Mar. 3

View 4 - custom chips

1) On chip macros
   - grand std cell
   - block RAMs
   - M9K, M10K

2) synthesized from verilog
   - SM cells
   - CLBs, LUTs
   - NAND, FF, ...

3) Off-chip
   - very large
   - flash
   - ...

Verilog:

Declare Ex: 16-bit, 128-word

```verilog
reg [15:0] mem [0:127];
```

Read port (combinatorial)

```verilog
source1 = mem [addr 3d];
```

16 x huge mux tree
Write port

\[ \text{Mem[addr\_wr]} \leftarrow \#1 \text{ data\_path\_c} ; \]

7-bit

Synchronous level

RD: memory

\[ \text{clk} \]

\[ \text{clk} \]
Fourier Transform

\( f(x) \) "time" domain

\( \mathcal{F}(\cdot) \) "frequency" domain

\[
\begin{align*}
\mathcal{F}(f) &= \int_{-\infty}^{\infty} f(x) e^{-i 2\pi \xi x} \, dx \\
\mathcal{F}^{-1}(\cdot) &= \int_{-\infty}^{\infty} f(x) e^{i 2\pi \xi x} \, dx
\end{align*}
\]

Discrete Fourier Transform (DFT)

\[
X(k) = \sum_{n=0}^{N-1} x(n) e^{-i 2\pi nk/N}, \quad k = 0, 1, \ldots, N-1
\]

Both \( x(n) \) and \( X(k) \) are length \( N \)

\[
x(n) = \frac{1}{N} \sum_{k=0}^{N-1} X(k) e^{i 2\pi nk/N}, \quad n = 0, 1, \ldots, N-1
\]

\[
W_N = e^{-i 2\pi / N}
\]

\[
= \cos \left( \frac{2\pi}{N} \right) - i \sin \left( \frac{2\pi}{N} \right)
\]

\[
X(k) = \sum_{n=0}^{N-1} x(n) W_N^{nk}
\]
$W_N$ is constant for a particular $N$

$W_N = N^{1/2}$ at unity

$W_N^n = 1$

\[
\chi(k) = \sum_{n=0}^{N-1} x(n) W_N^{nk}
\]

N output \quad N-1 \quad N inputs

DFT requires $O(N^2)$ calculations

same for IDFT

Fast Fourier Transform (FFT)

Cooley and Tukey, 1965 - read on web page

Calculates the same result as the DFT

$O(N \log N)$

Ex: $N = 1$ million

DFT \quad $10^7$ ops \quad 19.4 hours

FFT \quad $2 \times 10^7$ ops \quad 1 sec

$5 \times 10^6 \times$ speedup!
Bench Fg

- \( x = A + BW \)
- \( y = A - BW \)

Radix 2, D5666365 in Time (DIF)

- Input bit reversed

X

\( x, y, r_i \)

Re-AxKZ, Dec., in Frg. (DIF)

- Output bit reversed

\( x = A + B \)

\( y = (A - B) W \)
Dominic, MIT

A
B
C
D

Diagram of connections between A, B, C, and D.