



# The Systolic Ring: A Scalable Dynamically Reconfigurable Core for Embedded Systems

Pascal Benoit, Gilles Sassatelli, Michel Robert, Lionel Torres, Gaston Cambon, Thierry Gil

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# Application example - DCT 2D 8\*8

## 64\*64 image example - Comparisons

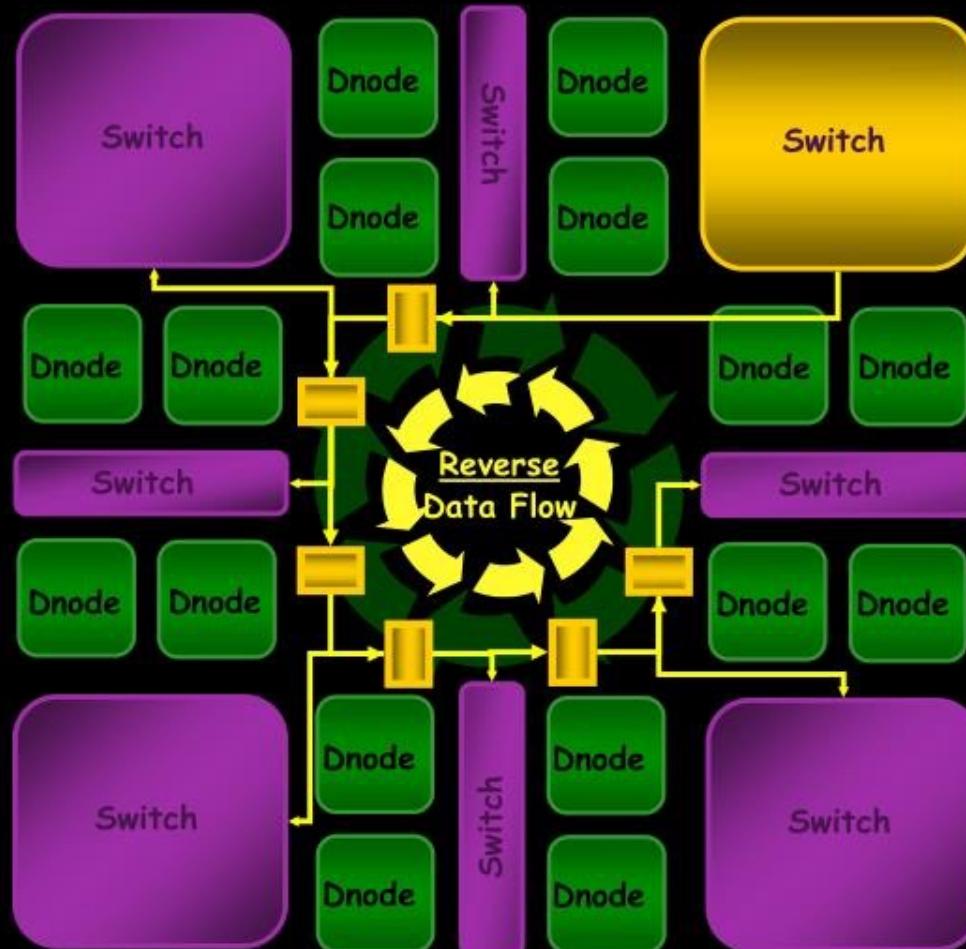
|                 | Pentium IV<br>Intel | DCT Core<br>Xilinx        | TMS320C62<br>TI | RING-16                     | RING-64 |
|-----------------|---------------------|---------------------------|-----------------|-----------------------------|---------|
| Cycles #        | 21248               | 4171                      | 10240           | 5120                        | 1280    |
| f (MHz)         | 1200                | 80*                       | 300             | 200                         | 200     |
| Proc. Time (μs) | 17.7                | 52.1                      | 34.1            | 12.8                        | 6.4     |
| Comment         | SSE2                | *Device dependant         | Matrix          | Even-Odd decomposition      |         |
| Type            | Super scalar        | Fine Grain Reconfigurable | VLIW            | Coarse Grain Reconfigurable |         |



Only Processing time !!

# The Systolic Ring - Operative Layer Topology

## Data Flows



### Forward Data Flow

Unidirectional data transit between successive layers (circular pipeline)

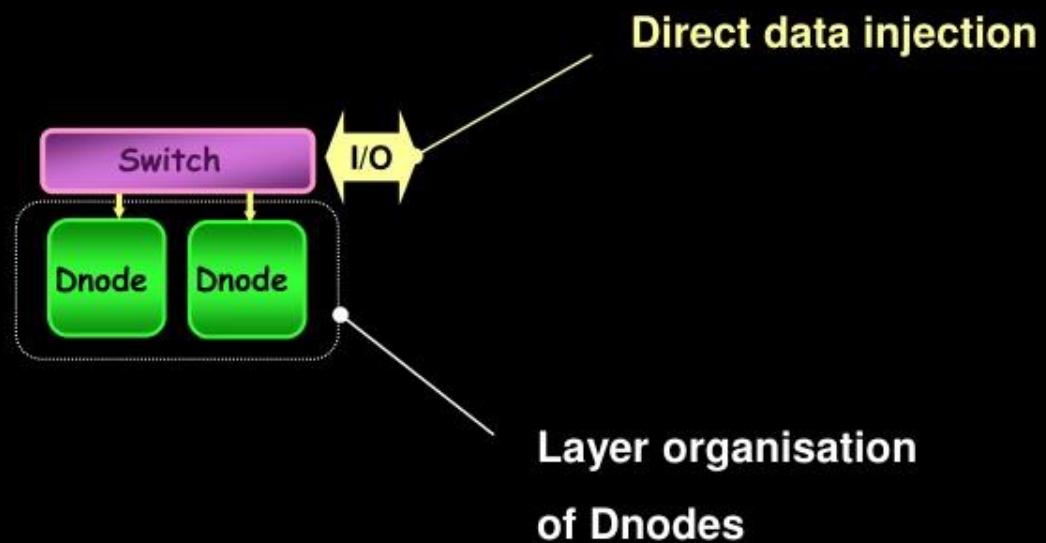
### Reverse Data Flow

Feedback pipeline network  
for recursive algorithms

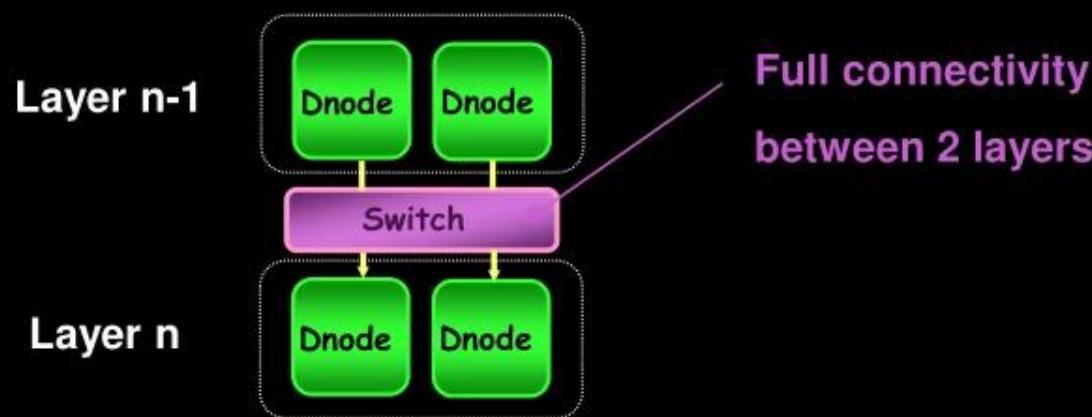
# The Systolic Ring - Dnode Clusters

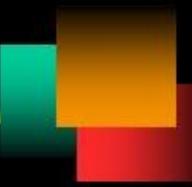


## Macro Node



# The Systolic Ring - Switch components

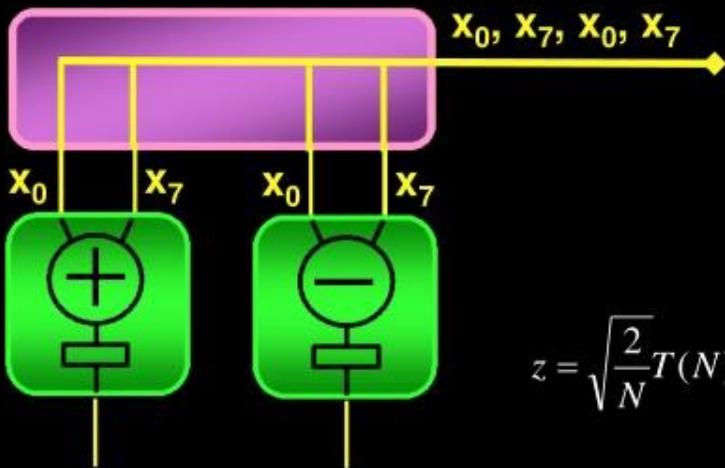




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Thank You

# Application example - 8\*8 2D DCT



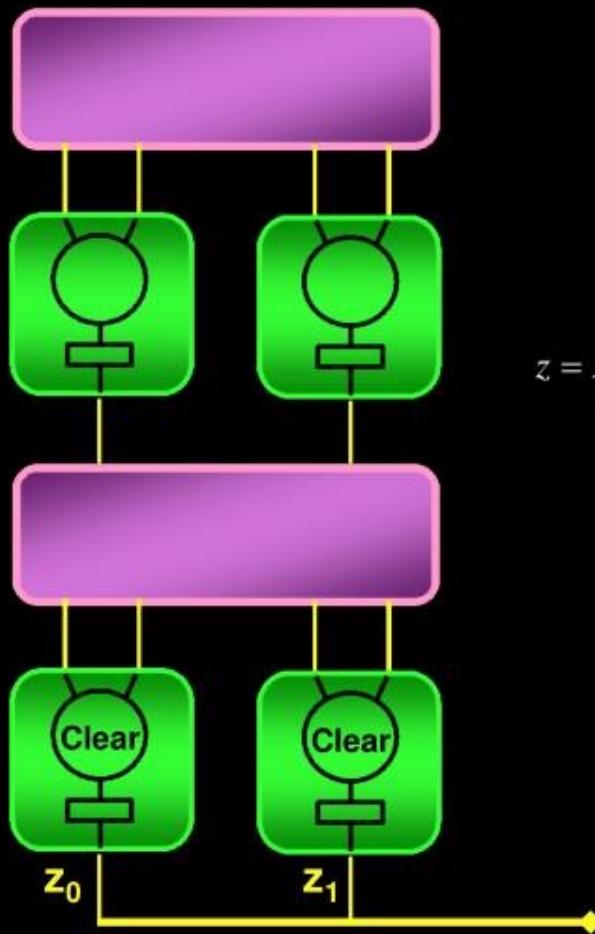
Cycle 0

$$z = \sqrt{\frac{2}{N}} T(N)x$$

$$\begin{cases} \begin{bmatrix} z_0 \\ z_2 \\ z_4 \\ z_6 \end{bmatrix} = \begin{bmatrix} 1/\sqrt{8} & 1/\sqrt{8} & 1/\sqrt{8} & 1/\sqrt{8} \\ \beta & \delta & -\delta & -\beta \\ \alpha & -\alpha & -\alpha & \alpha \\ \delta & -\beta & \beta & -\delta \end{bmatrix} \begin{bmatrix} x_0 + x_7 \\ x_1 + x_6 \\ x_2 + x_5 \\ x_3 + x_4 \end{bmatrix} & \left\{ \begin{array}{l} \alpha = 1/2 \cos(\pi/4) \\ \beta = 1/2 \cos(\pi/8) \\ \delta = 1/2 \sin(\pi/8) \end{array} \right. \\ \begin{bmatrix} z_1 \\ z_3 \\ z_5 \\ z_7 \end{bmatrix} = \begin{bmatrix} \lambda & \gamma & \mu & \nu \\ \gamma & -\nu & -\lambda & -\mu \\ \mu & -\lambda & \nu & \gamma \\ \nu & -\mu & \gamma & -\lambda \end{bmatrix} \begin{bmatrix} x_0 - x_7 \\ x_1 - x_6 \\ x_2 - x_5 \\ x_3 - x_4 \end{bmatrix} & \left\{ \begin{array}{l} \lambda = 1/2 \cos(\pi/16) \\ \gamma = 1/2 \cos(3\pi/16) \\ \mu = 1/2 \sin(3\pi/16) \\ \nu = 1/2 \sin(\pi/16) \end{array} \right. \end{cases}$$

# Application example - 8\*8 2D DCT

Cycle 5



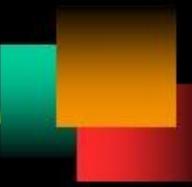
$$z = \sqrt{\frac{2}{N}} T(N)x \quad \left\{ \begin{array}{l} \begin{bmatrix} z_0 \\ z_2 \\ z_4 \\ z_6 \end{bmatrix} = \begin{bmatrix} 1/\sqrt{8} & 1/\sqrt{8} & 1/\sqrt{8} & 1/\sqrt{8} \\ \beta & \delta & -\delta & -\beta \\ \alpha & -\alpha & -\alpha & \alpha \\ \delta & -\beta & \beta & -\delta \end{bmatrix} \begin{bmatrix} x_0 + x_7 \\ x_1 + x_6 \\ x_2 + x_5 \\ x_3 + x_4 \end{bmatrix} \quad \left\{ \begin{array}{l} \alpha = 1/2 \cos(\pi/4) \\ \beta = 1/2 \cos(\pi/8) \\ \delta = 1/2 \sin(\pi/8) \end{array} \right. \\ \begin{bmatrix} z_1 \\ z_3 \\ z_5 \\ z_7 \end{bmatrix} = \begin{bmatrix} \lambda & \gamma & \mu & \nu \\ \gamma & -\nu & -\lambda & -\mu \\ \mu & -\lambda & \nu & \gamma \\ \nu & -\mu & \gamma & -\lambda \end{bmatrix} \begin{bmatrix} x_0 - x_7 \\ x_1 - x_6 \\ x_2 - x_5 \\ x_3 - x_4 \end{bmatrix} \quad \left\{ \begin{array}{l} \lambda = 1/2 \cos(\pi/16) \\ \gamma = 1/2 \cos(3\pi/16) \\ \mu = 1/2 \sin(3\pi/16) \\ \nu = 1/2 \sin(\pi/16) \end{array} \right. \end{array} \right.$$

2 transformed samples  
computed each 5 clock cycles



8\*8 2D transformed samples each 320 clock cycles

# Conclusion



## ■ DESIGN

- ➔ Reconfigurable IP Core for SoC
- ➔ Assembling Software
- ➔ RING-8 prototype

## ■ FEATURES

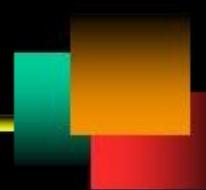
- ➔ Customisable IP Core
- ➔ Good performance / area trade-off : *Ring-8@200MHz (0.18μ)*

3.3 mm<sup>2</sup>

1600 MIPS

Results for DCT, Wavelet Transform, Motion Estimation

# Application example - 8\*8 2D DCT



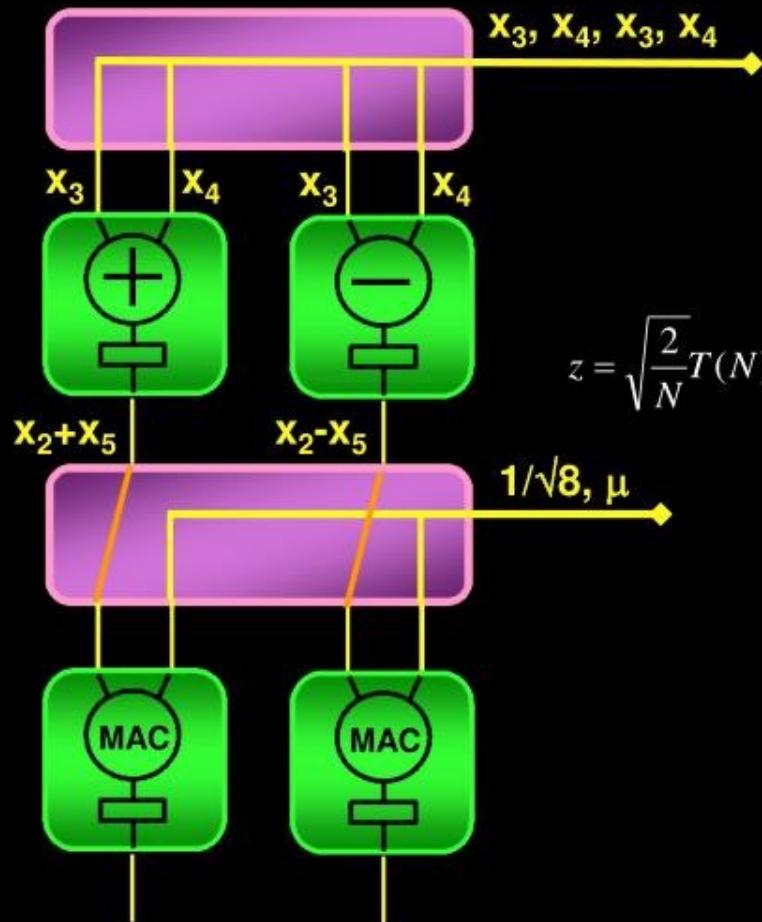
## Even-Odd frequency decomposition

$$z = \sqrt{\frac{2}{N}} T(N)x$$
$$\left\{ \begin{array}{l} \left[ \begin{array}{c} z_0 \\ z_2 \\ z_4 \\ z_6 \end{array} \right] = \left[ \begin{array}{cccc} 1/\sqrt{8} & 1/\sqrt{8} & 1/\sqrt{8} & 1/\sqrt{8} \\ \beta & \delta & -\delta & -\beta \\ \alpha & -\alpha & -\alpha & \alpha \\ \delta & -\beta & \beta & -\delta \end{array} \right] \left[ \begin{array}{c} x_0 + x_7 \\ x_1 + x_6 \\ x_2 + x_5 \\ x_3 + x_4 \end{array} \right] \\ \left[ \begin{array}{c} z_1 \\ z_3 \\ z_5 \\ z_7 \end{array} \right] = \left[ \begin{array}{cccc} \lambda & \gamma & \mu & \nu \\ \gamma & -\nu & -\lambda & -\mu \\ \mu & -\lambda & \nu & \gamma \\ \nu & -\mu & \gamma & -\lambda \end{array} \right] \left[ \begin{array}{c} x_0 - x_7 \\ x_1 - x_6 \\ x_2 - x_5 \\ x_3 - x_4 \end{array} \right] \end{array} \right\}$$
$$\left\{ \begin{array}{l} \alpha = 1/2 \cos(\pi/4) \\ \beta = 1/2 \cos(\pi/8) \\ \delta = 1/2 \sin(\pi/8) \\ \\ \lambda = 1/2 \cos(\pi/16) \\ \gamma = 1/2 \cos(3\pi/16) \\ \mu = 1/2 \sin(3\pi/16) \\ \nu = 1/2 \sin(\pi/16) \end{array} \right.$$

Independent Matrix Products (//)

# Application example - 8\*8 2D DCT

Cycle 3



$$z = \sqrt{\frac{2}{N}} T(N)x$$

$$\left\{ \begin{array}{l} \begin{bmatrix} z_0 \\ z_2 \\ z_4 \\ z_6 \end{bmatrix} = \begin{bmatrix} 1/\sqrt{8} & 1/\sqrt{8} & 1/\sqrt{8} & 1/\sqrt{8} \\ \beta & \delta & -\delta & -\beta \\ \alpha & -\alpha & -\alpha & \alpha \\ \delta & -\beta & \beta & -\delta \end{bmatrix} \begin{bmatrix} x_0 + x_7 \\ x_1 + x_6 \\ x_2 + x_5 \\ x_3 + x_4 \end{bmatrix} \\ \begin{bmatrix} z_1 \\ z_3 \\ z_5 \\ z_7 \end{bmatrix} = \begin{bmatrix} \lambda & \gamma & \mu & \nu \\ \gamma & -\nu & -\lambda & -\mu \\ \mu & -\lambda & \nu & \gamma \\ \nu & -\mu & \gamma & -\lambda \end{bmatrix} \begin{bmatrix} x_0 - x_7 \\ x_1 - x_6 \\ x_2 - x_5 \\ x_3 - x_4 \end{bmatrix} \end{array} \right. \quad \left. \begin{array}{l} \alpha = 1/2 \cos(\pi/4) \\ \beta = 1/2 \cos(\pi/8) \\ \delta = 1/2 \sin(\pi/8) \\ \lambda = 1/2 \cos(\pi/16) \\ \gamma = 1/2 \cos(3\pi/16) \\ \mu = 1/2 \sin(3\pi/16) \\ \nu = 1/2 \sin(\pi/16) \end{array} \right.$$

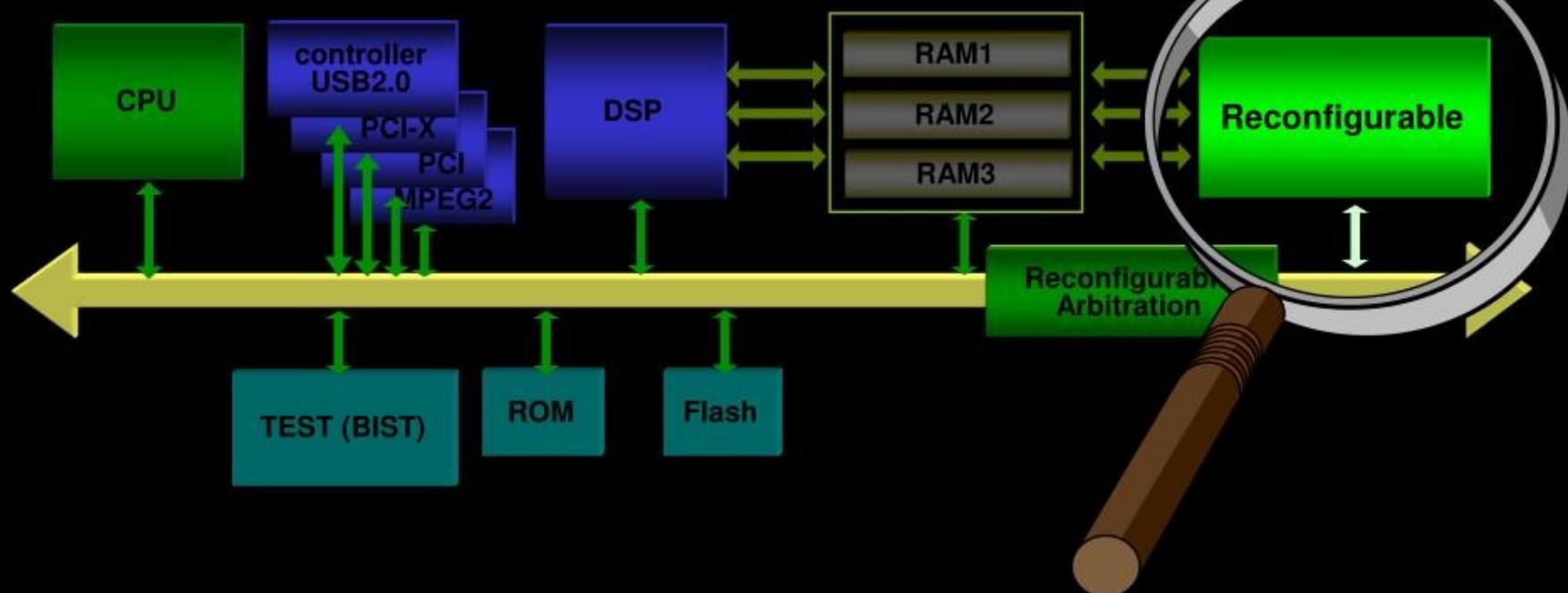
# Introduction



## Multimedia

Data flow oriented applications

**RECONFIGURATION**  
HARDWARE Static / Dynamic



# Introduction



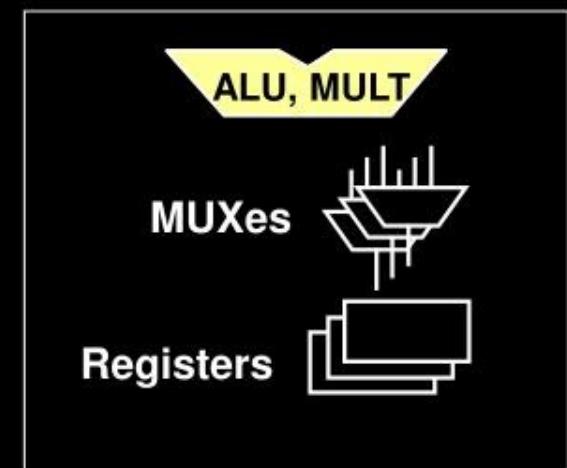
What kind of base block is suitable for Multimedia?

- **Coarse Grain:**

- Granularity: WORD

- adapted to DSP, data flow oriented processing

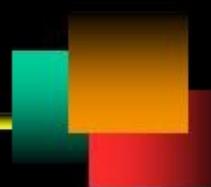
**SYSTOLIC  
RING**



Coarse Grain  
Dynamically Reconfigurable  
Architecture

- Low reconfiguration over-cost
- High level of performances

# Outline



## The Systolic Ring : A Scalable Dynamically Reconfigurable Core for Embedded Systems

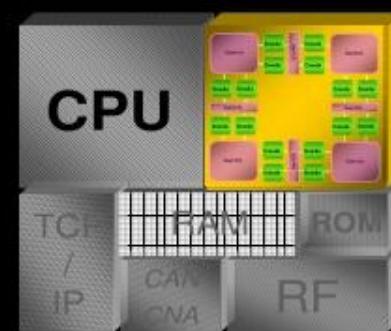
### ■ The Systolic Ring

- Building Block
- Operative Layer Topology
- System Overview
- Features

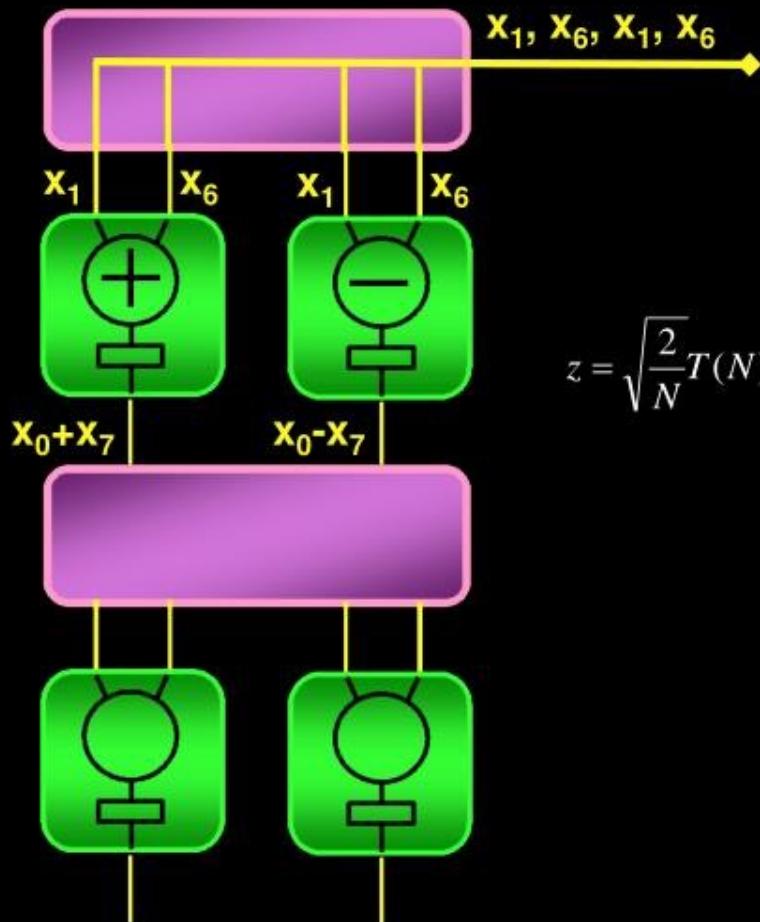
### ■ Application Example

- 8\*8 2D DCT
- Structural Mapping
- Performance Comparisons

### ■ Conclusion



# Application example - 8\*8 2D DCT



$$z = \sqrt{\frac{2}{N}} T(N)x$$

$$\begin{bmatrix} z_0 \\ z_2 \\ z_4 \\ z_6 \end{bmatrix} = \begin{bmatrix} 1/\sqrt{8} & 1/\sqrt{8} & 1/\sqrt{8} & 1/\sqrt{8} \\ \beta & \delta & -\delta & -\beta \\ \alpha & -\alpha & -\alpha & \alpha \\ \delta & -\beta & \beta & -\delta \end{bmatrix} \begin{bmatrix} x_0 + x_7 \\ x_1 + x_6 \\ x_2 + x_5 \\ x_3 + x_4 \end{bmatrix}$$

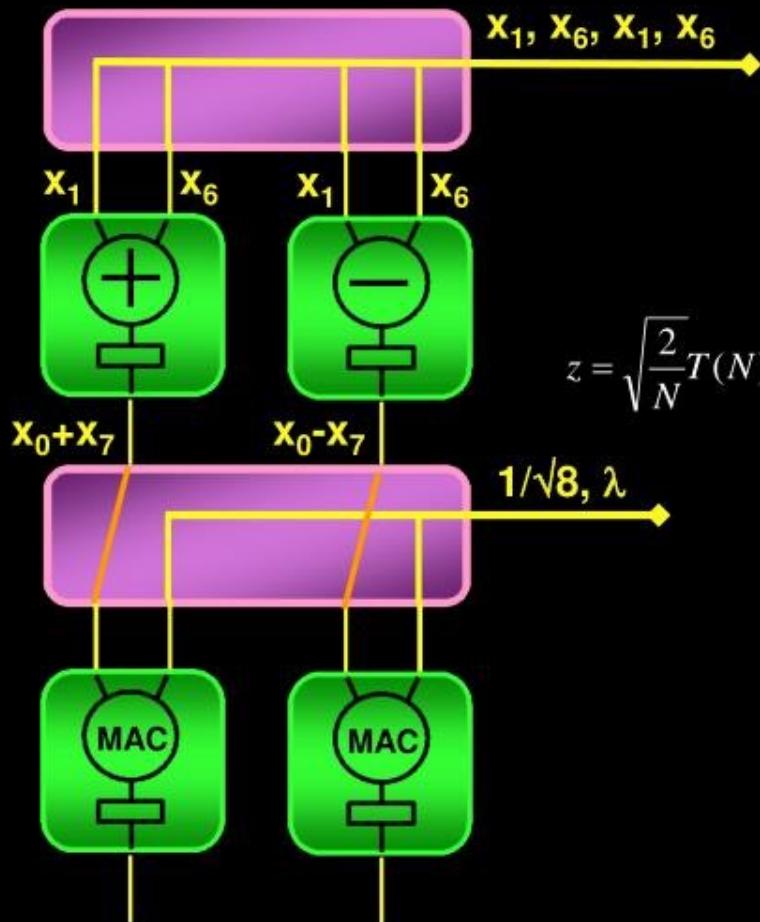
$$\left\{ \begin{array}{l} \alpha = 1/2 \cos(\pi/4) \\ \beta = 1/2 \cos(\pi/8) \\ \delta = 1/2 \sin(\pi/8) \end{array} \right.$$
  

$$\begin{bmatrix} z_1 \\ z_3 \\ z_5 \\ z_7 \end{bmatrix} = \begin{bmatrix} \lambda & \gamma & \mu & \nu \\ \gamma & -\nu & -\lambda & -\mu \\ \mu & -\lambda & \nu & \gamma \\ \nu & -\mu & \gamma & -\lambda \end{bmatrix} \begin{bmatrix} x_0 + x_7 \\ x_1 + x_6 \\ x_2 + x_5 \\ x_3 + x_4 \end{bmatrix}$$

$$\left\{ \begin{array}{l} \lambda = 1/2 \cos(\pi/16) \\ \gamma = 1/2 \cos(3\pi/16) \\ \mu = 1/2 \sin(3\pi/16) \\ \nu = 1/2 \sin(\pi/16) \end{array} \right.$$

Raw-Column product  $\rightarrow$  MAC operations

# Application example - 8\*8 2D DCT

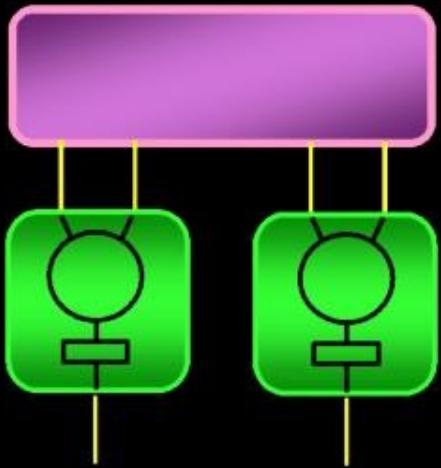


$$z = \sqrt{\frac{2}{N}} T(N) x$$

Cycle 1

$$\left\{ \begin{array}{l} \begin{aligned} \begin{bmatrix} z_0 \\ z_2 \\ z_4 \\ z_6 \end{bmatrix} &= \begin{bmatrix} 1/\sqrt{8} & 1/\sqrt{8} & 1/\sqrt{8} & 1/\sqrt{8} \\ \beta & \delta & -\delta & -\beta \\ \alpha & -\alpha & -\alpha & \alpha \\ \delta & -\beta & \beta & -\delta \end{bmatrix} \begin{bmatrix} x_0 + x_7 \\ x_1 + x_6 \\ x_2 + x_5 \\ x_3 + x_4 \end{bmatrix} \\ \begin{bmatrix} z_1 \\ z_3 \\ z_5 \\ z_7 \end{bmatrix} &= \begin{bmatrix} \lambda & \gamma & \mu & \nu \\ \gamma & -\nu & -\lambda & -\mu \\ \mu & -\lambda & \nu & \gamma \\ \nu & -\mu & \gamma & -\lambda \end{bmatrix} \begin{bmatrix} x_0 - x_7 \\ x_1 - x_6 \\ x_2 - x_5 \\ x_3 - x_4 \end{bmatrix} \end{aligned} \end{array} \right. \begin{array}{l} \left. \begin{aligned} \alpha &= 1/2 \cos(\pi/4) \\ \beta &= 1/2 \cos(\pi/8) \\ \delta &= 1/2 \sin(\pi/8) \end{aligned} \right. \\ \left. \begin{aligned} \lambda &= 1/2 \cos(\pi/16) \\ \gamma &= 1/2 \cos(3\pi/16) \\ \mu &= 1/2 \sin(3\pi/16) \\ \nu &= 1/2 \sin(\pi/16) \end{aligned} \right. \end{array}$$

# Application example - 8\*8 2D DCT

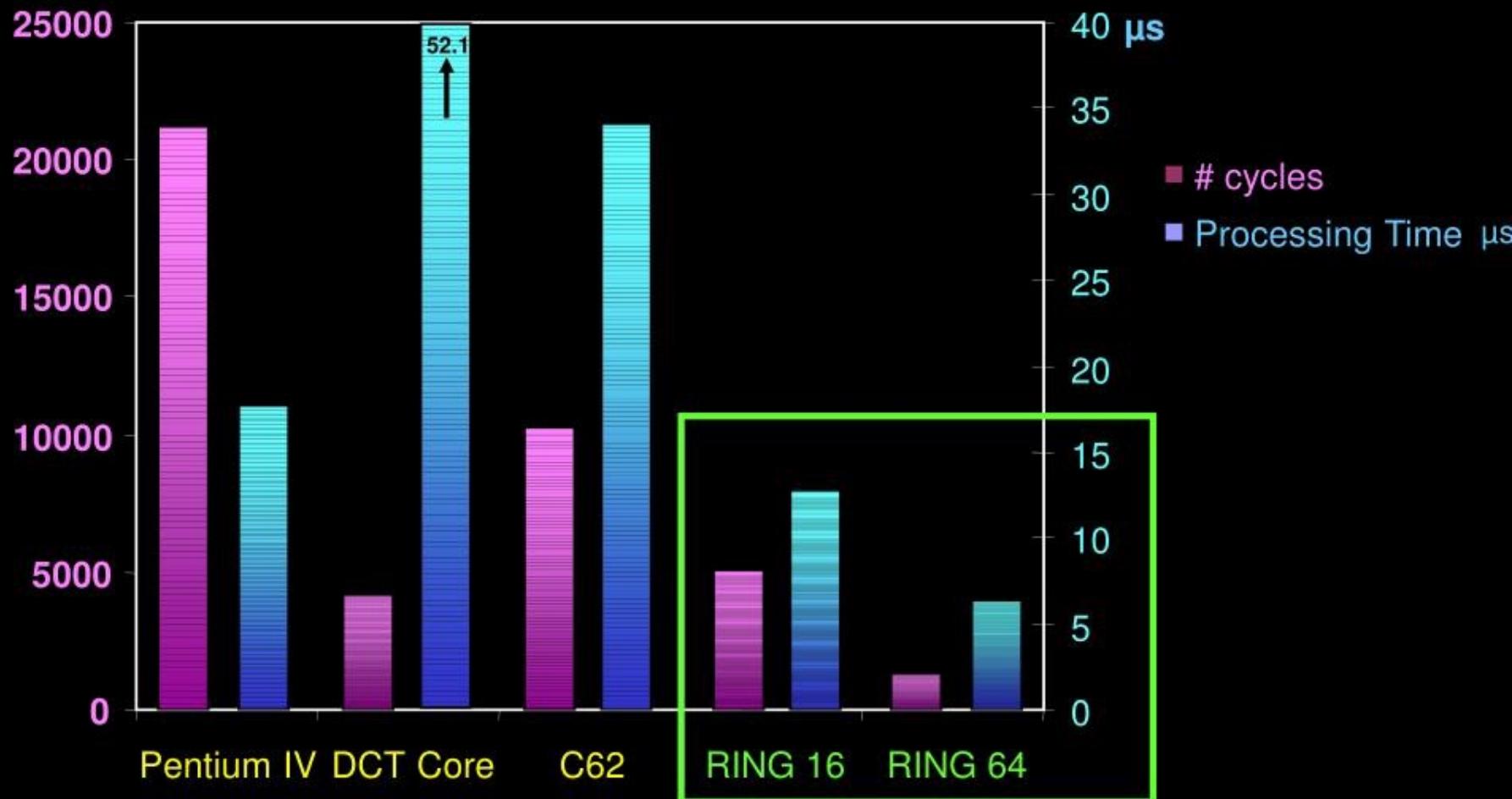


Addition & Subtraction of image samples

$$z = \sqrt{\frac{2}{N}} T(N)x$$
$$\begin{bmatrix} z_0 \\ z_2 \\ z_4 \\ z_6 \end{bmatrix} = \begin{bmatrix} 1/\sqrt{8} & 1/\sqrt{8} & 1/\sqrt{8} & 1/\sqrt{8} \\ \beta & \delta & -\delta & -\beta \\ \alpha & -\alpha & -\alpha & \alpha \\ \delta & -\beta & \beta & -\delta \end{bmatrix} \begin{bmatrix} x_0 + x_7 \\ x_1 + x_6 \\ x_2 + x_5 \\ x_3 + x_4 \end{bmatrix}$$
$$\left\{ \begin{array}{l} \alpha = 1/2 \cos (\pi/4) \\ \beta = 1/2 \cos (\pi/8) \\ \delta = 1/2 \sin (\pi/8) \end{array} \right.$$
$$\begin{bmatrix} z_1 \\ z_3 \\ z_5 \\ z_7 \end{bmatrix} = \begin{bmatrix} \lambda & \gamma & \mu & \nu \\ \gamma & -\nu & -\lambda & -\mu \\ \mu & -\lambda & \nu & \gamma \\ \nu & -\mu & \gamma & -\lambda \end{bmatrix} \begin{bmatrix} x_0 - x_7 \\ x_1 - x_6 \\ x_2 - x_5 \\ x_3 - x_4 \end{bmatrix}$$
$$\left\{ \begin{array}{l} \lambda = 1/2 \cos (\pi/16) \\ \gamma = 1/2 \cos (3\pi/16) \\ \mu = 1/2 \sin (3\pi/16) \\ \nu = 1/2 \sin (\pi/16) \end{array} \right.$$

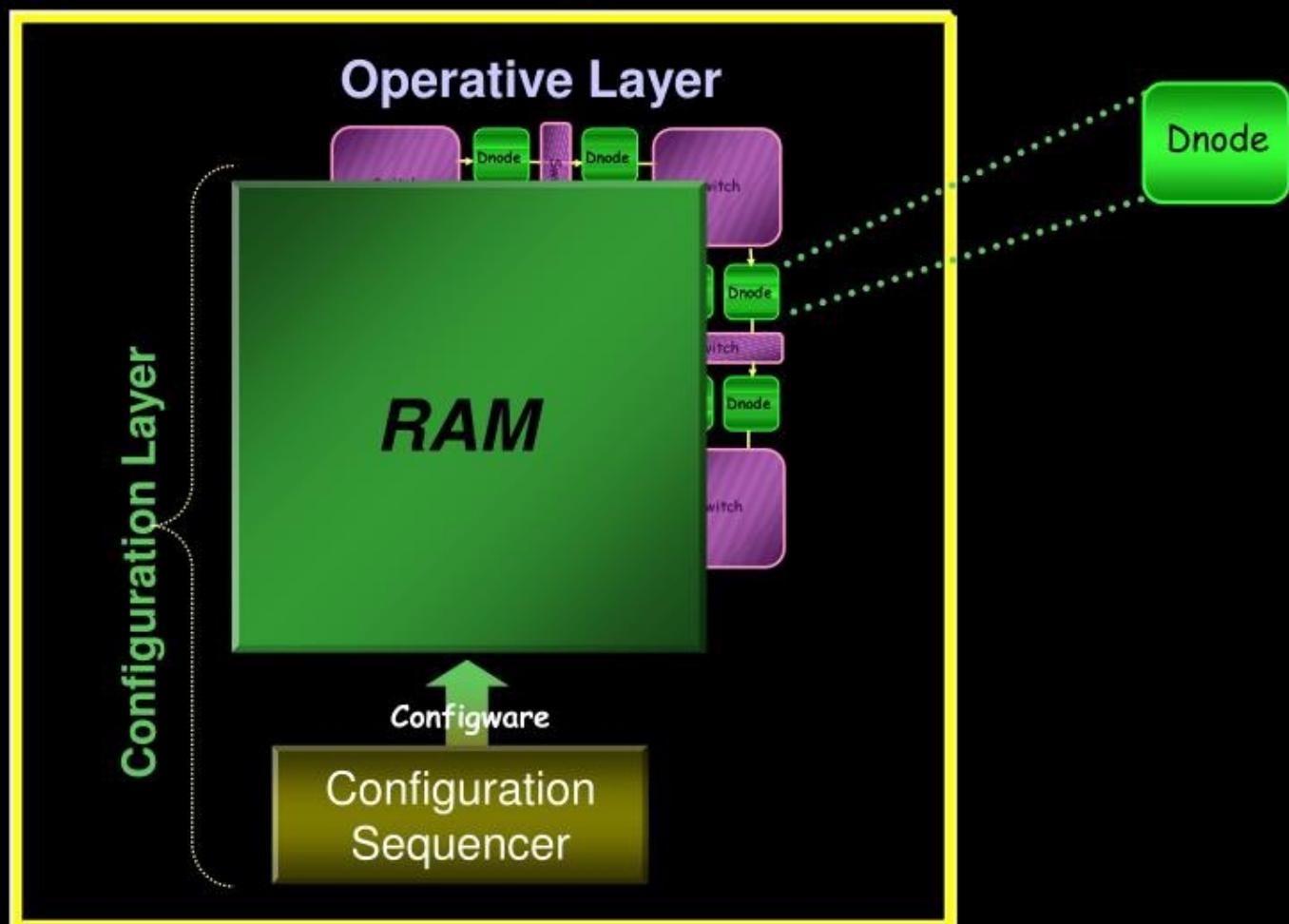
# Application example - DCT 2D 8\*8

## 64\*64 image example - Comparisons



# The Systolic Ring - System Overview

Two-layers based reconfigurable architecture

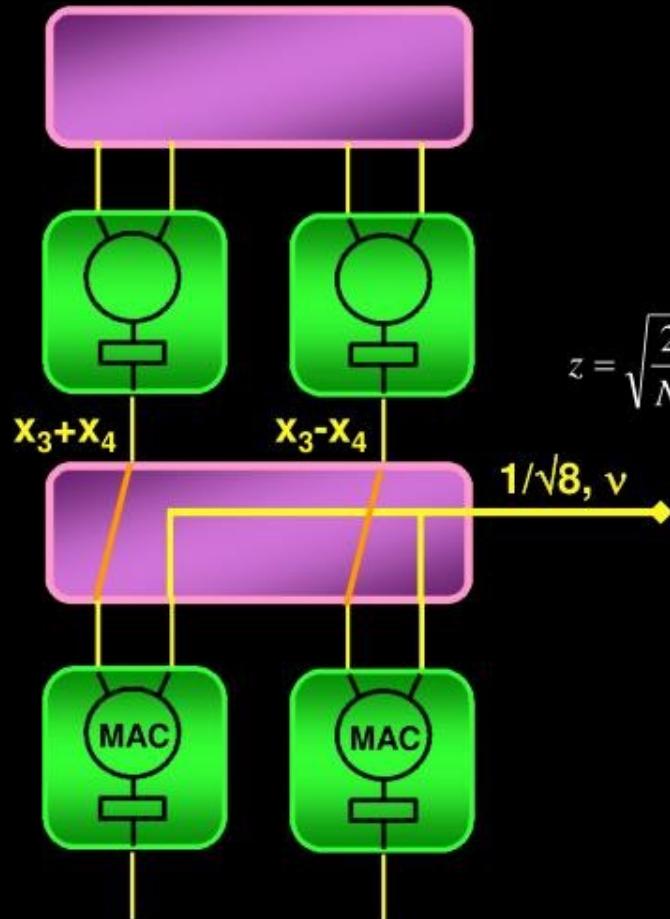


Coarse Grain Dynamically  
Reconfigurable Architecture

# Application example - 8\*8 2D DCT



Cycle 4



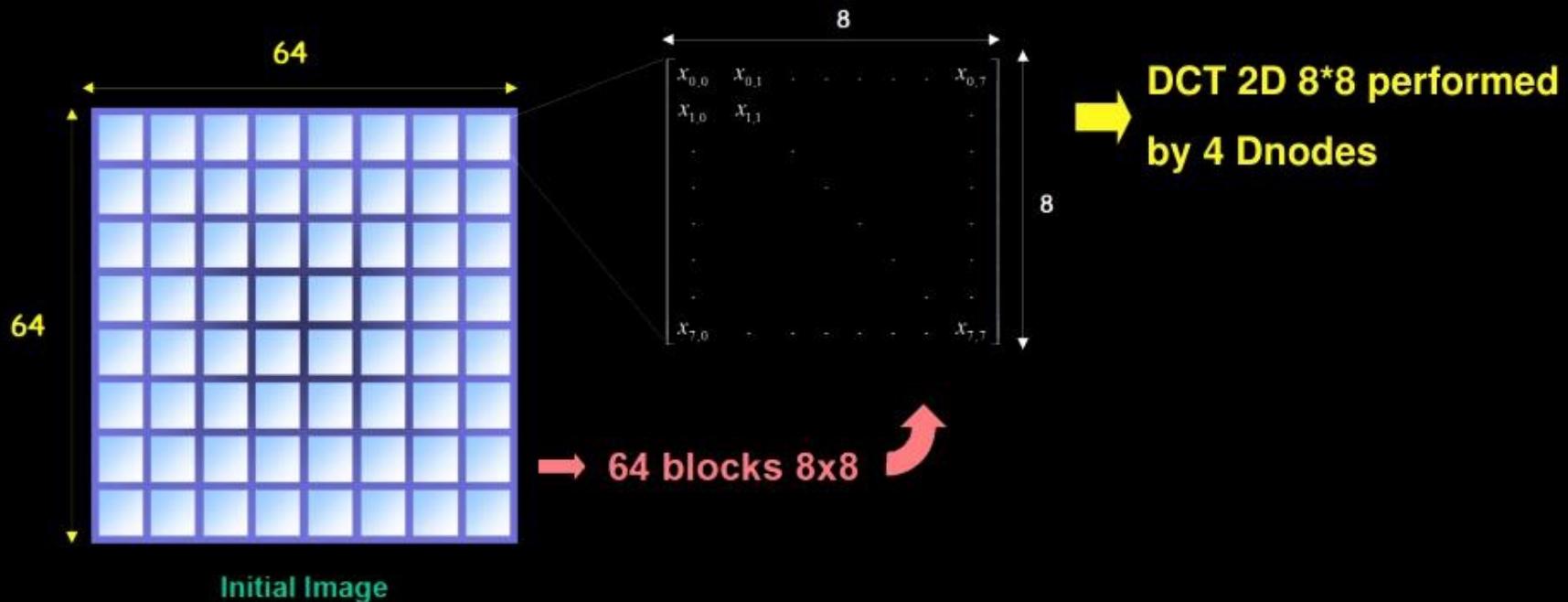
$$z = \sqrt{\frac{2}{N}} T(N)x$$

$$\left\{ \begin{array}{l} \begin{aligned} \begin{bmatrix} z_0 \\ z_2 \\ z_4 \\ z_6 \end{bmatrix} &= \begin{bmatrix} 1/\sqrt{8} & 1/\sqrt{8} & 1/\sqrt{8} & 1/\sqrt{8} \\ \beta & \delta & -\delta & -\beta \\ \alpha & -\alpha & -\alpha & \alpha \\ \delta & -\beta & \beta & -\delta \end{bmatrix} \begin{bmatrix} x_0 + x_7 \\ x_1 + x_6 \\ x_2 + x_5 \\ x_3 + x_4 \end{bmatrix} \\ z_1 &= \begin{bmatrix} \lambda & \gamma & \mu & v \\ \gamma & -v & -\lambda & -\mu \\ \mu & -\lambda & v & \gamma \\ v & -\mu & \gamma & -\lambda \end{bmatrix} \begin{bmatrix} x_0 - x_7 \\ x_1 - x_6 \\ x_2 - x_5 \\ x_3 - x_4 \end{bmatrix} \end{aligned} \end{array} \right. \quad \left. \begin{array}{l} \alpha = 1/2 \cos(\pi/4) \\ \beta = 1/2 \cos(\pi/8) \\ \delta = 1/2 \sin(\pi/8) \\ \lambda = 1/2 \cos(\pi/16) \\ \gamma = 1/2 \cos(3\pi/16) \\ \mu = 1/2 \sin(3\pi/16) \\ v = 1/2 \sin(\pi/16) \end{array} \right.$$

# Application example - DCT 2D 8\*8



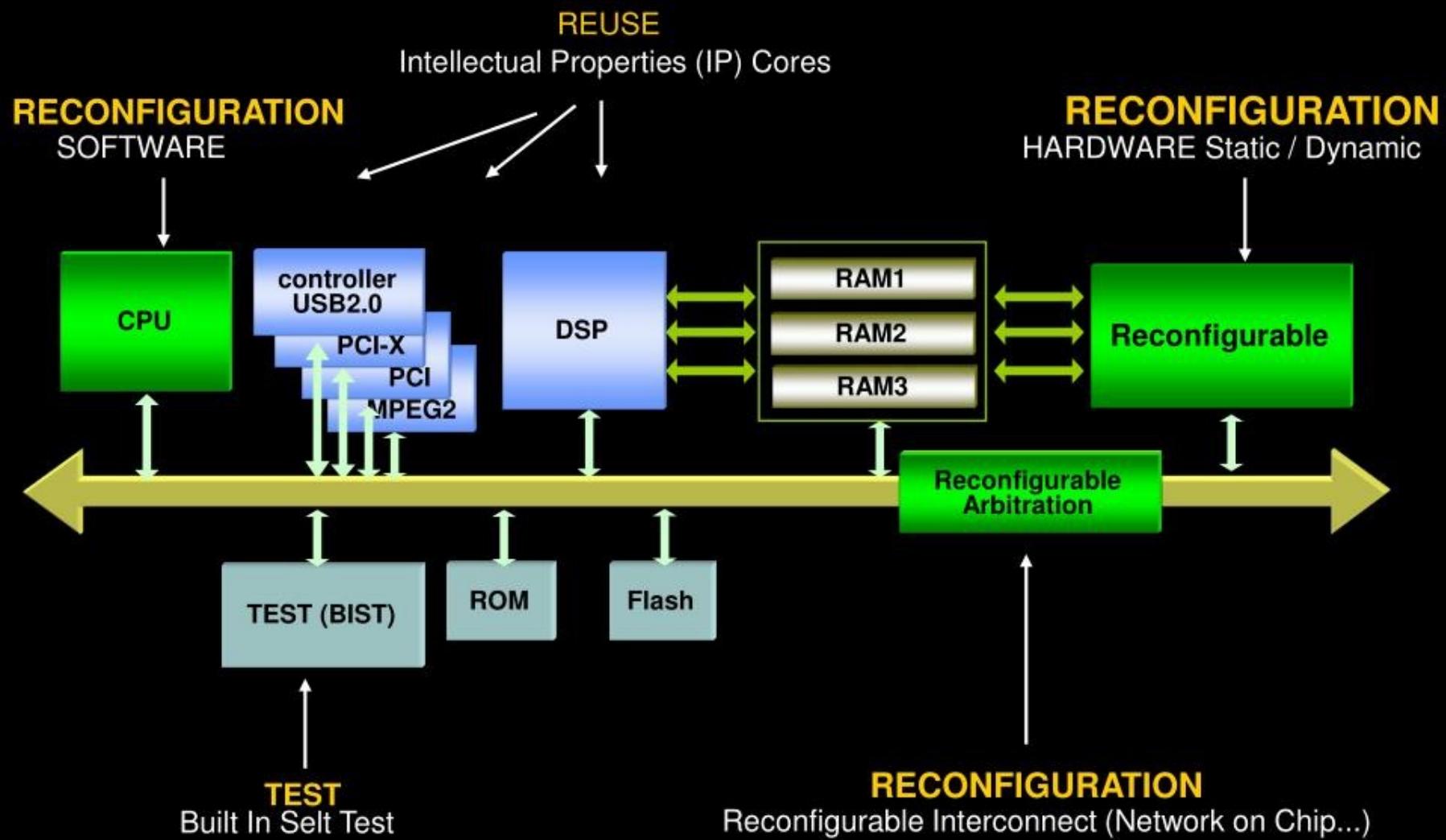
64\*64 image example



$$\# \text{ computation clock cycles} = 320 \cdot (\# \text{ of } 8\text{-points 2D blocks}) \cdot \frac{4}{N}$$

RING-N implementation ( N Dnodes)

# Introduction - SoC architectures





# System on a Chip

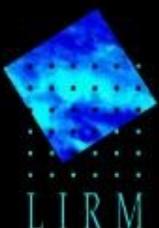
Sophia Antipolis  
9-10 Oct 2002



## The Systolic Ring : A Scalable Dynamically Reconfigurable Core for Embedded Systems

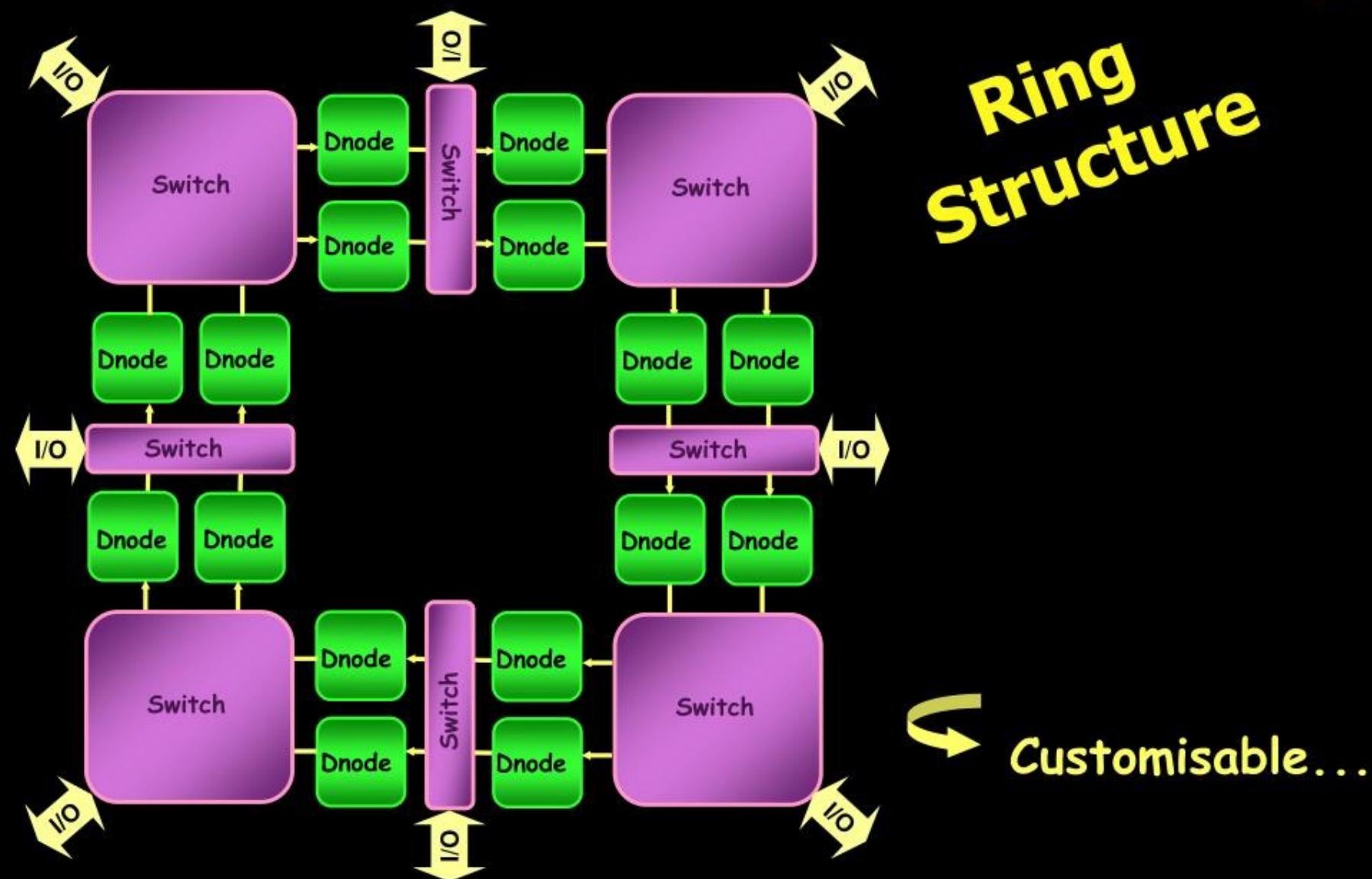
Pascal BENOIT,

G. SASSATELLI, M. ROBERT, L. TORRES, G. CAMBON, T. GIL



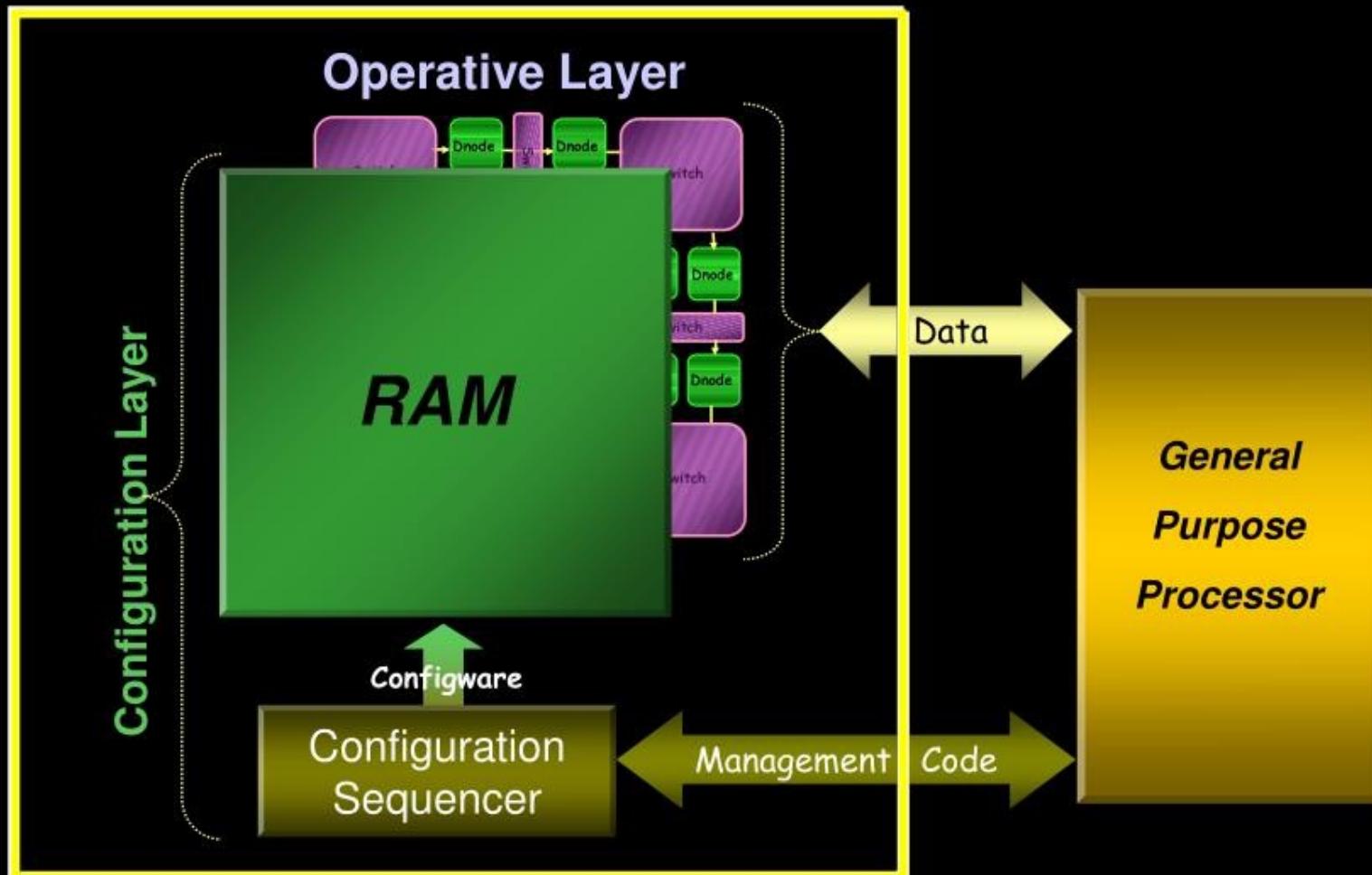
UNIVERSITE MONTPELLIER II  
SCIENCES ET TECHNIQUES DU LANGUEDOC

# The Systolic Ring - Operative Layer Topology



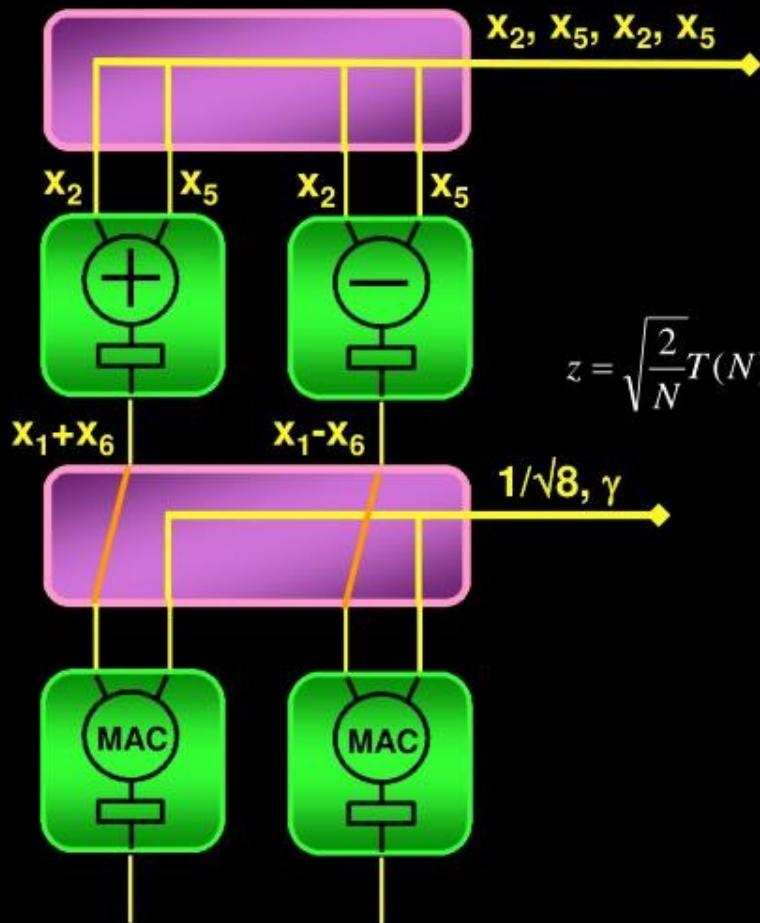
# The Systolic Ring - System Overview

Not a stand-alone solution



Coprocessor for data flow oriented applications

# Application example - 8\*8 2D DCT



$$z = \sqrt{\frac{2}{N}} T(N)x$$

Cycle 2

$$\begin{cases} \begin{bmatrix} z_0 \\ z_2 \\ z_4 \\ z_6 \end{bmatrix} = \begin{bmatrix} 1/\sqrt{8} & 1/\sqrt{8} & 1/\sqrt{8} & 1/\sqrt{8} \\ \beta & \delta & -\delta & -\beta \\ \alpha & -\alpha & -\alpha & \alpha \\ \delta & -\beta & \beta & -\delta \end{bmatrix} \begin{bmatrix} x_0 + x_7 \\ x_1 + x_6 \\ x_2 + x_5 \\ x_3 + x_4 \end{bmatrix} & \left\{ \begin{array}{l} \alpha = 1/2 \cos(\pi/4) \\ \beta = 1/2 \cos(\pi/8) \\ \delta = 1/2 \sin(\pi/8) \end{array} \right. \\ \begin{bmatrix} z_1 \\ z_3 \\ z_5 \\ z_7 \end{bmatrix} = \begin{bmatrix} \lambda & \gamma & \mu & \nu \\ \gamma & -\nu & -\lambda & -\mu \\ \mu & -\lambda & \nu & \gamma \\ \nu & -\mu & \gamma & -\lambda \end{bmatrix} \begin{bmatrix} x_0 - x_7 \\ x_1 - x_6 \\ x_2 - x_5 \\ x_3 - x_4 \end{bmatrix} & \left\{ \begin{array}{l} \lambda = 1/2 \cos(\pi/16) \\ \gamma = 1/2 \cos(3\pi/16) \\ \mu = 1/2 \sin(3\pi/16) \\ \nu = 1/2 \sin(\pi/16) \end{array} \right. \end{cases}$$

# Introduction

## What kind of base block is suitable for Multimedia?

- **Fine grain:**

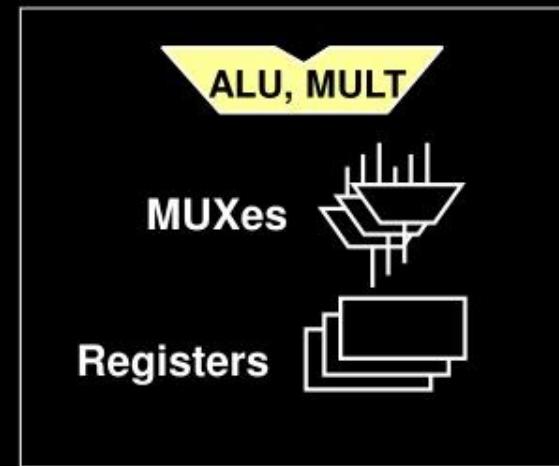
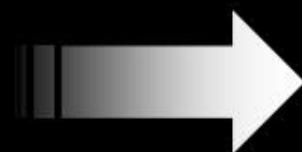
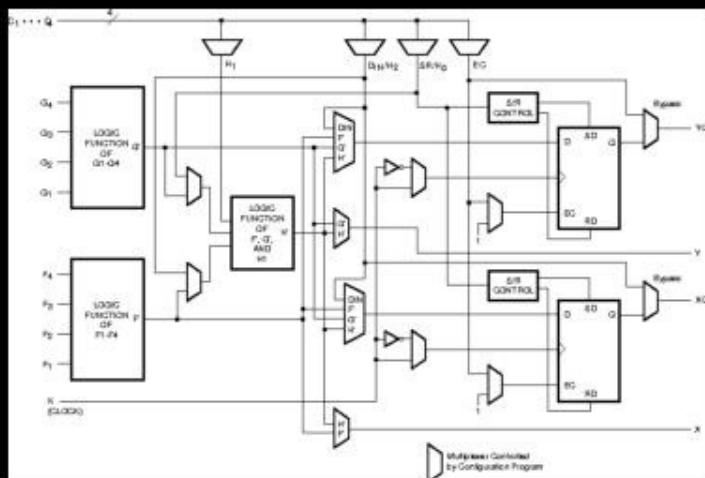
- Granularity: BIT

- adapted to Prototyping, Encryption

- **Coarse Grain:**

- Granularity: WORD

- adapted to DSP, data flow oriented processing



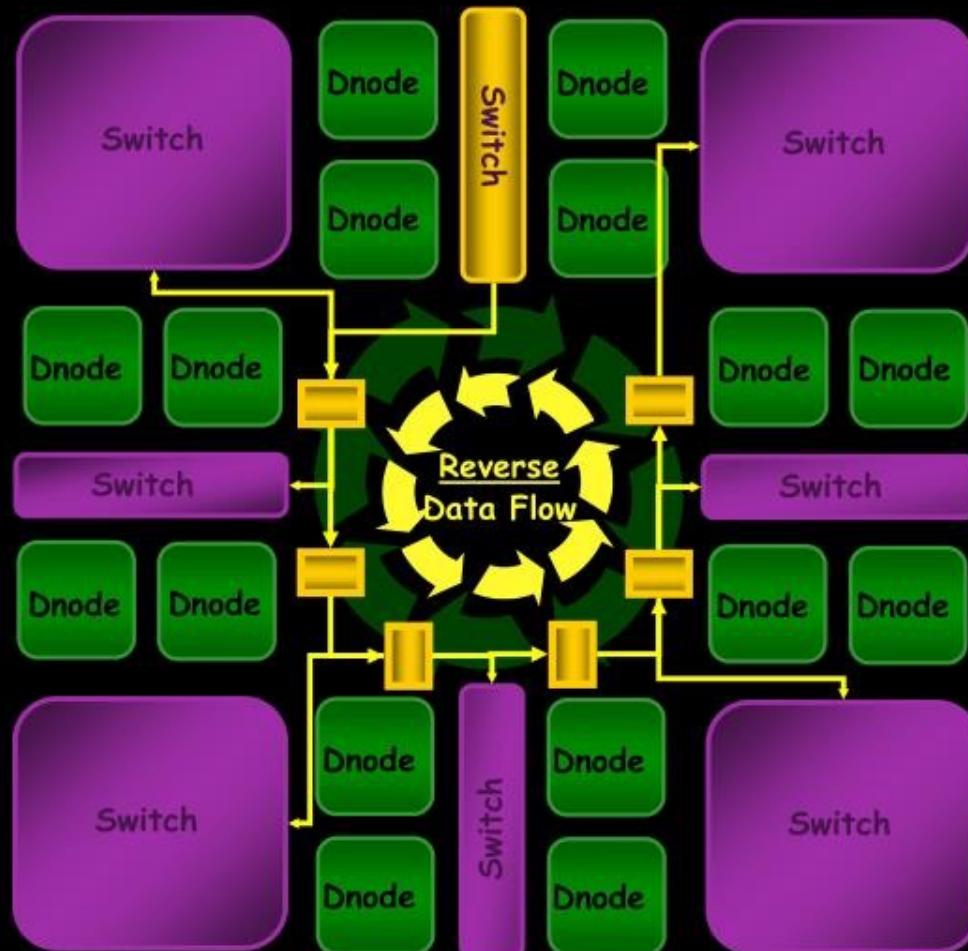
- High reconfiguration over-cost
  - Low Functional frequencies

- Low reconfiguration over-cost
  - High level of performances

# The Systolic Ring - Operative Layer Topology



## Data Flows



### Forward Data Flow

Unidirectional data transit between successive layers (circular pipeline)

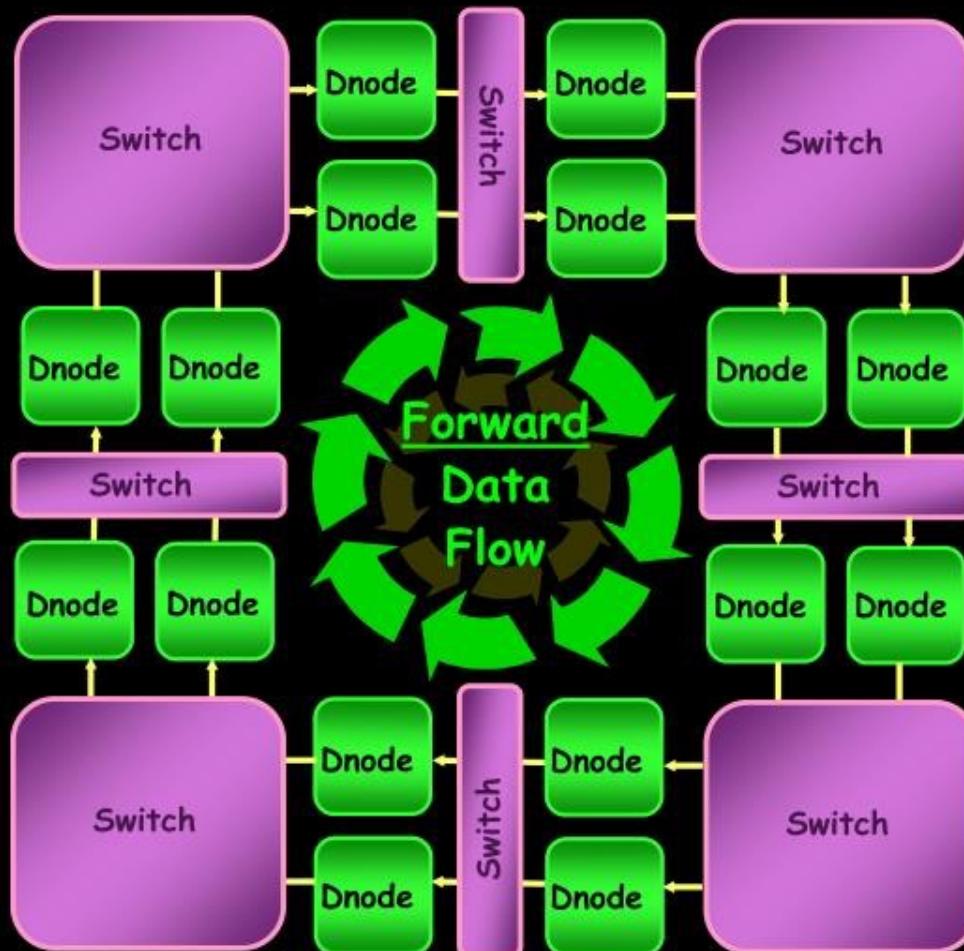
### Reverse Data Flow

Feedback pipeline network  
for recursive algorithms

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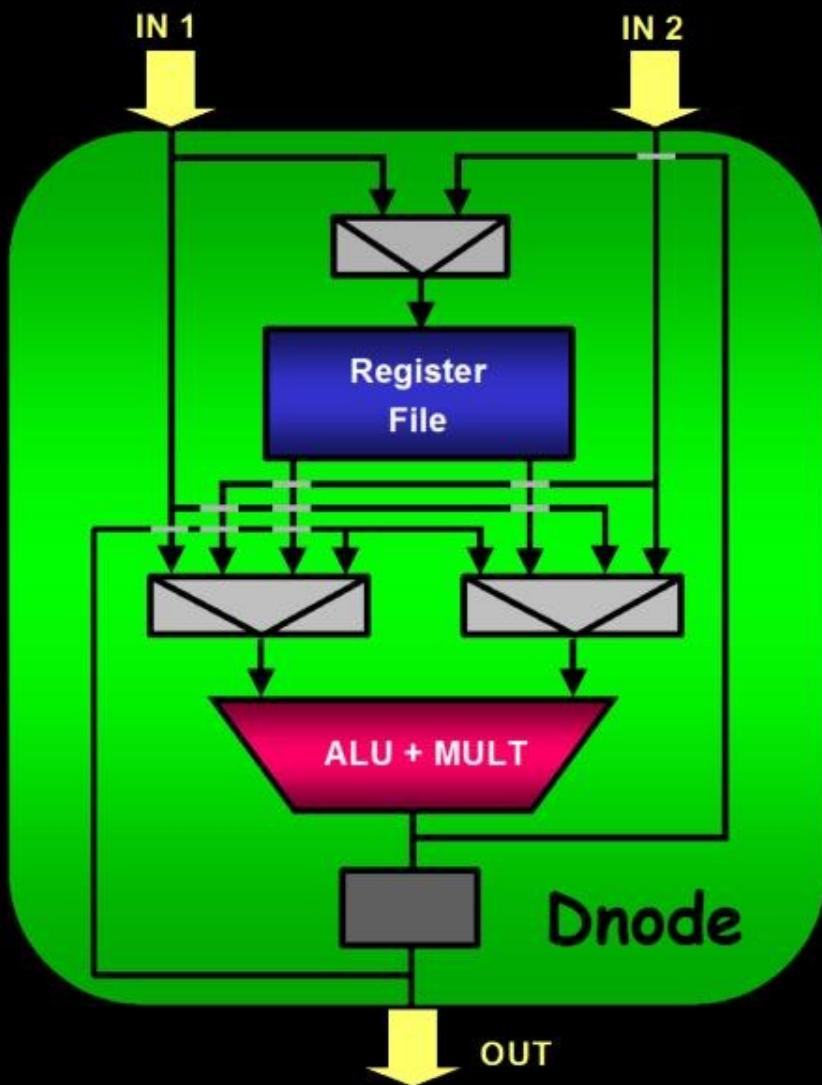
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# The Systolic Ring - Building block



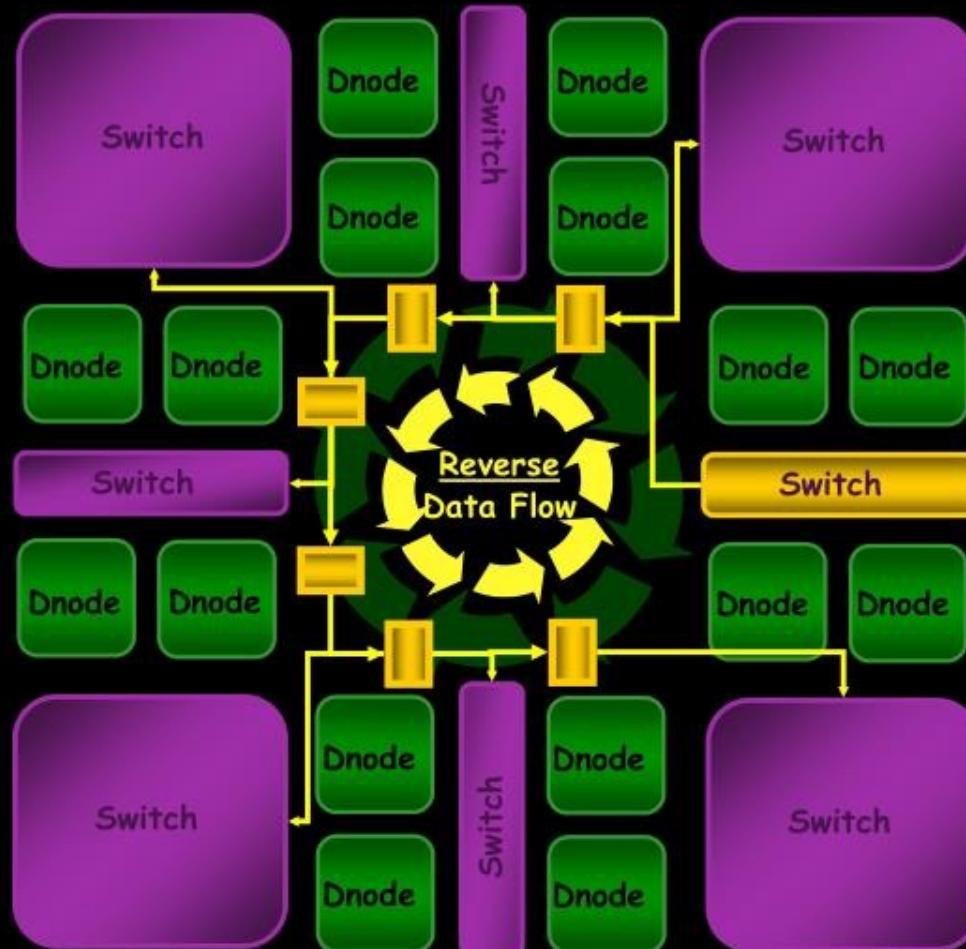
## DNODE (Data Node)



- **Data processing oriented block**
  - ALU + Multiplier  $\uparrow$  MAC)
- **Programmable component**
  - Local Sequencer
    - Dynamic and autonomous configuration management
  - *one instruction per cycle*

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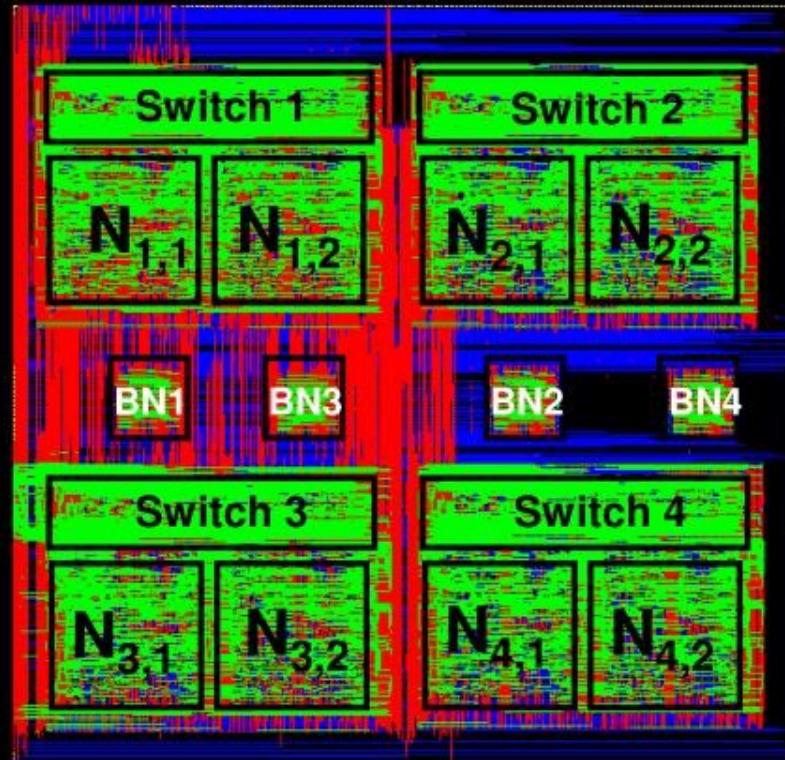
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# The Systolic Ring



## Systolic Ring Features



*Operative Layer Layout*

### ■ RING-8 (8 Dnodes)

→ 0.18 $\mu$  technology

3.3 mm<sup>2</sup>

200 MHz

1600 MIPS

1600 MMACs / s

Process geometry dropping ⇒ increase Dnode #