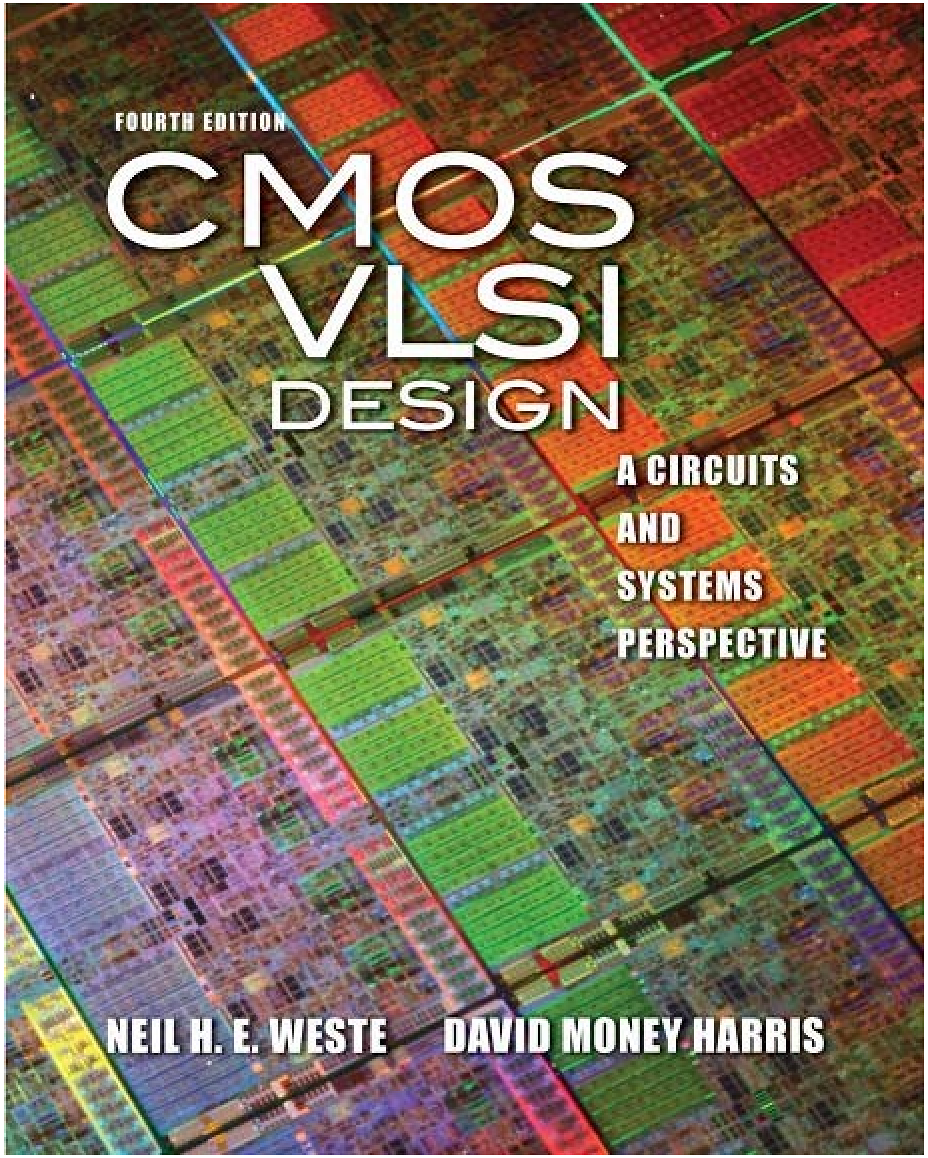


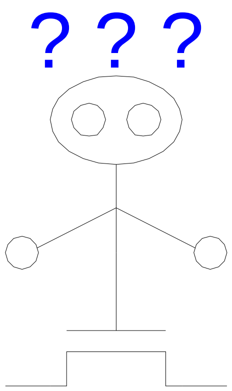
Lecture 6: Logical Effort

Outline

- Logical Effort
- Delay in a Logic Gate
- Multistage Logic Networks
- Choosing the Best Number of Stages
- Example
- Summary

Introduction

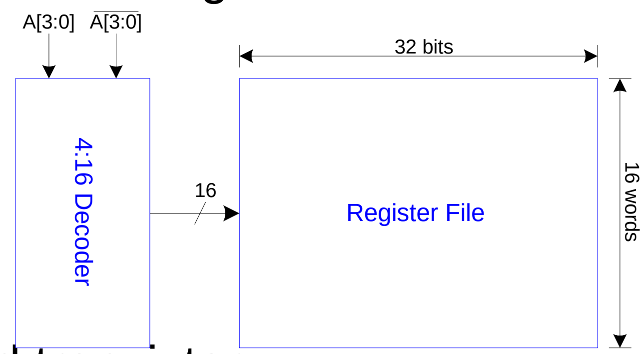
- Chip designers face a bewildering array of choices
  - What is the best circuit topology for a function?
  - How many stages of logic give least delay?
  - How wide should the transistors be?



- Logical effort is a method to make these decisions
  - Uses a simple model of delay
  - Allows back-of-the-envelope calculations
  - Helps make rapid comparisons between alternatives
  - Emphasizes remarkable symmetries

Example

- Ben Bitdiddle is the memory designer for the Motoroil 68W86, an embedded automotive processor. Help Ben design the decoder for a register file.



- Decoder specifications:
  - 16 word register file
  - Each word is 32 bits wide
  - Each bit presents load of 3 unit-sized transistors
  - True and complementary address inputs A[3:0]
  - Each input may drive 10 unit-sized transistors
- Ben needs to decide:
  - How many stages to use?
  - How large should each gate be?
  - How fast can decoder operate?

Delay in a Logic Gate

- Express delays in process-independent unit
- Delay has two components: d = f + p
- *f*: *effort delay* = *gh* (a.k.a. stage effort)
  - Again has two components
- *g*: *logical effort*
  - Measures relative ability of gate to deliver current
  - $g \equiv 1$ for inverter
- *h*: *electrical effort* = C_{out} / C_{in}
  - Ratio of output to input capacitance
  - Sometimes called fanout
- *p*: parasitic delay
  - Represents delay of gate driving no load
  - Set by internal parasitic capacitance

$$d = \frac{d_{abs}}{\tau}$$

τ = 3RC

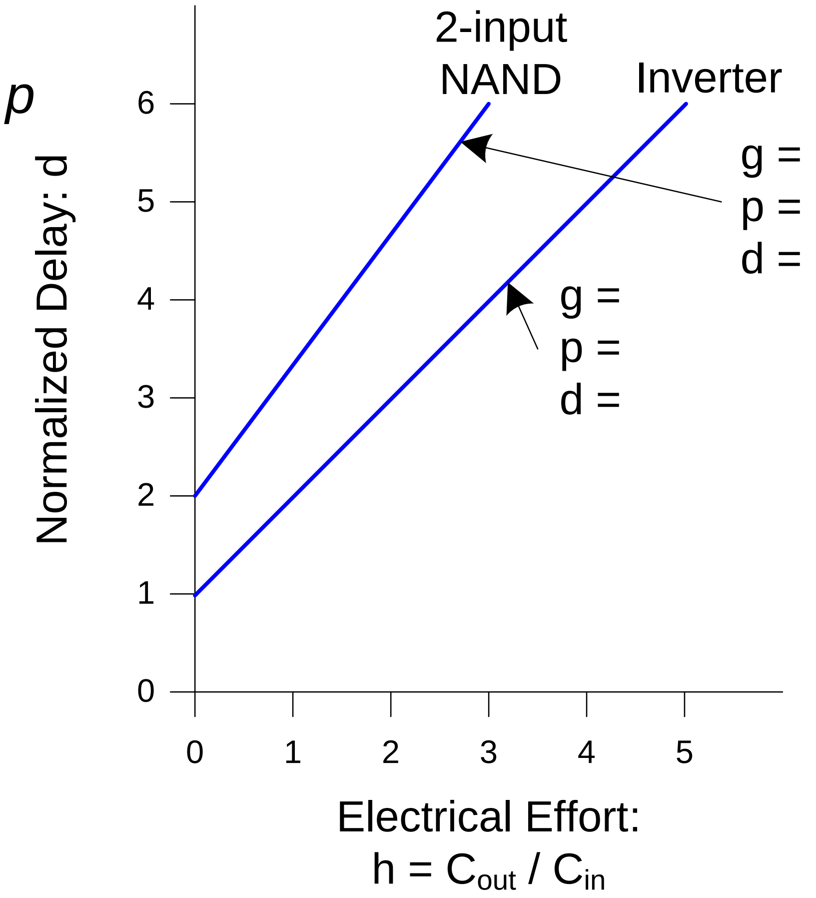
$\approx$ 3 ps in 65 nm process

60 ps in 0.6 μm process

Delay Plots

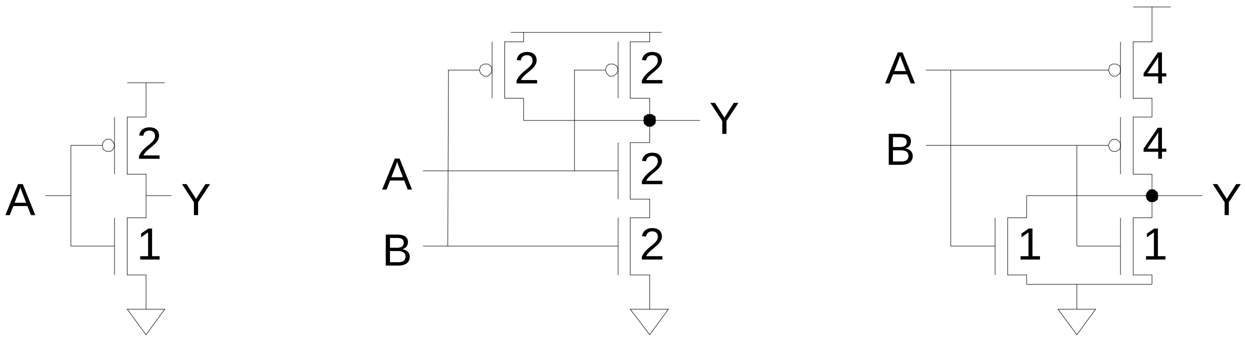
$d = f + p$

$= gh + p$



Computing Logical Effort

- DEF: *Logical effort is the ratio of the input capacitance of a gate to the input capacitance of an inverter delivering the same output current*.
- Measure from delay vs. fanout plots
- Or estimate by counting transistor widths



$C_{in} = 3$
$g = 3/3$

$C_{in} = 4$
$g = 4/3$

$C_{in} = 5$
$g = 5/3$

Catalog of Gates

- Logical effort of common gates

Gate type	Number of inputs				
	1	2	3	4	n
Inverter	1				
NAND		4/3	5/3	6/3	(n+2)/3
NOR		5/3	7/3	9/3	(2n+1)/3
Tristate / mux	2	2	2	2	2
XOR, XNOR		4, 4	6, 12, 6	8, 16, 16, 8	

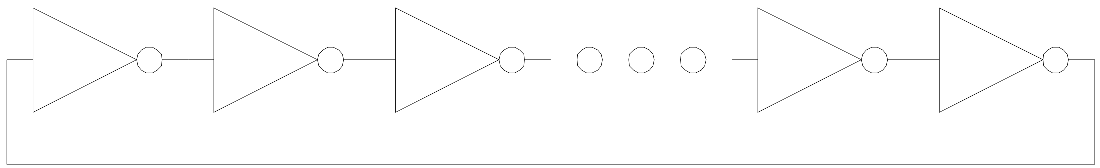
Catalog of Gates

- Parasitic delay of common gates
  - In multiples of p_{inv} ($\approx$1)

Gate type	Number of inputs				
	1	2	3	4	n
Inverter	1				
NAND		2	3	4	n
NOR		2	3	4	n
Tristate / mux	2	4	6	8	2n
XOR, XNOR		4	6	8	

Example: Ring Oscillator

- Estimate the frequency of an N-stage ring oscillator



Logical Effort:

Electrical Effort:

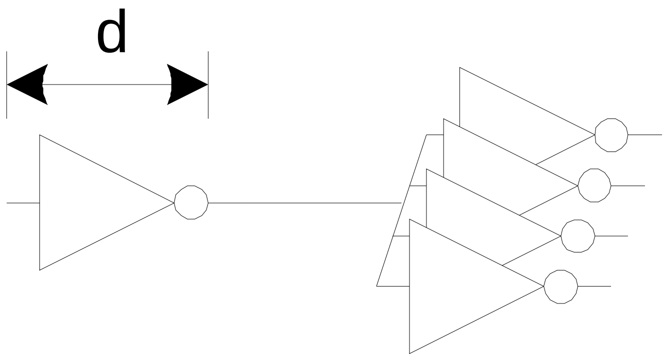
Parasitic Delay:

Stage Delay: d = 2

Frequency: $f_{osc} = 1/(2$

Example: FO4 Inverter

- Estimate the delay of a fanout-of-4 (FO4) inverter



Logical Effort:

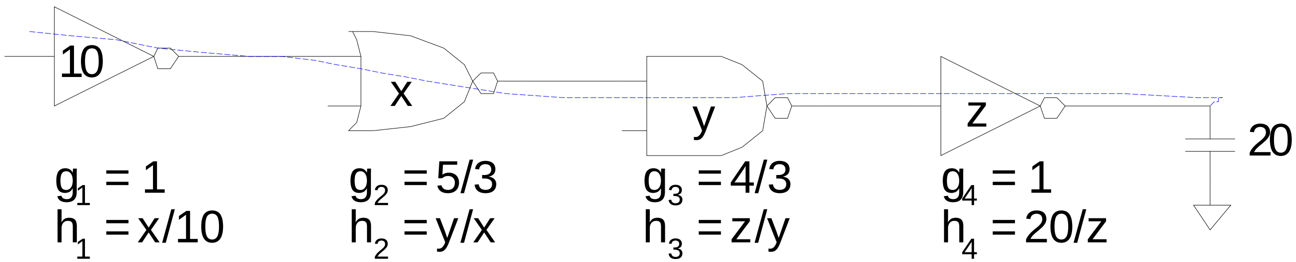
Electrical Effort:

Parasitic Delay:

Stage Delay: d = 5

Multistage Logic Networks

- Logical effort generalizes to multistage networks
- *Path Logical Effort* $$G = \prod g_i$$
- *Path Electrical Effort* $$H = \frac{C_{\text{out-path}}}{C_{\text{in-path}}}$$
- *Path Effort* $$F = \prod f_i = \prod g_i h_i$$



Multistage Logic Networks

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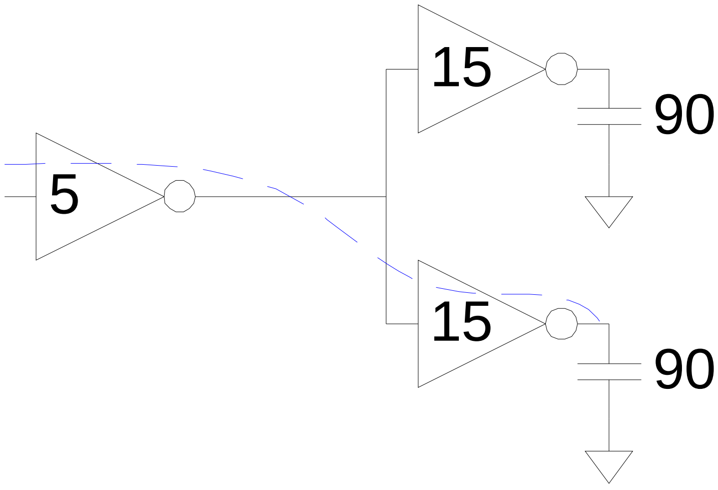
- *Path Effort* $$F = \prod f_i = \prod g_i h_i$$
- Can we write F = GH?

Paths that Branch

- No! Consider paths that branch:



G

H

GH

h_1

h_2

F $g_1 g_2 h_1 h_2$ 36 2GH

Branching Effort

- Introduce *branching effort*
  - Accounts for branching between stages in path

$$b = \frac{C_{\text{on path}} + C_{\text{off path}}}{C_{\text{on path}}}$$

$$B = \prod b_i$$

Note:

$$\prod h_i = BH$$

- Now we compute the path effort
  - F = GBH

Multistage Delays

- Path Effort Delay $D_F = \sum f_i$
- Path Parasitic Delay $P = \sum p_i$
- Path Delay $D = \sum d_i = D_F + P$

Designing Fast Circuits

$$D = \sum d_i = D_F + P$$

- Delay is smallest when each stage bears same effort

$$\hat{f} = g_i h_i = F^{\frac{1}{N}}$$

- Thus minimum delay of N stage path is

- This is a key result of logical effort
  - Find fastest possible delay
  - Doesn't require calculating gate sizes

Gate Sizes

- How wide should the gates be for least delay?

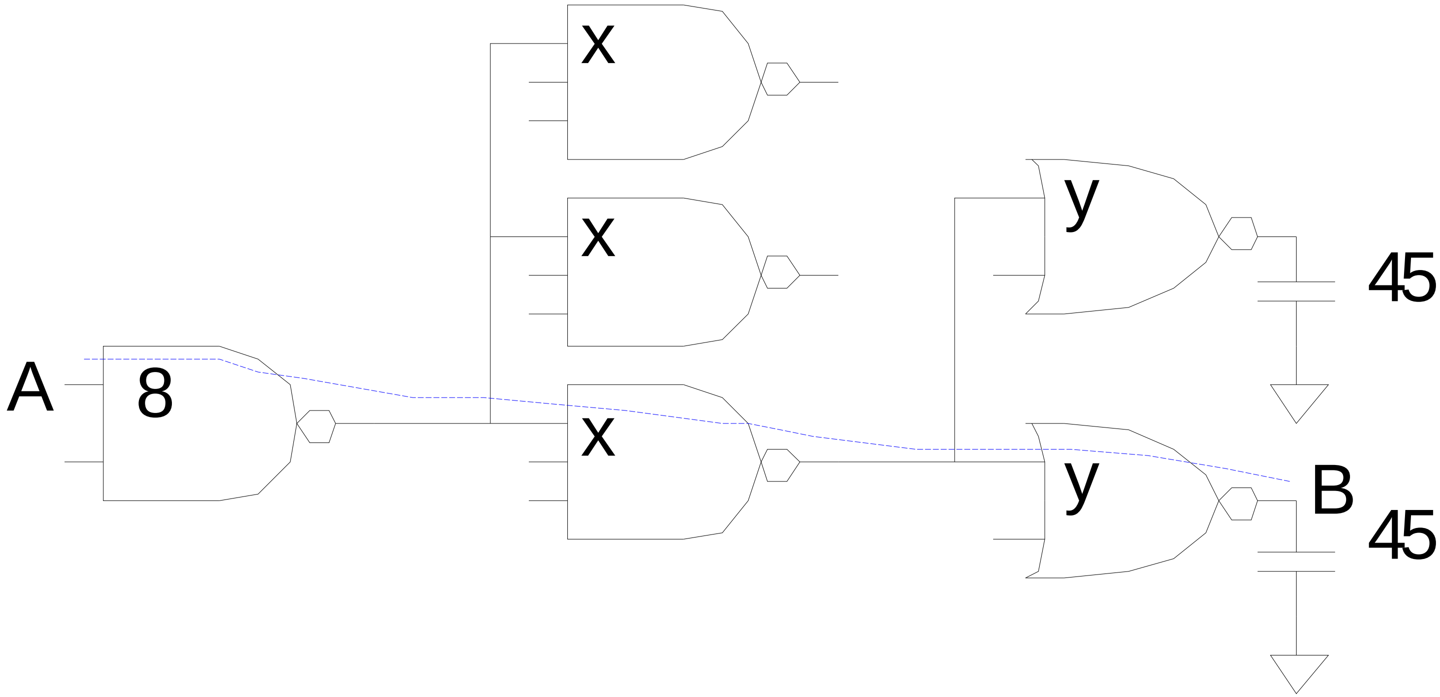
$$\hat{f} = gh = g\frac{C_{out}}{C_{in}}$$

$$\Rightarrow C_{in_i} = \frac{g_i C_{out_i}}{\hat{f}}$$

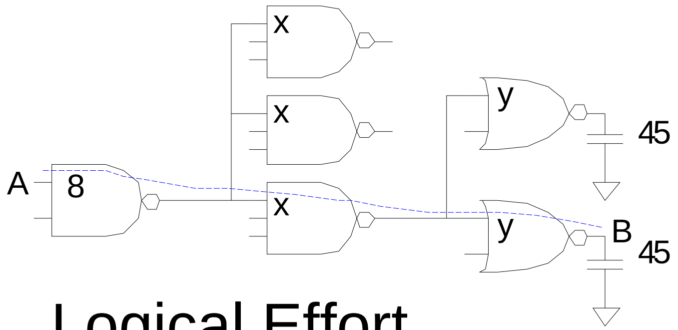
- Working backward, apply capacitance transformation to find input capacitance of each gate given load it drives.
- Check work by verifying input cap spec is met.

Example: 3-stage path

- Select gate sizes x and y for least delay from A to B



Example: 3-stage path



Logical Effort G
100/27

Electrical Effort H = 45/8

Branching Effort B = 3 * 2 =

Path Effort F

Best Stage Effort $\hat{f} =$

Parasitic Delay P = 2 + 3

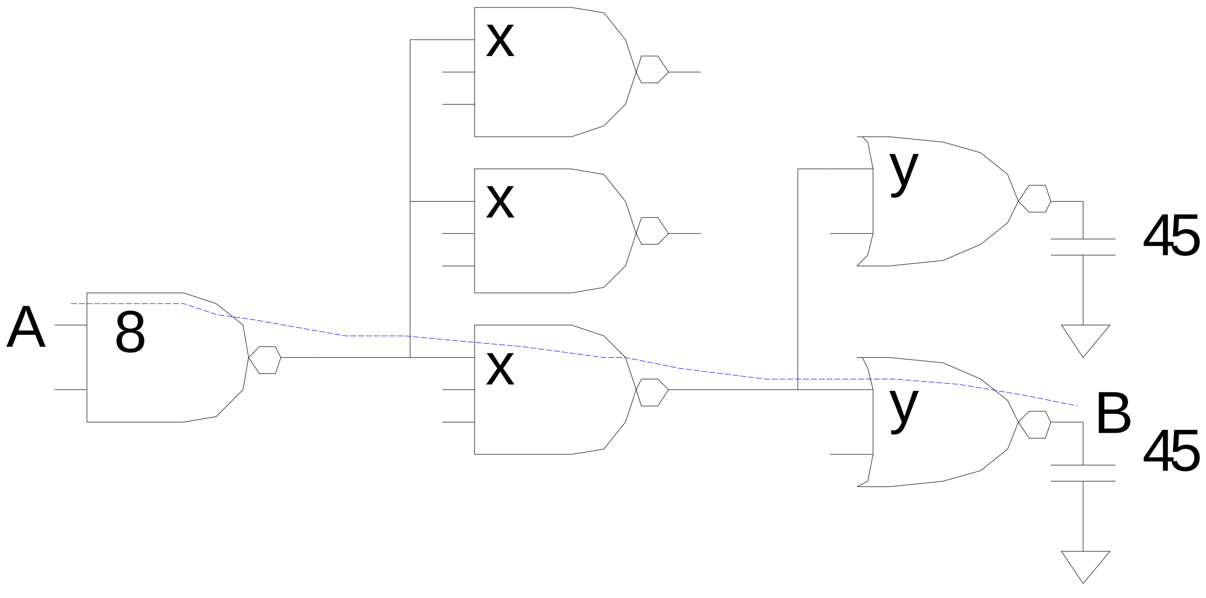
Delay D = 3*5 + 7 = 22 = …

Example: 3-stage path

- Work backward for sizes

  y =

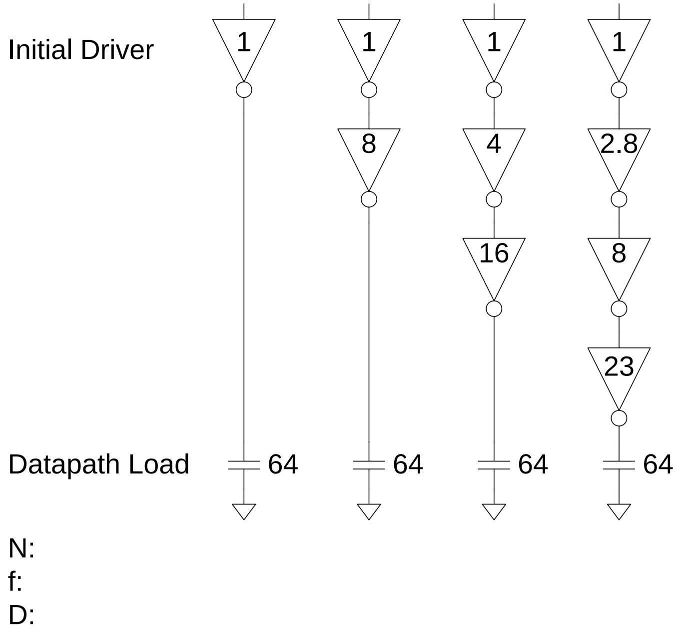
  x =



Best Number of Stages

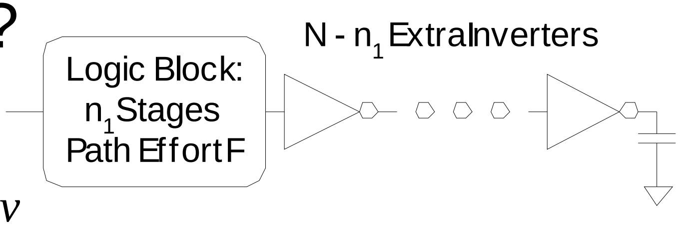
- How many stages should a path use?
  - Minimizing number of stages is not always fastest
- Example: drive 64-bit datapath with unit inverter

D



Derivation

- Consider adding inverters to end of path
  - How many give least delay?



$$D = NF^{\frac{1}{N}} + \sum_{i=1}^{n_1} p_i + (N - n_1) p_{inv}$$

$$\frac{\partial D}{\partial N} = -F^{\frac{1}{N}} \ln F^{\frac{1}{N}} + F^{\frac{1}{N}} + p_{inv} = 0$$

- Define best stage effort $\rho = F^{\frac{1}{N}}$

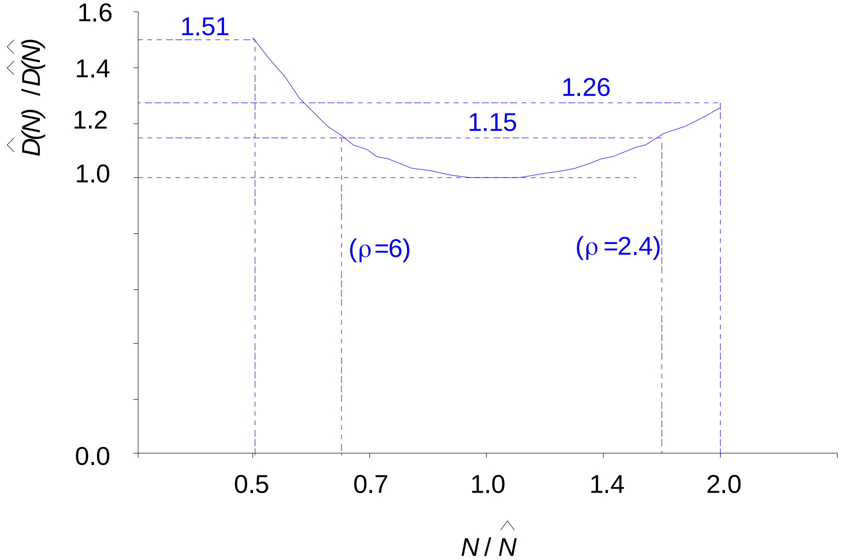
$$p_{inv} + \rho(1 - \ln \rho) = 0$$

Best Stage Effort

- $p_{inv} + \rho\left(1 - \ln\rho\right) = 0$ has no closed-form solution
- Neglecting parasitics (p_{inv} = 0), we find ρ = 2.718 (e)
- For p_{inv} = 1, solve numerically for ρ = 3.59

Sensitivity Analysis

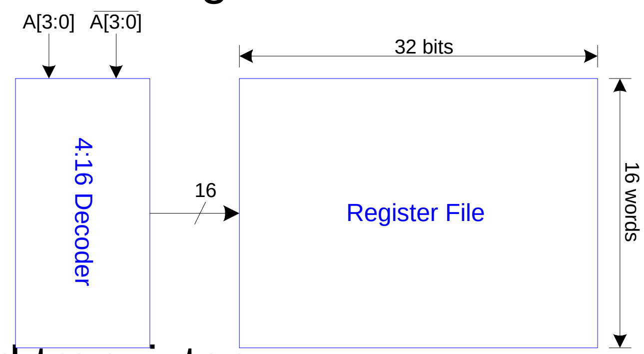
- How sensitive is delay to using exactly the best number of stages?



- 2.4 < ρ < 6 gives delay within 15% of optimal
  - We can be sloppy!
  - I like ρ = 4

Example, Revisited

- Ben Bitdiddle is the memory designer for the Motoroil 68W86, an embedded automotive processor. Help Ben design the decoder for a register file.



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- Ben needs to decide:
  - How many stages to use?
  - How large should each gate be?
  - How fast can decoder operate?

Number of Stages

- Decoder effort is mainly electrical and branching

  Electrical Effort: H 9.6

  Branching Effort: B

- If we neglect logical effort (assume G = 1)

  Path Effort: F = GB

  Number of Stages: N = log

- Try a -stage design

Gate Sizes & Delay

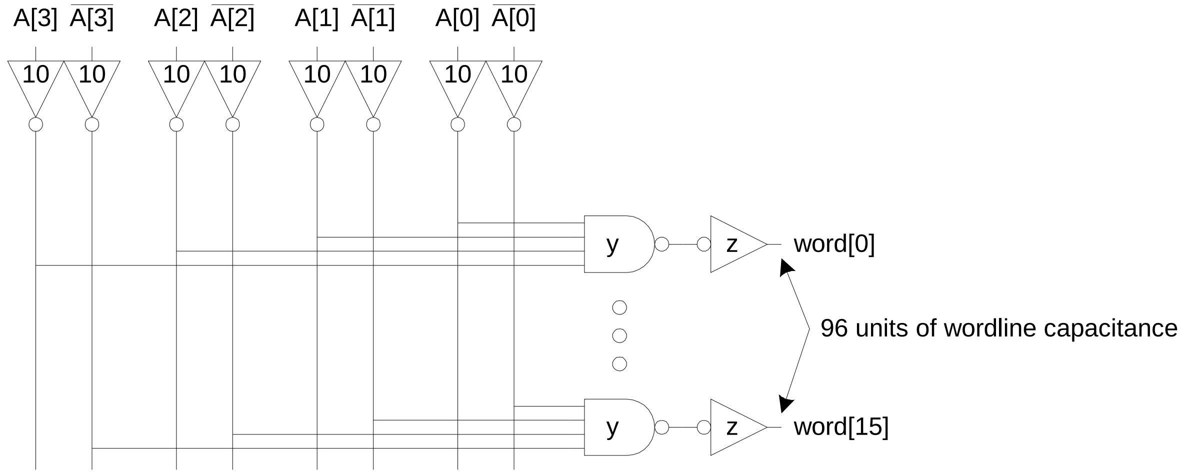
Logical Effort: (2

Path Effort: F = GB

Stage Effort: $\hat{f} =$

Path Delay: $D =$

Gate sizes: z = 96*1   = 18*2



Comparison

- Compare many alternatives with a spreadsheet
- $D = N(76.8\ G)^{1/N} + P$

Design	N	G	P	D
NOR4	1	3	4	234
NAND4-INV	2	2	5	29.8
NAND2-NOR2	2	20/9	4	30.1
INV-NAND4-INV	3	2	6	22.1
NAND4-INV-INV-INV	4	2	7	21.1
NAND2-NOR2-INV-INV	4	20/9	6	20.5
NAND2-INV-NAND2-INV	4	16/9	6	19.7
INV-NAND2-INV-NAND2-INV	5	16/9	7	20.4
NAND2-INV-NAND2-INV-INV-INV	6	16/9	8	21.6

Review of Definitions

Term	Stage	Path
number of stages	1	N
logical effort	g	$G = \prod g_i$
electrical effort	$h = \frac{C_{\text{out}}}{C_{\text{in}}}$	$H = \frac{C_{\text{out-path}}}{C_{\text{in-path}}}$
branching effort	$b = \frac{C_{\text{on-path}} + C_{\text{off-path}}}{C_{\text{on-path}}}$	$B = \prod b_i$
effort	$f = gh$	$F = GBH$
effort delay	f	$D_F = \sum f_i$
parasitic delay	p	$P = \sum p_i$
delay	$d = f + p$	$D = \sum d_i = D_F + P$

Method of Logical Effort

1) Compute path effort $F = GBH$
2) Estimate best number of stages $N = \log_4 F$
3) Sketch path with N stages
4) Estimate least delay $D = NF^{\frac{1}{N}} + P$
5) Determine best stage effort $\hat{f} = F^{\frac{1}{N}}$
6) Find gate sizes $C_{in_i} = \frac{g_i C_{out_i}}{\hat{f}}$

Limits of Logical Effort

- Chicken and egg problem
  - Need path to compute G
  - But don't know number of stages without G
- Simplistic delay model
  - Neglects input rise time effects
- Interconnect
  - Iteration required in designs with wire
- Maximum speed only
  - Not minimum area/power for constrained delay

Summary

- Logical effort is useful for thinking of delay in circuits
  - Numeric logical effort characterizes gates
  - NANDs are faster than NORs in CMOS
  - Paths are fastest when effort delays are ~4
  - Path delay is weakly sensitive to stages, sizes
  - But using fewer stages doesn't mean faster paths
  - Delay of path is about $\log_4 F$ FO4 inverter delays
  - Inverters and NAND2 best for driving large caps
- Provides language for discussing fast circuits
  - But requires practice to master