Ειδικά Θέματα Αρχιτεκτονικής και Προγραμματισμού Μικροεπεξεργαστών

Ενότητα 2: Απόδοση

Διδάσκων: Βαρτζιώτης Φώτιος
Τμήμα Πληροφορικής και Τηλεπικοινωνιών

Performance

- *Performance is the key to understanding underlying motivation for the hardware and its organization*
- Measure, report, and summarize performance to enable users to
  - make intelligent choices
  - see through the marketing hype!

- *Why is some hardware better than others for different programs?*
- *What factors of system performance are hardware related? (e.g., do we need a new machine, or a new operating system?)*
- *How does the machine's instruction set affect performance?*

Computer Performance: TIME, TIME, TIME!!!

- *Response Time* (*elapsed time*, *latency*):
  - how long does it take for *my* job to run?
  - how long does it take to execute (start to finish) *my* job?
  - how long must *I* wait for the database query?
- *Throughput*:
  - how *many* jobs can the machine run at once?
  - what is the *average* execution rate?
  - how *much* work is getting done?
- *If we upgrade a machine with a new processor what do we increase?*
- *If we add a new machine to the lab what do we increase?*

Individual user concerns…

Systems manager concerns…

Execution Time

- *Elapsed Time*
  - counts everything (*disk and memory accesses, waiting for I/O, running other programs, etc.*) from start to finish
  - a useful number, but often not good for comparison purposes

  elapsed time = CPU time + wait time (I/O, other programs, etc.)

- *CPU time*
  - doesn't count waiting for I/O or time spent running other programs
  - can be divided into *user CPU time* and *system CPU time* (OS calls)

  CPU time = user CPU time + system CPU time

  $\Rightarrow$ elapsed time = user CPU time + system CPU time + wait time

- Our focus: *user CPU time* (*CPU execution time* or, simply, *execution time*)
  - time spent executing the lines of code that are *in our program*

Definition of Performance

- For some program running on machine X:

$$\text{Performance}_X = 1 / \text{Execution time}_X$$

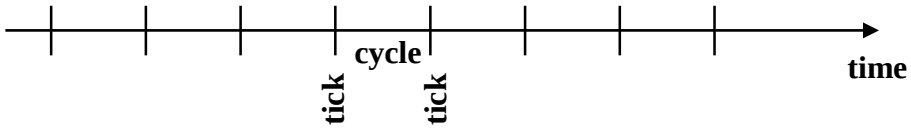
- *X is n times faster than Y* means:

$$\text{Performance}_X \ / \text{Performance}_Y = n$$

Clock Cycles

- Instead of reporting execution time in seconds, we often use *cycles*. In modern computers hardware events progress cycle by cycle: in other words, each event, e.g., multiplication, addition, etc., is a sequence of cycles

- *Clock ticks* indicate start and end of cycles:



- *cycle time* = time between ticks = seconds per cycle
- *clock rate* (*frequency*) = cycles per second (1 Hz = 1 cycle/sec, 1 MHz = 10^6 cycles/sec)
- *Example*: A 200 Mhz clock has a cycle time

Performance Equation I

$$\frac{\text{seconds}}{\text{program}} = \frac{\text{cycles}}{\text{program}} \times \frac{\text{seconds}}{\text{cycle}}$$

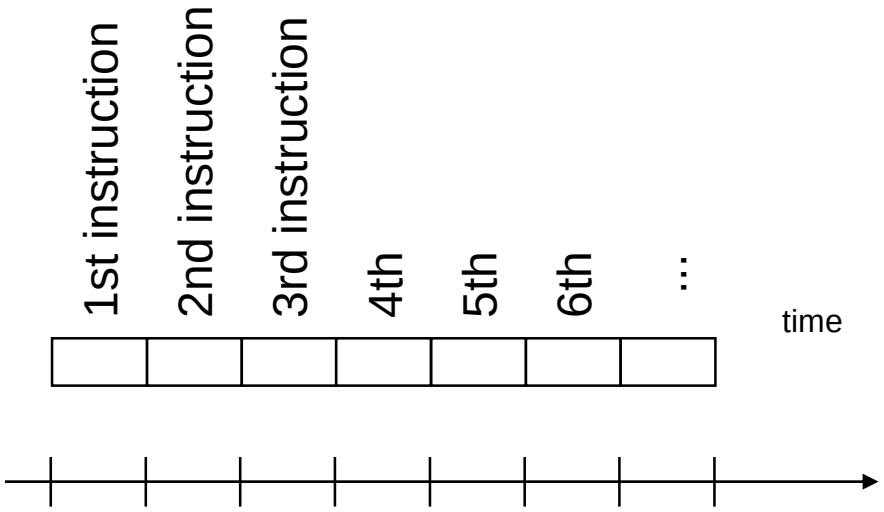
equivalently

$$\text{CPU execution time for a program} = \text{CPU clock cycles for a program} \times \text{Clock cycle time}$$

- So, to improve performance one can either:
  - reduce the number of cycles for a program, or
  - reduce the clock cycle time, or, equivalently,
  - increase the clock rate

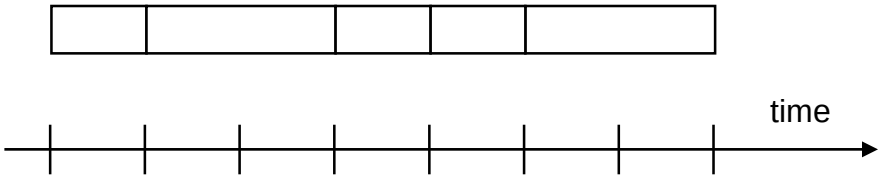
How many cycles are required for a program?

- Could assume that # of cycles = # of instructions



- *This assumption is incorrect!* Because:
  - Different instructions take different amounts of time (cycles)
  - Why…?

How many cycles are required for a program?



- Multiplication takes more time than addition
- Floating point operations take longer than integer ones
- Accessing memory takes more time than accessing registers
- *Important point*: changing the cycle time often changes the number of cycles required for various instructions because it means changing the hardware design. More later…

Example

- Our favorite program runs in 10 seconds on computer A, which has a 400Mhz clock.
- We are trying to help a computer designer build a new machine B, that will run this program in 6 seconds. The designer can use new (or perhaps more expensive) technology to substantially increase the clock rate, but has informed us that this increase will affect the rest of the CPU design, causing machine B to require 1.2 times as many clock cycles as machine A for the same program.

- *What clock rate should we tell the designer to target?*

Terminology

- A given program will require:
  - some number of instructions (machine instructions)
  - some number of cycles
  - some number of seconds
- We have a vocabulary that relates these quantities:
  - *cycle time* (seconds per cycle)
  - *clock rate* (cycles per second)
  - (*average*) *CPI* (cycles per instruction)
    - a floating point intensive application might have a higher average CPI
  - *MIPS* (millions of instructions per second)
    - this would be higher for a program using simple instructions

Performance Measure

- *Performance is determined by execution time*

- Do any of these other variables equal performance?
  - # of cycles to execute program?
  - # of instructions in program?
  - # of cycles per second?
  - average # of cycles per instruction?
  - average # of instructions per second?

- *Common pitfall* : thinking one of the variables is indicative of performance when it really isn't

Performance Equation II

CPU execution time for a program = Instruction count for a program × average CPI × Clock cycle time

- *Derive the above equation from Performance Equation I*

CPI Example I

- Suppose we have two implementations of the same instruction set architecture (ISA). For some program:
  - machine A has a clock cycle time of 10 ns and a CPI of 2.0
  - machine B has a clock cycle time of 20 ns and a CPI of 1.2

- *Which machine is faster for this program, and by how much?*
- *If two machines have the same ISA, which of our quantities (e.g., clock rate, CPI, execution time, # of instructions, MIPS) will always be identical?*

CPI Example II

- A compiler designer is trying to decide between two code sequences for a particular machine.
- Based on the hardware implementation, there are three different classes of instructions: Class A, Class B, and Class C, and they require 1, 2 and 3 cycles (respectively).
- The first code sequence has 5 instructions:

  2 of A, 1 of B, and 2 of C

  The second sequence has 6 instructions:

  4 of A, 1 of B, and 1 of C.

- *Which sequence will be faster? How much? What is the CPI for each sequence?*

MIPS Example

- Two different compilers are being tested for a 500 MHz. machine with three different classes of instructions: Class A, Class B, and Class C, which require 1, 2 and 3 cycles (respectively). Both compilers are used to produce code for a large piece of software.
- Compiler 1 generates code with 5 billion Class A instructions, 1 billion Class B instructions, and 1 billion Class C instructions.
- Compiler 2 generates code with 10 billion Class A instructions, 1 billion Class B instructions, and 1 billion Class C instructions.

- *Which sequence will be faster according to MIPS?*
- *Which sequence will be faster according to execution time?*

Benchmarks

- Performance best determined by running a real application
  - use programs typical of expected workload
  - or, typical of expected class of applications
    e.g., compilers/editors, scientific applications, graphics, etc.
- Small benchmarks
  - nice for architects and designers
  - easy to standardize
  - can be abused!
- Benchmark suites
  - Electronic Design News Embedded Microprocessor Benchmark Consortium (or EEMBC, pronounced “embassy”) benchmarks
  - Perfect Club: set of application codes
  - Livermore Loops: 24 loop kernels
  - Linpack: linear algebra package
  - SPEC: mix of code from industry organization

SPEC (System Performance Evaluation Corporation)

- Sponsored by industry but independent and self-managed – trusted by code developers and machine vendors
- Clear guides for testing, see www.spec.org
- Regular updates (benchmarks are dropped and new ones added periodically according to relevance)
- Specialized benchmarks for particular classes of applications
- Can still be abused…, by selective optimization!

SPEC History

- First Round: SPEC CPU89
  - 10 programs yielding a single number
- Second Round: SPEC CPU92
  - SPEC CINT92 (6 integer programs) and SPEC CFP92 (14 floating point programs)
  - compiler flags can be set differently for different programs
- Third Round: SPEC CPU95
  - new set of programs: SPEC CINT95 (8 integer programs) and SPEC CFP95 (10 floating point)
  - single flag setting for all programs
- Fourth Round: SPEC CPU2000
  - new set of programs: SPEC CINT2000 (12 integer programs) and SPEC CFP2000 (14 floating point)
  - single flag setting for all programs
  - programs in C, C++, Fortran 77, and Fortran 90

CINT2000 (Integer component of SPEC CPU2000)

Program	Language	What It Is
164.gzip	C	Compression
175.vpr	C	FPGA Circuit Placement and Routing
176.gcc	C	C Programming Language Compiler
181.mcf	C	Combinatorial Optimization
186.crafty	C	Game Playing: Chess
197.parser	C	Word Processing
252.eon	C++	Computer Visualization
253.perlbmk	C	PERL Programming Language
254.gap	C	Group Theory, Interpreter
255.vortex	C	Object-oriented Database
256.bzip2	C	Compression
300.twolf	C	Place and Route Simulator

CFP2000 (Floating point component of SPEC CPU2000)

Program	Language	What It Is
168.wupwise	Fortran 77	Physics / Quantum Chromodynamics
171.swim	Fortran 77	Shallow Water Modeling
172.mgrid	Fortran 77	Multi-grid Solver: 3D Potential Field
173.applu	Fortran 77	Parabolic / Elliptic Differential Equations
177.mesa	C	3-D Graphics Library
178.galgel	Fortran 90	Computational Fluid Dynamics
179.art	C	Image Recognition / Neural Networks
183.equake	C	Seismic Wave Propagation Simulation
187.facerec	Fortran 90	Image Processing: Face Recognition
188.ammp	C	Computational Chemistry
189.lucas	Fortran 90	Number Theory / Primality Testing
191.fma3d	Fortran 90	Finite-element Crash Simulation
200.sixtrack	Fortran 77	High Energy Physics Accelerator Design
301.apsi	Fortran 77	Meteorology: Pollutant Distribution

SPEC- Single number result - How

Arithmetic mean of wall-clock time

- Biased by long-running programs
- May rank designs in non-intuitive ways:
  - Machine A: Program $P_1 \rightarrow$ 1000 secs., $P_2 \rightarrow$ 1 secs.
  - Machine B: Program $P_1 \rightarrow$ 800 secs., $P_2 \rightarrow$ 100 secs.
  - What if machine runs P_2 most of the time?

Means

- Total time ignores program contribution to total workload
- Arithmetic mean biased by long programs
- Weighted arithmetic mean a better choice?
- How do we calculate weights?

SPEC- Single number result

Weighted arithmetic mean

$$\sum_{i=1}^{n} Weight_i \times Time_i$$

Example, W(1) = W(2) = 50

	Computer A	Computer B	Computer C
Program P1 (secs)	1	10	20
Program P2 (secs)	1000	100	20
Total time (secs)	1001	110	40
Weighted mean	500.50	55.00	20.00

SPEC- Single number result - How

Weighted arithmetic mean

$$\sum_{i=1}^{n} Weight_i \times Time_i$$

Example, W(1) = 0.909 W(2) = 0.091

	Computer A	Computer B	Computer C
Program P1 (secs)	1	10	20
Program P2 (secs)	1000	100	20
Total time (secs)	1001	110	40
Weighted mean	91.91	18.19	20.00

SPEC- Single number result - How

Weighted arithmetic mean

$$\sum_{i=1}^{n} Weight_i \times Time_i$$

Example, W(1) = 0.999 W(2) = 0.001

	Computer A	Computer B	Computer C
Program P1 (secs)	1	10	20
Program P2 (secs)	1000	100	20
Total time (secs)	1001	110	40
Weighted mean	2.00	10.09	20.00

SPEC- Single number result - How

Measuring against a reference computer

$$SPEC_{ratio_A} = \frac{Execution\ time_{reference}}{Execution\ time_A} = Performance_A / Performance_{reference}$$

$$n = \frac{SPEC_{ratio_A}}{SPEC_{ratio_B}} = \frac{\frac{Execution\ time_{reference}}{Execution\ time_A}}{\frac{Execution\ time_{reference}}{Execution\ time_B}} = \frac{Execution\ time_B}{Execution\ time_A} = \frac{Performance_A}{Performance_B}$$

Using ratios

- Ratios against reference machine are independent of running time of programs

SPEC CPU2000 reporting

- Refer SPEC website www.spec.org for documentation
- Single number result – geometric mean of normalized ratios for each code in the suite

$$\text{Geometric mean} = \sqrt[n]{\prod_{i=1}^{n} sample_i}$$

- Report precise description of machine
- Report compiler flag setting

CFP2000 Result

Advanced Micro Devices

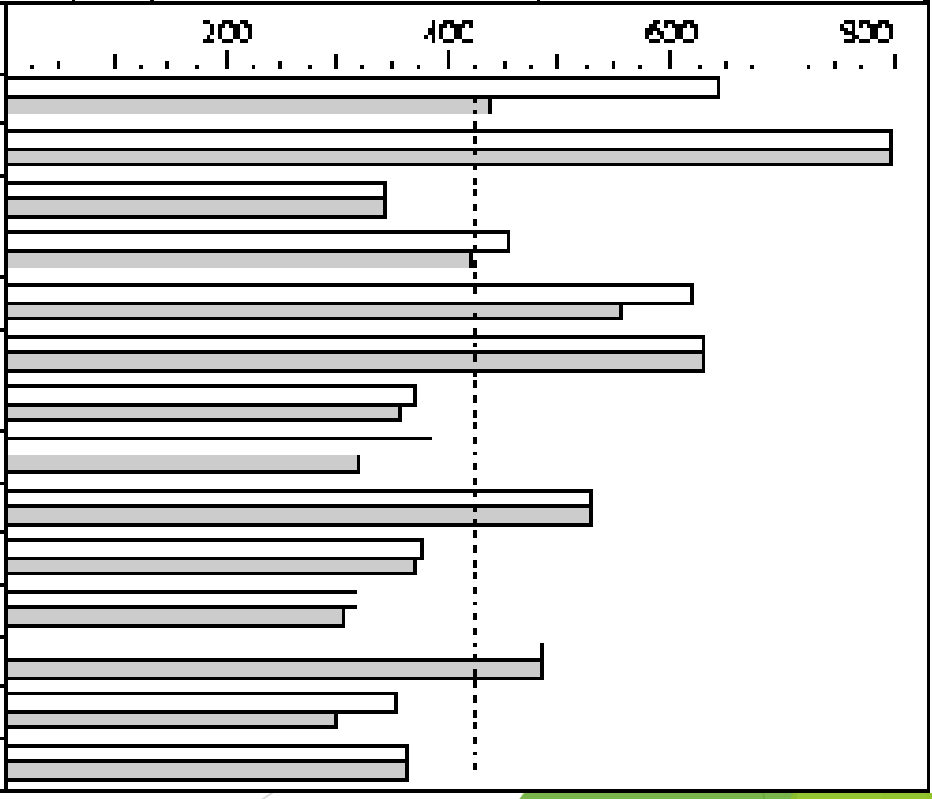
Gigabyte GA-7DX Motherboard, 1.4GHz Athlon Processor

SPECfp2000 = 458

SPECfp_base2000 = 426

SPEC license # 4 | Tested by: AMD Austin TX | Test date: May-2001 | Hardware Avail: Jun-2001 | Software Avail: Jun-2001

Benchmark	Reference Time	Base Runtime	Base Ratio	Runtime	Ratio
168.wupwise	1600	366	438	349	458
171.swim	3100	339	797	339	797
172.mgrid	1800	525	343	525	343
173.applu	2100	500	420	453	463
177.mesa	1400	252	556	225	621
178.galgel	2900	461	629	461	630
179.art	2600	725	359	701	371
183.equake	1300	403	323	337	386
187.facerec	1900	358	531	357	531
188.ammp	2200	591	372	585	376
189.lucas	2000	604	306	631	317
191.fma3d	2100	434	483	434	483
200.sixtrack	1100	366	301	311	354
301.apsi	2600	714	364	714	364



Specialized SPEC Benchmarks

- I/O
- Network
- Graphics
- Java
- Web server
- Transaction processing (databases)

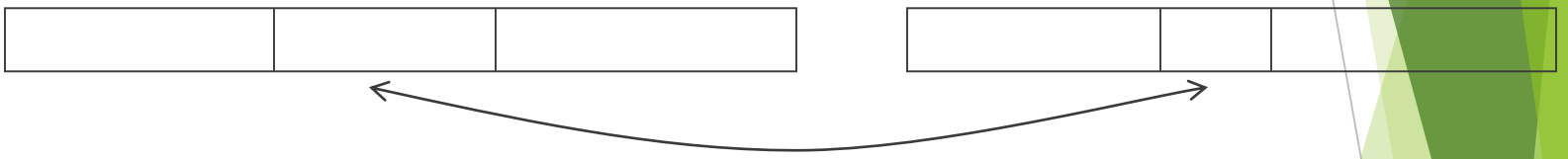
Principles of Computer Design

- Take Advantage of Parallelism
  - e.g. multiple processors, disks, memory banks, pipelining, multiple functional units
- Principle of Locality
  - Reuse of data and instructions
    - 90 -10 rule: 90% of execution time spent running 10% of instructions
    - programs access data in nearby addresses
- Focus on the Common Case!!!
  - Amdahl's Law

Amdahl's Law

- Execution Time After Improvement =

  Execution Time Unaffected + (Execution Time Affected / Rate of Improvement)



- *Example*:
  - Suppose a program runs in 100 seconds on a machine, with multiply responsible for 80 seconds of this time.
  - *How much do we have to improve the speed of multiplication if we want the program to run 4 times faster?*
  - *How about making it 5 times faster?*

- Design Principle: *Make the common case fast*

Amdahl's Law

$$\text{ExTime}_{new} = \text{ExTime}_{old} \times \left[\left(1 - \text{Fraction}_{enhanced}\right) + \frac{\text{Fraction}_{enhanced}}{\text{Speedup}_{enhanced}} \right]$$

$$\text{Speedup}_{overall} = \frac{\text{ExTime}_{old}}{\text{ExTime}_{new}} = \frac{1}{\left(1 - \text{Fraction}_{enhanced}\right) + \frac{\text{Fraction}_{enhanced}}{\text{Speedup}_{enhanced}}}$$

Best you could ever hope to get:

F=0.1 => S ~= 1.1
F=0.5 => S = 2
F=0.9 => S = 10

$$\text{Speedup}_{maximum} = \frac{1}{\left(1 - \text{Fraction}_{enhanced}\right)}$$

Examples

- Suppose we enhance a machine making all floating-point instructions run five times faster. The execution time of some benchmark before the floating-point enhancement is 10 seconds.
  - *What will the speedup be if half of the 10 seconds is spent executing floating-point instructions?*
- We are looking for a benchmark to show off the new floating-point unit described above, and want the overall benchmark to show a speedup of 3. One benchmark we are considering runs for 100 seconds with the old floating-point hardware.
  - *How much of the execution time would floating-point instructions have to account for in this program in order to yield our desired speedup on this benchmark?*

Performance Summary

- Performance is specific to a particular program
  - total execution time is a consistent summary of performance
- For a given architecture performance increases come from:
  - increases in clock rate (without adverse CPI affects)
  - improvements in processor organization that lower CPI
  - compiler enhancements that lower CPI and/or instruction count
- *Pitfall*: expecting improvement in one aspect of a machine's performance to affect the total performance

Power and Energy

- Problem: Get power in, get power out
- Thermal Design Power (TDP)
  - Characterizes sustained power consumption
  - Used as target for power supply and cooling system
  - Lower than peak power, higher than average power consumption
  - Envelop?
- Clock rate can be reduced dynamically to limit power consumption
- Energy per task is often a better measurement

Dynamic Energy and Power

- Dynamic energy
  - Transistor switch from 0 -> 1 or 1 -> 0
  - f x Capacitive load x Voltage2
  - f is activity factor
  - For f= ½ we get ½ x Capacitive load x Voltage2
  - Typical assumption for activity factor is ½
- Dynamic power
  - ½ x Capacitive load x Voltage2 x Frequency switched
  - Again, assumes activity factor is ½
- Reducing clock rate reduces power, not energy

Reducing Power

- Techniques for reducing power:
  - Dynamic Voltage Scaling (DVS)
  - Dynamic Frequency Scaling (DFS)
  - Dynamic Voltage-Frequency Scaling (DVFS)
  - Low power state for DRAM, disks
  - Sleep modes

Static Power

- Static power consumption
- $Current_{static}$ x Voltage
- Scales with number of transistors
- To reduce: power gating

- The new primary evaluation for design innovation
  - Tasks per joule
  - Performance per watt (joules /sec)

Dependability

- Systems alternate between two states of service with respect to Service Level Agreements/Objectives (SLA/SLO):
  - Service accomplishment, where service is delivered as specified by SLA
  - Service interruption, where the delivered service is different from the SLA
- Module reliability:
  - Mean time to failure (MTTF)
  - Failures in Time - per billion hours (FIT) = 10^9/ MTTF
  - Mean time to repair (MTTR)
  - Mean time between failures (MTBF) = MTTF + MTTR
  - Availability = MTTF / MTBF

$$FIT_{system} = \sum_{i=1}^{\#components} FIT_i$$

MTTF = 1,000,000 hours → FIT = ?

Dependability - Example

- Assume a disk subsystem with the following components and MTTF:
  - 10 disks, each rated at 1,000,000-hour MTTF
  - 1 ATA controller, 500,000-hour MTTF
  - 1 power supply, 200,000-hour MTTF
  - 1 fan, 200,000-hour MTTF
  - 1 ATA cable, 1,000,000-hour MTTF

Using the simplifying assumptions that the lifetimes are exponentially distributed and that failures are independent, compute the MTTF of the system as a whole.

The sum of the failure rates is

$$\text{Failure rate}_{\text{system}} = 10 \times \frac{1}{1{,}000{,}000} + \frac{1}{500{,}000} + \frac{1}{200{,}000} + \frac{1}{200{,}000} + \frac{1}{1{,}000{,}000}$$

$$= \frac{10 + 2 + 5 + 5 + 1}{1{,}000{,}000 \text{ hours}} = \frac{23}{1{,}000{,}000} = \frac{23{,}000}{1{,}000{,}000{,}000 \text{ hours}}$$

or 23,000 FIT. The MTTF for the system is just the inverse of the failure rate:

$$\text{MTTF}_{\text{system}} = \frac{1}{\text{Failure rate}_{\text{system}}} = \frac{1{,}000{,}000{,}000 \text{ hours}}{23{,}000} = 43{,}500 \text{ hours}$$

or just under 5 years

Integrated Circuit Cost

- Integrated circuit

$$\text{Cost of integrated circuit} = \frac{\text{Cost of die} + \text{Cost of testing die} + \text{Cost of packaging and final test}}{\text{Final test yield}}$$

$$\text{Cost of die} = \frac{\text{Cost of wafer}}{\text{Dies per wafer} \times \text{Die yield}}$$

$$\text{Dies per wafer} = \frac{\pi \times (\text{Wafer diameter}/2)^2}{\text{Die area}} - \frac{\pi \times \text{Wafer diameter}}{\sqrt{2 \times \text{Die area}}}$$

$$\text{Die yield} = \text{Wafer yield} \times 1/(1 + \text{Defects per unit area} \times \text{Die area})^N$$

- Defects per unit area = 0.016-0.057 defects per square cm (2010)
- N = process-complexity factor = 11.5-15.5 (40 nm, 2010)
- The manufacturing process dictates the wafer cost, wafer yield and defects per unit area
- The architect's design affects the die area, which in turn affects the defects and cost per die

Integrated Circuit Cost - Example

- Find the number of dies per 300 mm (30 cm) wafer for a die that is 1.5 cm on a side and for a die that is 1.0 cm on a side.
- Find the die yield for dies that are 1.5 cm on a side and 1.0 cm on a side, assuming a defect density of 0.031 per cm2 and N is 13.5.
- Processing of a 300 mm (12-inch) diameter wafer in a leading-edge technology cost between $5000 and $6000 in 2010. Find the cost of die for dies that are 1.5 cm on a side and 1.0 cm on a side, assuming a processed wafer cost of $5500.