applications	Cellar, PDA, DVD	Set-top boxes, wireless PDA	Internet applications, anything portable	Ubiquitous computing, intelligent, interconnected controllers
Design cycle (month)	18 - 12	12 - 10	10 - 8	8 - 6
Derivative cycle (month)	8 - 6	6 - 4	4 - 2	3 - 2

* Adapted from "Surviving the SOC Revolution."

Productivity Gap

人類設計的速度跟不上製程成長的速度

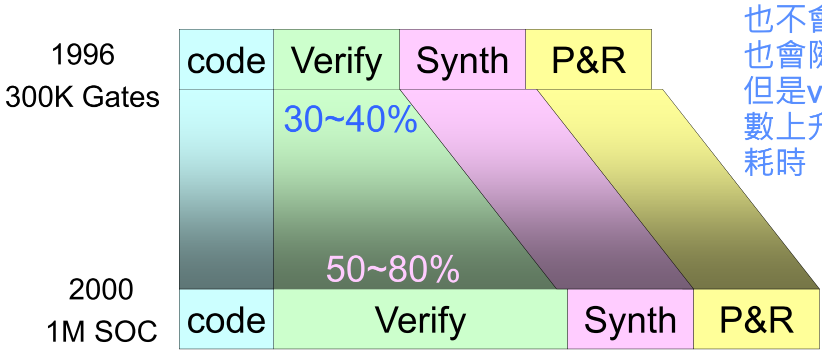
- We do need more efficient design methodology



Source : ITRS Roadmap 1999 Edition, SIA.

Verification Bottleneck

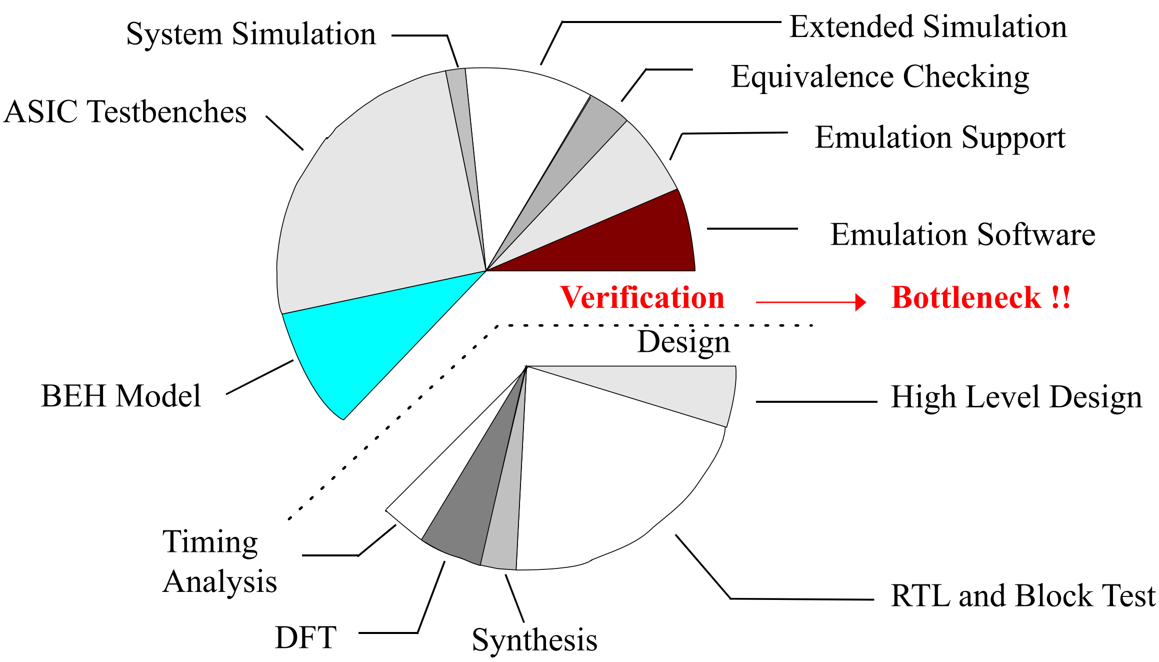
- Verification becomes the major bottleneck of the modern design flows
  - From 30%-40% to 50%-80%



coding時間並不會有太大差距
跑EDA tool進行Synthesis與合成
也不會有太大差距，因為工作站
也會隨著製程變快
但是verification所花時間是成指
數上升，複雜的系統的驗證非常
耗時

- An effective verification methodology is also highly desirable

An Industrial Example



Source : "Functional Verification on Large ASICs"
by Adrian Evans, etc., 35th DAC, June 1998.

SoC Challenges

- Increasing complexity
  - Time-to-market pressure
  - Verification bottleneck
- Integration
  - Hardware v.s. software
  - Digital circuits v.s. analog circuits
  - Testing issues
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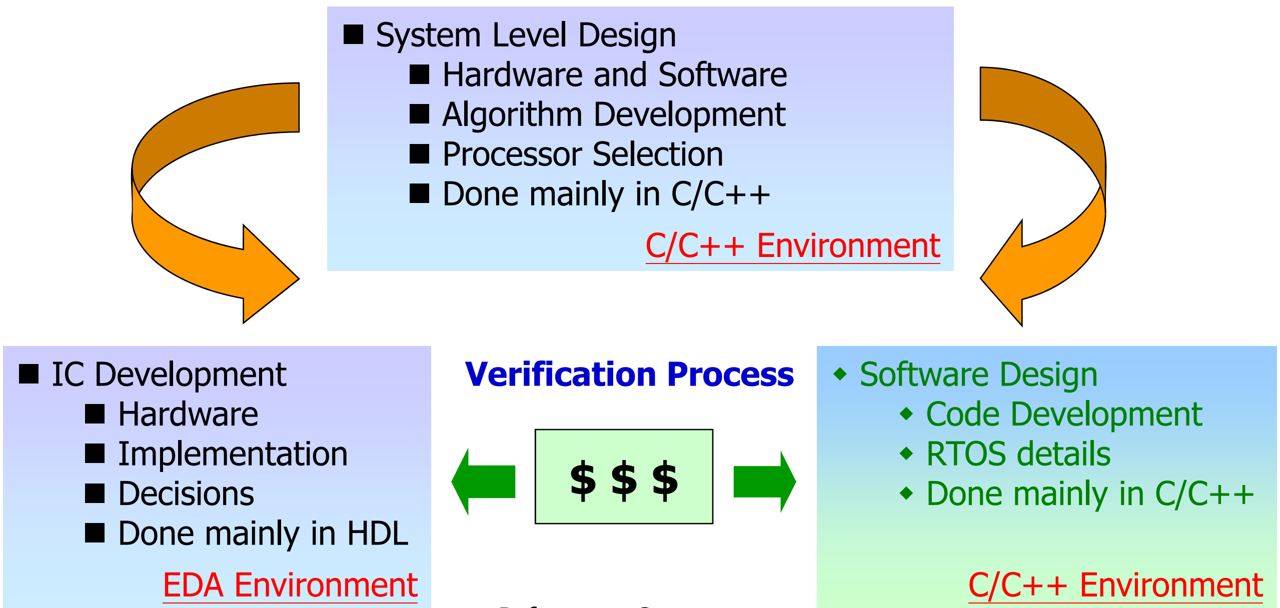
  - Reliability problem

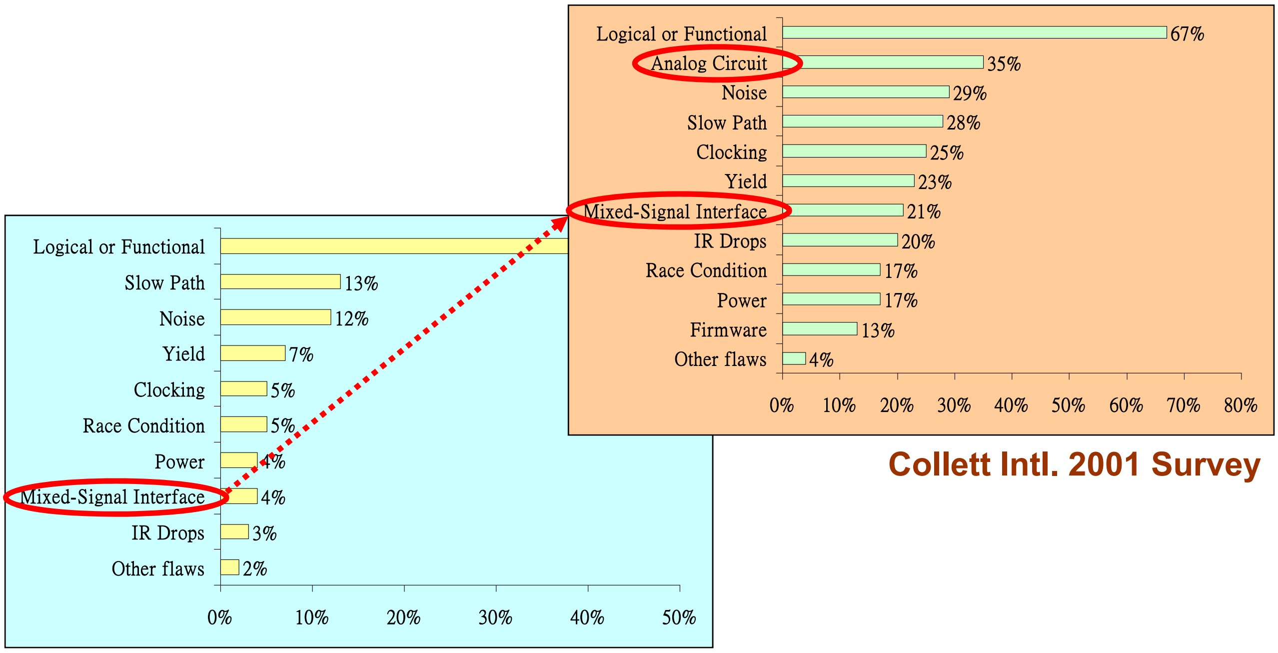
HW/SW Integration

- Integrating HW/SW at the final step may require high cost to fix inconsistency problems



Reference : Synopsys

Mixed Signals in SoC



Collett Intl. 2001 Survey

Collett Intl. 2000 Survey

Challenges for MS Designs

- Design challenges
  - Chip-level simulation takes too much time
  - Design budgets are not distributed in a well-defined manner
  - Too much time is spent on low-level iterations
  - Design is not completely systematic
  - There is limited or no use of HDL
- Solutions:
  - Use a systematic, top-down design approach to capture design intent
  - Develop some tools for rapid targeting of different design technologies

SoC Testing Challenges

- Distributed design and test
  - Core provider does not know the target environment
  - System integrator is responsible for manufacturing testing
- Test access
  - Difficulties to access deeply embedded cores
  - Bandwidth, I/O pin count limitations
- Test optimization
  - Minimizing test cost while satisfying constraints such as power, resources, coverage, etc.

SoC Challenges

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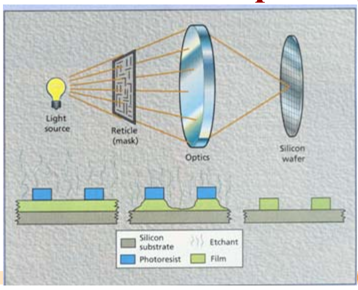
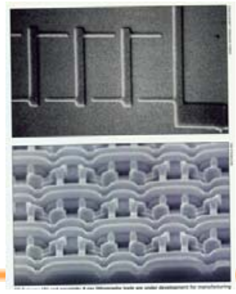
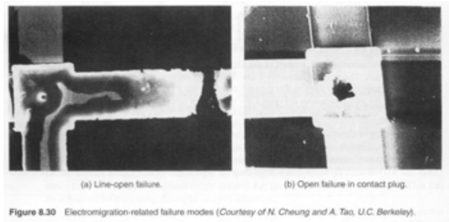
Nanometer Design Challenges

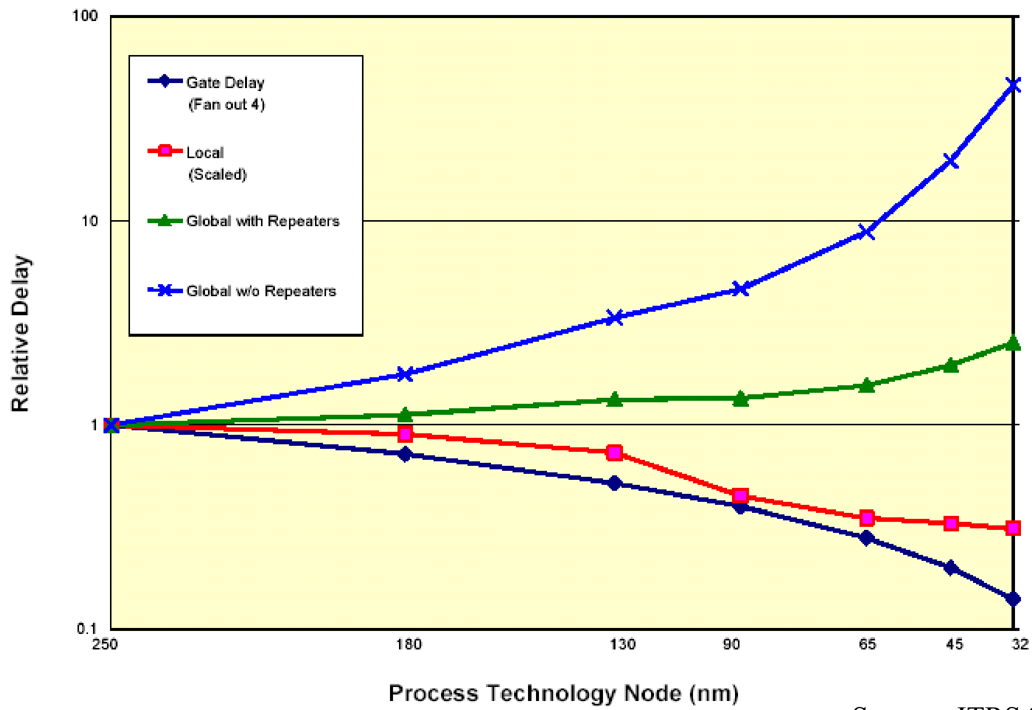
- In 2005, feature size ≈ 0.1 μm, μ P frequency ≈ 3.5 GHz, die size ≈ 520 mm^2, μ P transistor count per chip ≈ 200M, wiring level ≈ 8 layers, supply voltage ≈ 1 V, power consumption ≈ 160 W.
  - **Feature size ↓ → sub-wavelength lithography (impacts of process variation)? noise? wire coupling? reliability?**
  - **Frequency ↑, dimension ↑ → interconnect delay? electromagnetic field effects? timing closure?**
  - **Chip complexity ↑ → large-scale system design methodology?**
  - **Supply voltage ↓ → signal integrity (noise, IR drop, etc)?**
  - **Wiring level ↑ → manufacturability? 3D layout?**
  - **Power consumption ↑ → power & thermal issues?**







Wiring Delay vs. Feature Size



Source : ITRS 2001

Timing Closure Problem

- Wire delay starts to dominate total delay in DSM process
  - Cannot be ignored as taught in digital design course
- Only statistical wire delay model can be used at design phase
  - Lack of physical information about wire length
- Incorrect estimations require long iterations to meeting timing
  - Design schedule will be seriously delayed !!

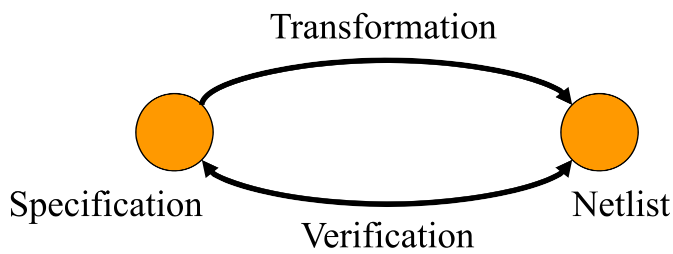
Path name	Pre-layout delay	Post-layout delay
P1	21.72	40.92 (+88.4%)
P2	6.65	7.81 (+17.4%)
P3	11.14	10.43 (-6.4%)
P4	5.03	5.44 (+8.15%)
P5	6.35	13.21 (+108.0%)
P6	6.42	13.20 (+105.6%)

Outline

- Moving to SOC
- What is Verification?
- Functional Verification Solutions
- System Verification Solutions

What is Verification ?

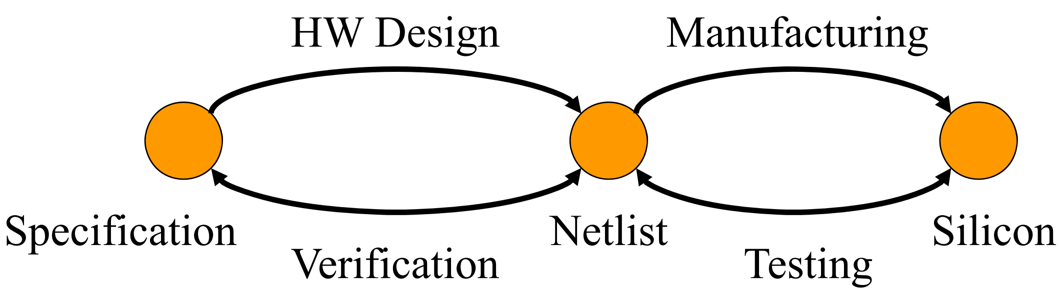
- A process used to demonstrate the functional correctness of a design
- To making sure that you are indeed implementing what you want
- To ensure that the result of some transformation is as expected



Source : "Writing Test Benches – Functional Verification of HDL Models" by Janick Bergeron, KAP, 2000.

Testing v.s. Verification

- Testing verifies manufacturing 驗證"製造出"的晶片是否功能正常
  - Verify that the design was manufactured correctly



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Verification Complexity

- For a single flip-flop:
  - Number of states = 2
  - Number of test patterns required = 4
- For a Z80 microprocessor (~5K gates)
  - Has 208 register bits and 13 primary inputs
  - Possible state transitions = $2^{bits+inputs} = 2^{221}$
  - At 1M IPS would take 10^{53} years to simulate all transitions 指數形成長，超大
- For a chip with 20M gates
  - ??????

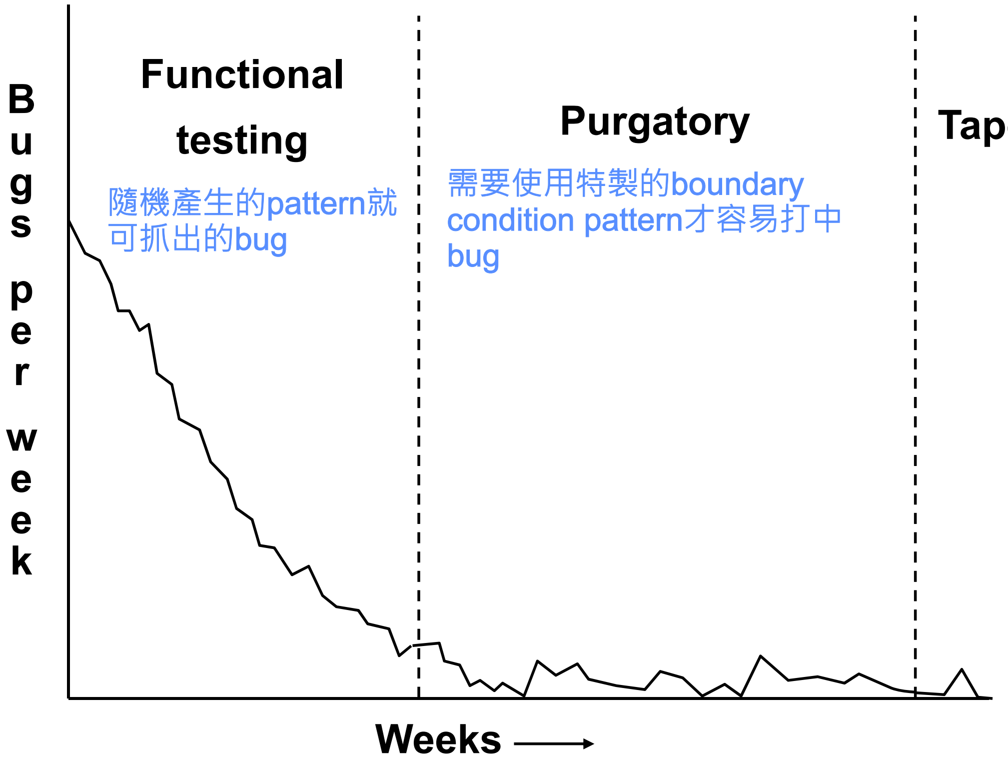
*IPS = Instruction Per Second

When is Verification Complete ?

- Some answers from real designers:
  - When we run out of time or money
  - When we need to ship the product
  - When we have exercised each line of the HDL code
  - When we have tested for a week and not found a new bug
  - ***We have no idea!!***
- Designs are often too complex to ensure full functional coverage
  - The number of possible vectors greatly exceeds the time available for test

目標就是在有限的時間內做最多的驗證(因為不可能做完，做多少算多少)

Typical Verification Experience



Verification Approaches

- Top-down verification approach
  - From system to individual components
- Bottom-up verification approach
  - From individual components to system
- Platform-based verification approach 先前已經有既有的平台，只是將上面的元件代換成新的東西，就可以使用以前的平台進行驗證
  - Verify the developed IPs in an existing platform
- System interface-based verification approach
  - Model each block at the interface level
  - Suitable for final integration verification

Bottom-Up Verification Steps

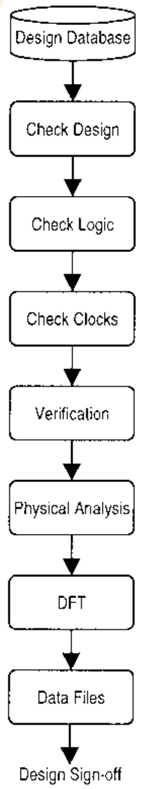
- Verify the leaf IPs
  - Many techniques are proposed and will be discussed later
- Verify the interface among IPs
- Run a set of complex applications
- Prototype the full chip and run the application software
- Decide when to release for mass production

Interesting Observations

- 90% of ASICs work at the first silicon but only 50% work in the target system
  - Do not perform system level verification (with software)
- If a SoC design consisting of 10 blocks
  - P(work)= $.9^{10}$ =.35
- If a SoC design consisting of 2 new blocks and 8 pre-verified robust blocks
  - P(work) = $.9^{2} * .98^{8}$ =.69
- To achieve 90% of first-silicon success SoC
  - P(work) = $.99^{10}$ =.90

Design Sign-off

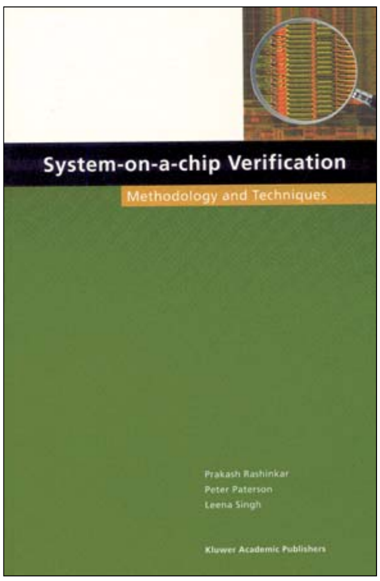
- Sign-off is the final step in the design process
- It determines whether the design is ready to be taped out for fabrication
- No corrections can be made after this step
- The design team needs to be confident that the design is 100% correct
  - Many items need to be checked



Source : "System-on-a-chip Verification – Methodology and Techniques" by P. Rashinkar, etc., KAP, 2001.

A Reference Book

- **System-on-a-Chip Verification Methodology and Techniques**
- by
  Prakash Rashinkar
  Peter Paterson
  Leena Singh
  Cadence Design Systems Inc., USA
- published by
  Kluwer Academic Publishers, 2001



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- What is Verification?
- Functional Verification Solutions
  - Simulation-Based Techniques
  - Static Verification Techniques
- System Verification Solutions

Simulation-Based Verification

- Still the primary approach for functional verification
  - In both gate-level and register-transfer level (RTL)
- Test cases
  - User-provided (often)
  - Randomly generated
- Hard to gauge how well a design has been tested
  - Often results in a huge test bench to test large designs
- Near-term improvements
  - Faster simulators
    - Compiled code, cycle-based, emulation, …
  - Testbench tools
    - Make the generation of pseudo-random patterns better/easier
- Incremental improvements won't be enough

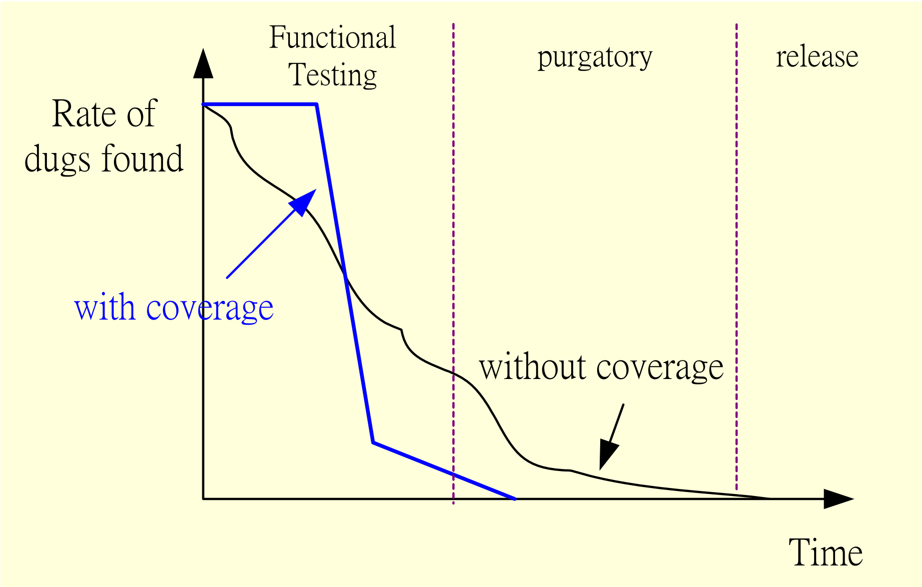
Simulator Improvements

- Event-driven: 會根據變化的訊號去尋找哪些gate被影響，然後再對這些gate進行分析
  - Timing accurate but slower
- Cycle-based: 在意的是每個clock結束時，sample到的值都要是對的，其他時間點都不會去進行檢查，因此較快 (但無法檢查timing問題)
  - Faster simulation (5x – 100x) but only cycle accurate
  - Require other tools to check timing problems
- Transaction-based: 檢查連線(bus)是否正確，通常用於接線複雜的design
  - Require bus functional model (BFM) of each design
  - Only check the transactions between components
  - Have faster speed by raising the level of abstraction 因為省略很多東西，所以很快
- Assistant hardware:
  - To speed up logic simulation by mapping some gate-level netlist into specific hardware 把部分電路mapping到FPGA上以硬體的速度進行驗證，會比單純用軟體驗證快

Coverage-Driven Verification

- Coverage reports can indicate how much of the design has been exercised
  - Point out what areas need additional verification
- Optimize regression suite runs
  - Redundancy removal (to minimize the test suites)
  - Minimizes the use of simulation resources
- Quantitative sign-off criterion
- Easy to use, low-complexity
- A good guidance but cannot guarantee 100% error-free designs

The Rate of Bug Detection



source : "Verification Methodology Manual For Code Coverage In HDL Designs" by Dempster and Stuart

Testbench Automation

- Require both ***generator*** and ***predictor*** in an integrated environment
- Generator: constrained random patterns
  - Ex: keep A in [10 … 100]; keep A + B == 120;
  - Hardware verification languages (HVL) are often used
- Predictor: generate the estimated outputs
  - Require a behavioral model of the system
- Only pseudo-random patterns are available
  - Good to check corner cases
  - Relationship to real functionality is week
- Many improvements are made on this approach
  - Popular in industry now

Assertion-Based Verification

- Assertions are ***active* comments** that can
  - Monitor signals on interfaces when connecting blocks
  - Track expected behavior documented in the assertions
  - Watch for forbidden behavior with a design block
- Assertions turn design specification into verification objects
  - Design can be continuously checked against these spec. throughout its life cycle
- Assertion increases observability in simulation
  - Debugging time is greatly reduced
- A new approach that is worthy to be watched

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  - Static Verification Techniques 不用跑simulation
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HDL Linter 比較像在抓coding style的錯誤

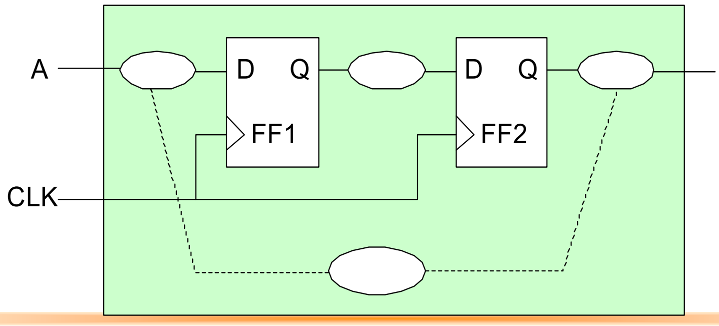
- Fast static RTL code checker
  - Preprocessor of the synthesizer
- **RTL purification (RTL DRC)**
  - Syntax, semantics, simulation
- Check for built-in or user-specified rules
  - Testability, reusability, …
- Lint-liked tools can help spot defects without simulation
  - Avoid error code that increases design iterations
- Only trivial bugs can be found
  - Depend on the completeness of the database

Formal Verification

- Ensure the consistency with specification for *all* possible inputs (100% coverage)
- Primary applications
  - Equivalence Checking 比對design在轉換前、後功能是否相同
  - Model Checking
- Solve the completeness problem in simulation-based methods
- Cannot handle large designs due to its high complexity
- Valuable, but not a general solution

Static Timing Analysis (STA)

- Determine if a circuit meets timing constraints without having to simulate
  - No input patterns are required (100% coverage)
  - Functionality is not checked
- Faster but may be inaccurate (too pessimistic)
- Cannot be applied to all cases
  - Gate-level simulation may still required for some cases



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Prototyping

- Verify designs using real hardware
  - FPGA, emulator
- Better throughput in handling complex designs
- **Software-driven verification**
  - Verify HW using SW
- Interfaced with real HW components
- May have a little performance degradation
- May have capacity limitation
- Poor debugging capability
- High cost to fix design problems

把大design partition為許多小design
並分配至FPGA上進行驗證
速度較快，但是若有錯誤發生只能知
道該design有問題，並無法得知是在
哪個環節出問題
因此Prototyping通常只用來證明
design是對的，並非拿來debug用

Limited Production

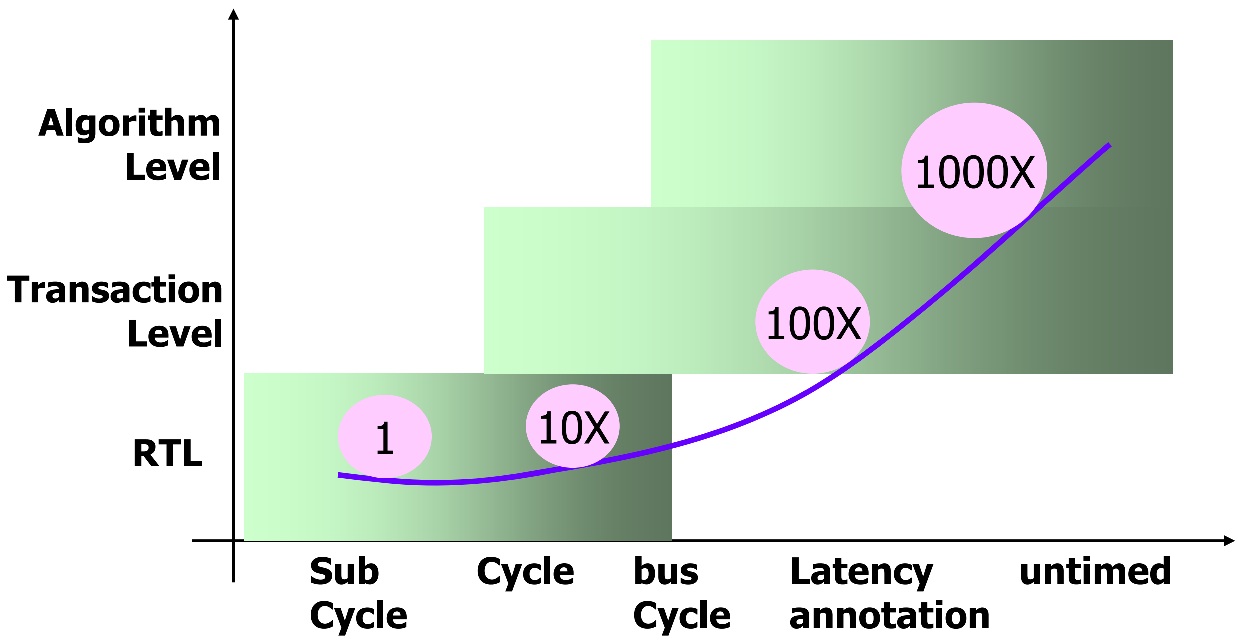
- Even after robust verification process and prototyping, it's still not guaranteed to be bug-free
- A limited production for new macro is necessary
  - Often called engineering samples
  - 1 to 4 customers
  - Small volume
  - Reducing the risk of supporting problems
- Same as real cases but more ***expensive***
- Only used as the final check before mass production

先下個幾顆試試看，
與真實量產時的結果
最為接近，只是很貴

HW/SW Co-Simulation

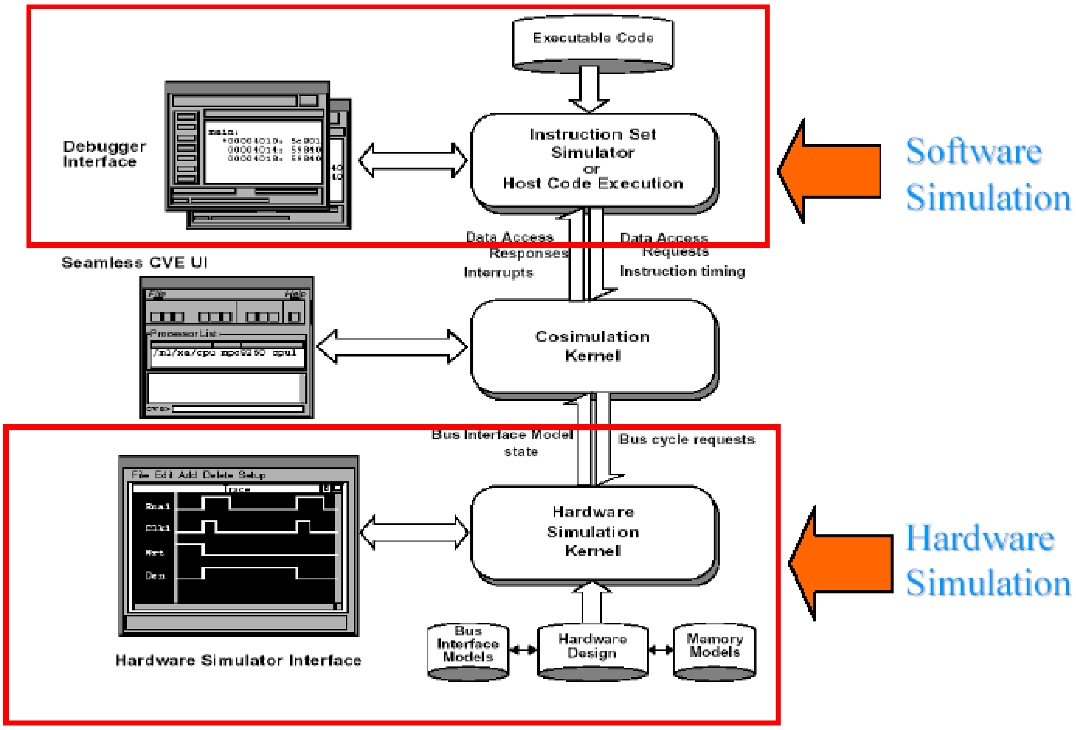
- Couple a software execution environment with a hardware simulator
- Simulate the system at higher levels
  - Software normally executed on an **Instruction Set Simulator** (ISS)
  - A **Bus Interface Model** (BIM) converts software operations into detailed pin operations
- Allows earlier system integration
- Start software development 6 months earlier
- Provide a significant performance improvement for system verification
  - Simulate 100x~1000x faster than RTL

Verification Speed



Reference : Synopsys

Many Available Tools for Co-Sim.



Reference : Mentor Graphics

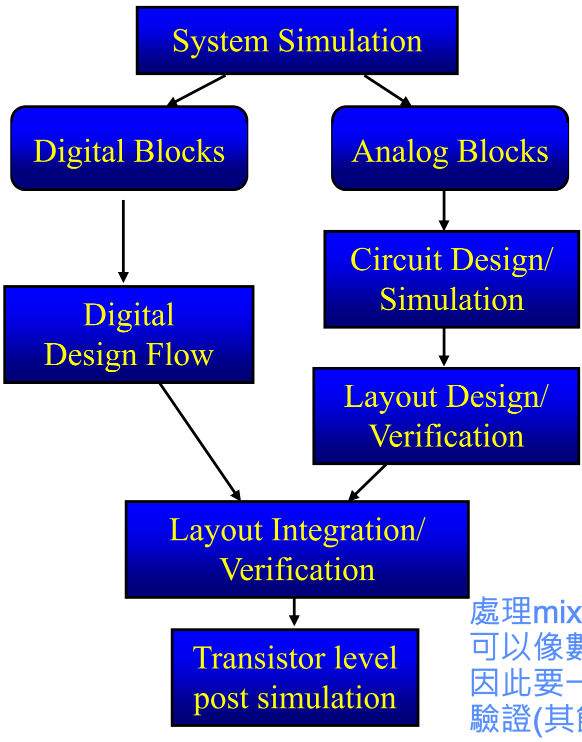
System Verification Today

- Many good verification techniques have been proposed at each design stage
  - Hard to reuse for other stages and design projects
- The fragmented functional verification processes limit the speed and efficiency
  - An unified verification methodology that supports all design domains may be the solution
- An unified ***verification platform*** that optimally supports the methodology is the key
  - Require system-level languages, such as SystemC, SystemVerilog, …

Outline

- Moving to SOC
- What is Verification?
- Functional Verification Solutions
- System Verification Solutions
  - Hardware v.s. software
  - Digital circuits v.s. analog circuits

Conventional MS Design Approach

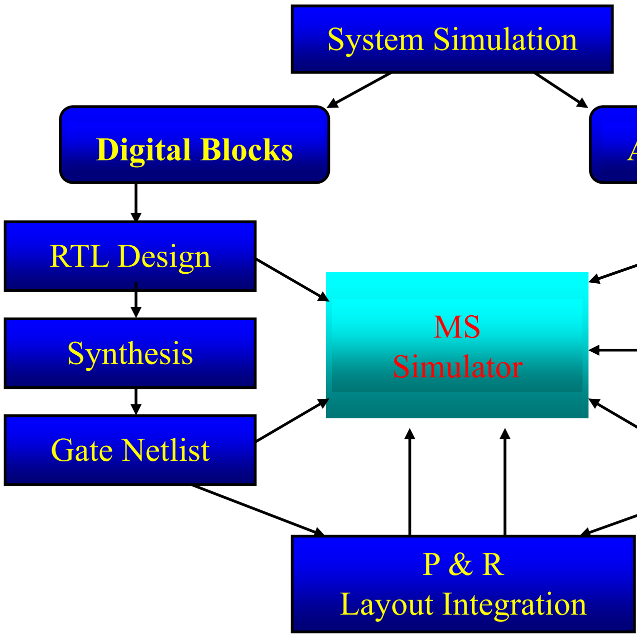


- Design and simulate digital and analog circuits separately
  - May miss the effects between each other
- Can perform co-simulation at transistor level only
  - High complexity
  - Too slow

處理mix signal design時，由於類比電路並沒有EDA tool可以像數位電路那樣由verilog code --> ... --> layout
因此要一直到layout部分才可以將數位電路與類比電路結合驗證(其餘時刻都是分開進行設計與驗證)

Top-Down MS Design Flow

- Starting from **behavioral models**
  - Can check whole system behavior in advance



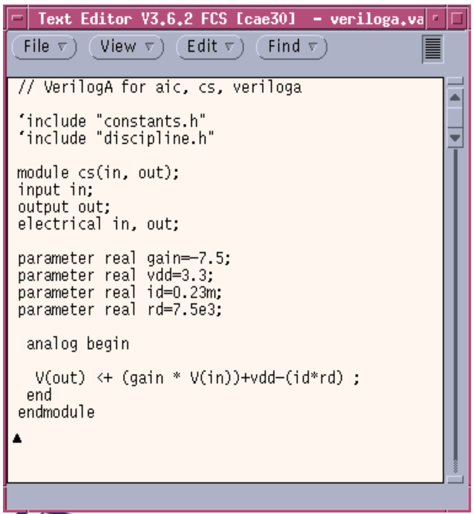
Analog Behavioral Modeling

- A mathematical model written in **Hardware Description Language (HDL)**
  - Verilog-AMS
  - VHDL-AMS
  - Matlab
  - C/C++
  - ……
- Emulate circuit block functionality by sensing and responding to circuit conditions
  - Simulate at **behavioral level**
- **Faster** simulation time
  - Allow **whole chip simulation**

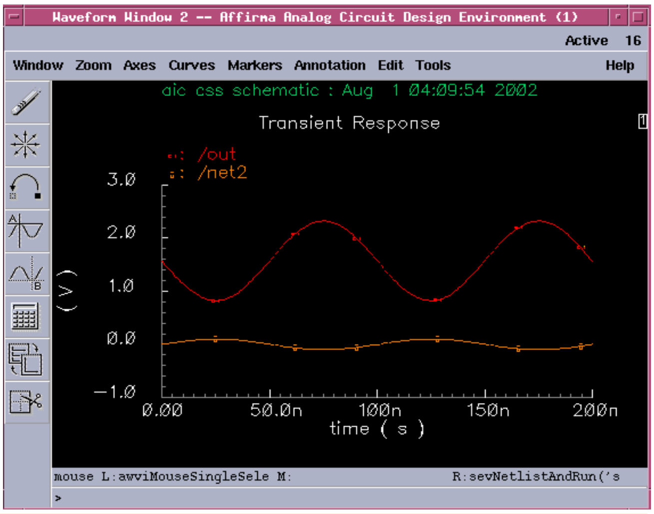
An Example of Verilog-A Code

- **Keys to a good behavioral model**
  - Concise mathematical equations of the behavior
    - For faster simulation time

      通常類比電路的model都會用數學式呈現
  - Appropriate value for each parameter
    - For accurate simulation results



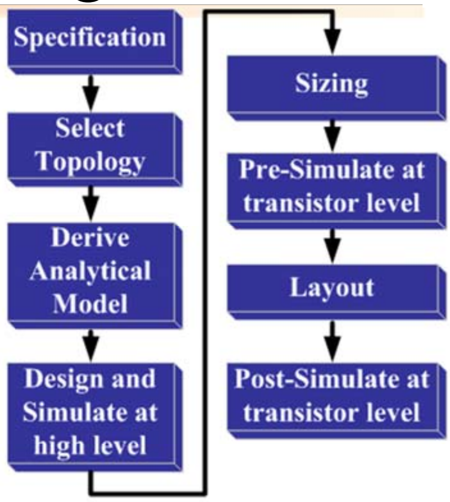
```
// VerilogA for aic, cs, veriloga

`include "constants.h"
`include "discipline.h"

module cs(in, out);
input in;
output out;
electrical in, out;

parameter real gain=-7.5;
parameter real vdd=3.3;
parameter real id=0.23m;
parameter real rd=7.5e3;

 analog begin

  V(out) <+ (gain * V(in))+vdd-(id*rd) ;
 end
endmodule
```

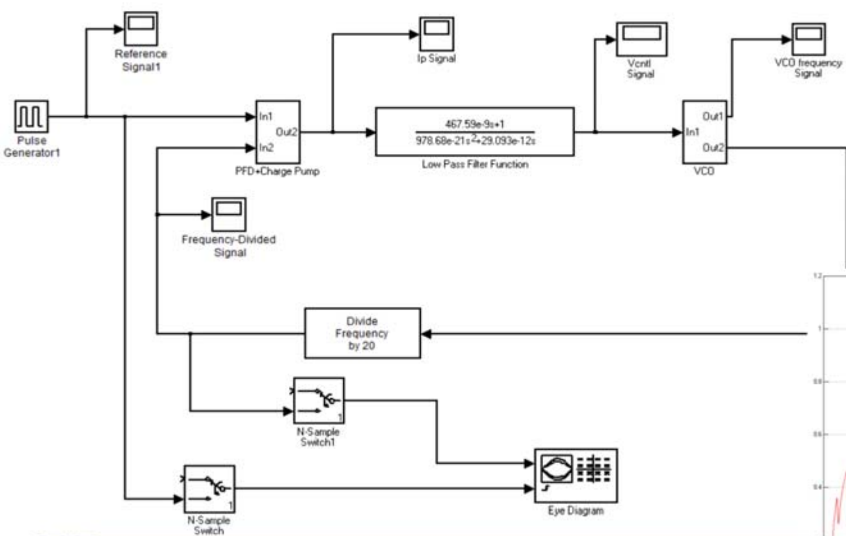


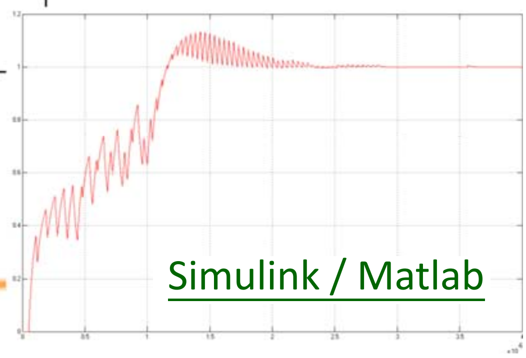
並不是使用Verilog-a後對類比電路的simulation的速度就會變快，
而是因為用數學式對model的行為進行簡化後才變快

Top-Down Modeling

- Verify whole AMS system **roughly** before implemented
  - Suitable for **newly-created designs**
  - Inaccurate on non-ideal circuit properties



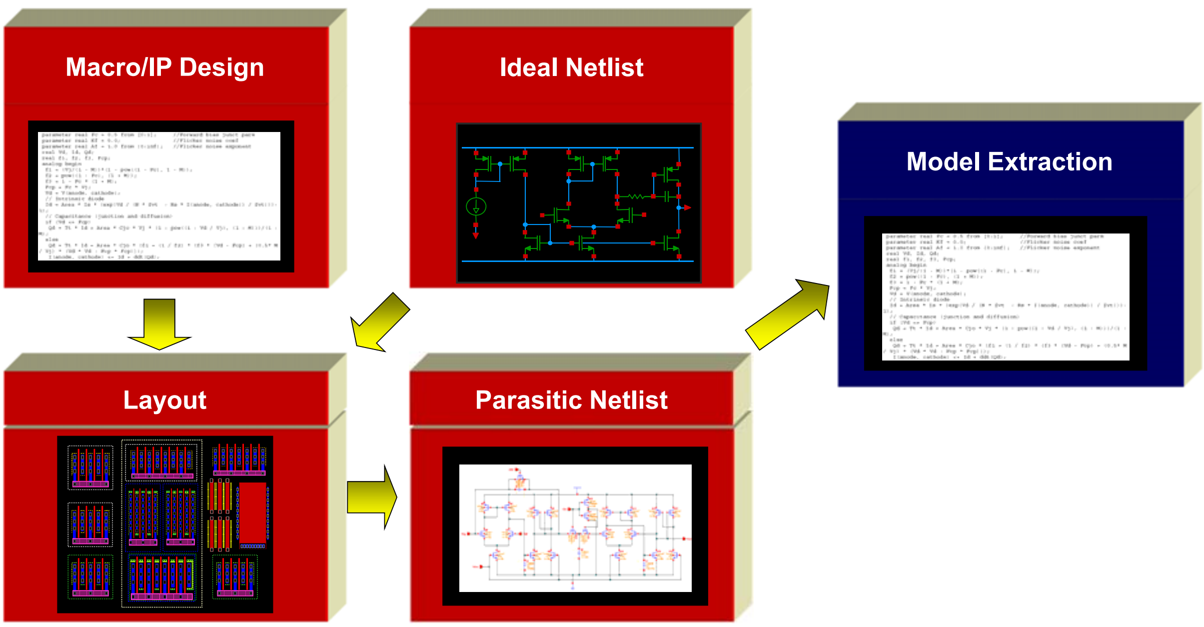




Bottom-Up Modeling Approach

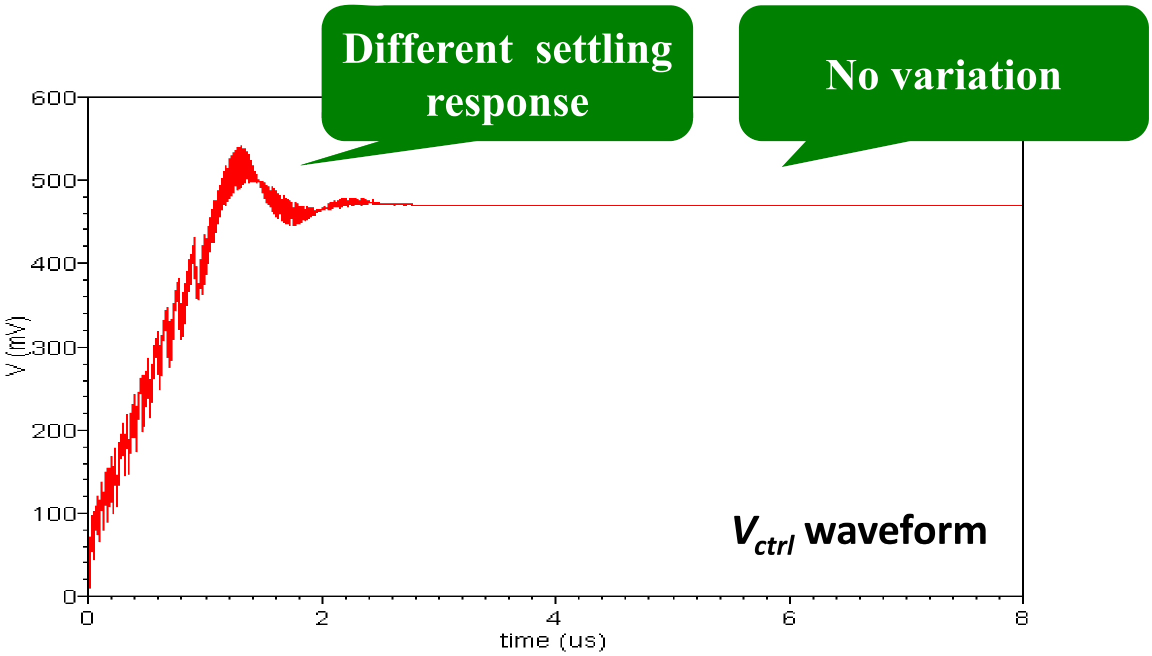
- While using ***existing*** blocks, bottom-up ***behavior extraction*** is required for system verification
  - An interesting research direction
- Bottom-up approach can be much accurate
  - Detailed effects can be considered, such as the delay time of PLL, the effects of parasitic devices (R, L, C, ...)
- Bottom-up approach can still effective when those design parameters are hard to obtain
  - Only have transistor-level design (ex: IP)
  - Circuits are already flattened

Bottom-Up Behavior Extraction



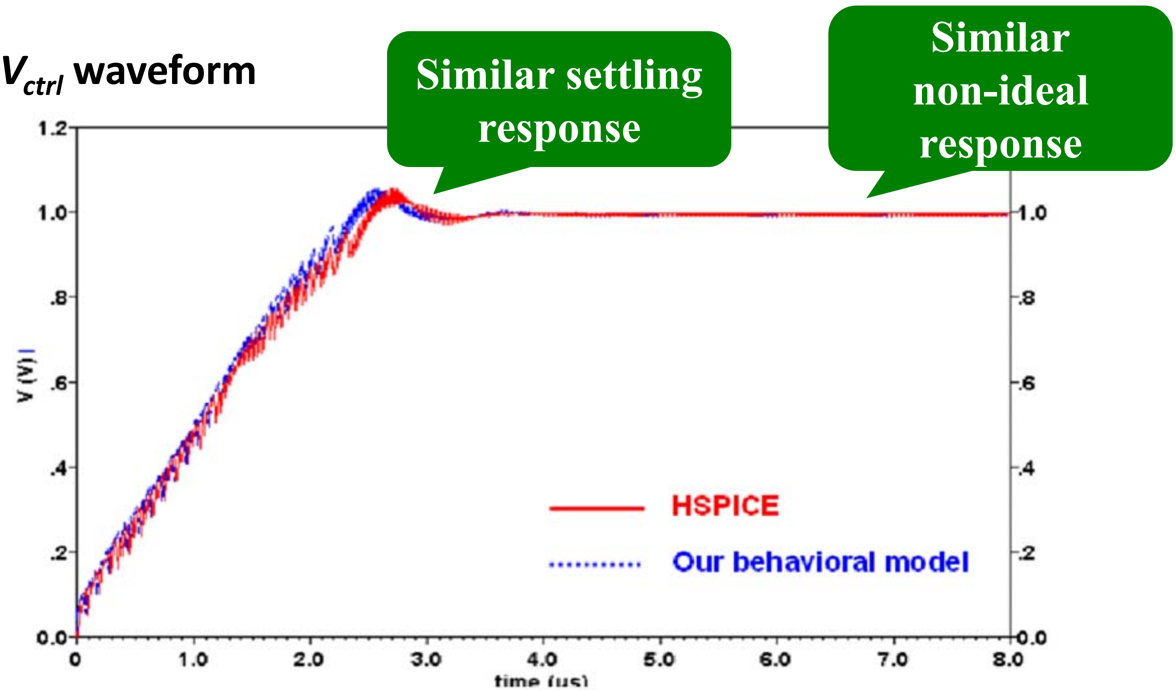
Top-Down Behavioral Model

- Use the embedded behavioral blocks from **Cadence's AHDL library** to model a PLL

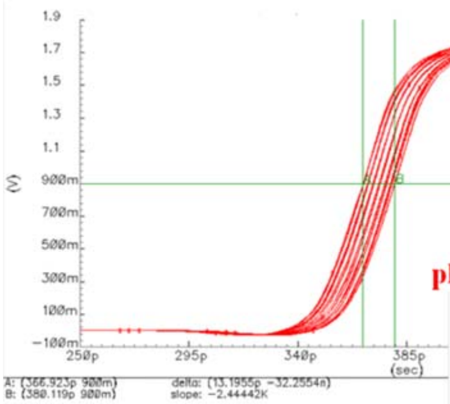


Extracted Behavioral Model

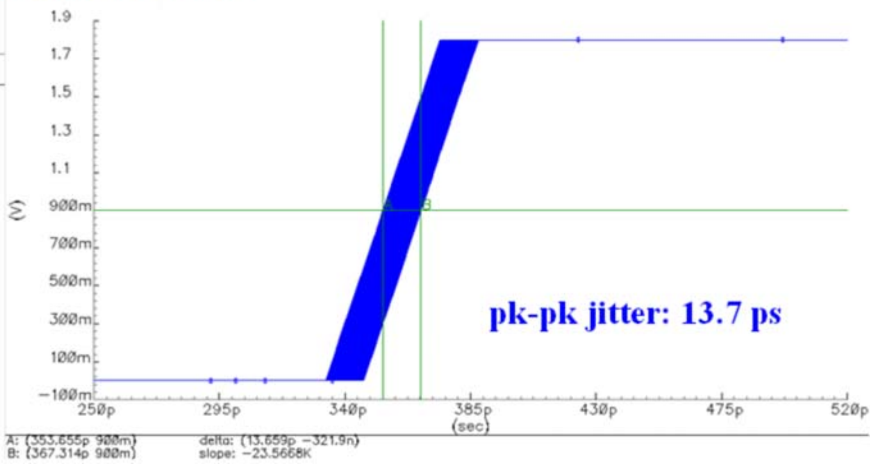
V_{ctrl} waveform



Peak-to-peak Jitter



HSPICE : 13.2 ps
$T_{sim.}$: 22074 sec



Beh model: 13.7ps
$T_{sim.}$: 122 sec (180x)

Conclusions

工欲善其事
必先利其器 !!

- SoC is really a big challenge for IC designers
- Design methodology requires a big change
  - Reusing existing IPs and platforms is the key
- Verification has become the major bottleneck
  - Simulation only is hard to cover all functionality
- More powerful tools are essential to solve those difficult design problems