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Analog Field Programmable Gate Arrays

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Outline

1. Background
2. Analog computing then and now
3. Analog computing with FPA/MAs
4. Applications of FPA/MAs
5. Examples
6. Conclusions

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1. Background

Who needs analog Field Programmable Gate Arrays ?

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Who needs analog circuits ?

We define analog circuits as:

- Continuous in time (c-t)
- Continuous in signal domain

Such definition covers all other circuits as subclasses.

	Continuous-time	Discrete-time
Continuous-signal	**Analog circuits and systems**	Analog systolic processors, CNNs
Discrete-signal	?	MVL and digital circuits

1. “Real” world is primarily analog in nature (we assume so)

   - Almost every digital system which directly interacts with the real world must have analog-to-digital (A/D) and digital-to-analog (D/A) interfaces
   - These interfaces may be simple A/D and D/A converters, or ...
   - They can contain quite sophisticated signal conditioning systems

- Required speed of information processing may favor an analog solution (for technological or economical reasons), or ...

- Continuous-time processing may be a requirement (example: anti-aliasing)

2. **Digital information** could be processed in **analog** form to gain speed (example: image processing requiring many multiplications)

- Even if a digital solution exists and is economically acceptable, an analog solution may turn out to be
  - **smaller**
  - require **less power**
  - generate **less noise**, and
  - be **more reliable** (a smaller number of elements to go wrong)

Why, therefore, are analog circuits and systems so widely avoided ?

- **Design of analog *circuits*** is difficult, often involves rare expertise, and is very hard to automate

- ***System*** **analog design** is even harder: a “standard cell” or “gate” approach is rather uncommon – consequently analog system designers must consider low-level circuit interactions

- Analog systems suffer several kinds of **dependencies** (on the temperature, fabrication run, time (aging))

- Analog systems have **finite precision**

Design

- can be greatly simplified by Field Programmable Analog Arrays. Design process would consist of
  - **selection** of predesigned cells in the FPAA structure
  - **programming** their **functions** and **parameters,** and
  - programming **signal interconnections** between the cells

Dependencies

- do not have to be fatal if the circuitry is designed carefully
- the circuitry of the FPAA is designed **once and for all**, therefore it can be **optimized**

Precision

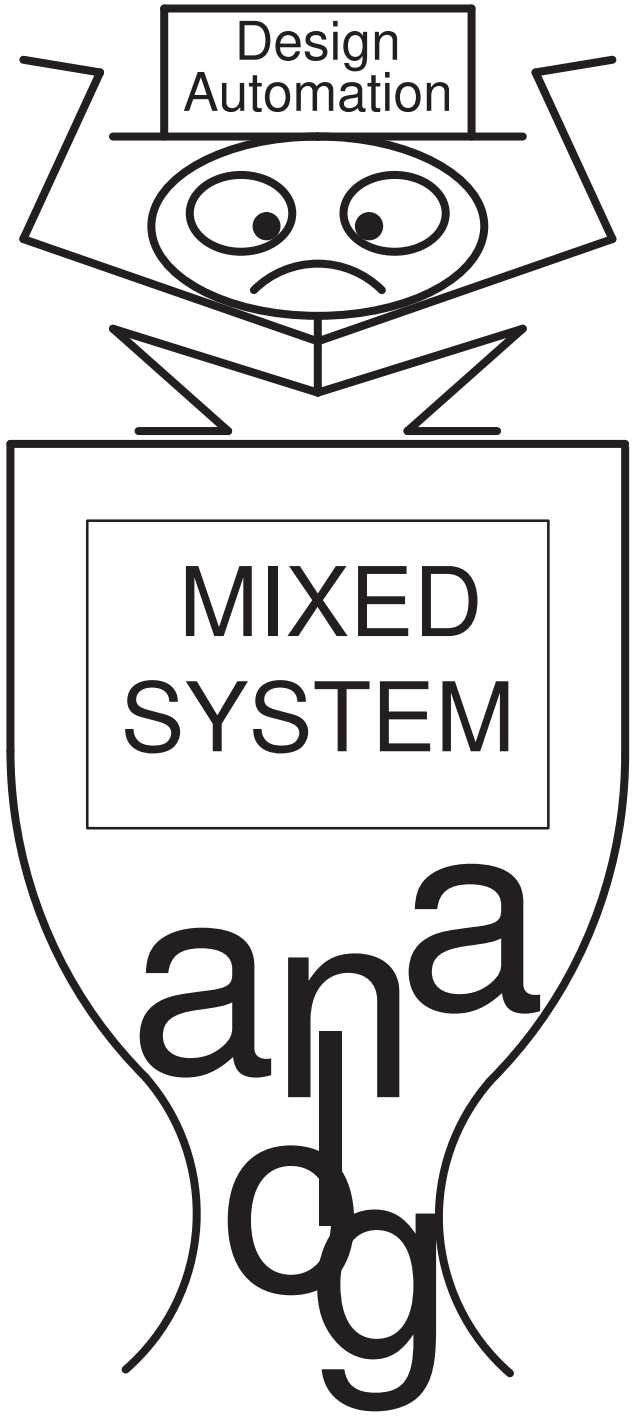
- is not an issue in many applications
- sometimes can be traded for speed (example: feedback control systems)
- even the most accurate digital system interacting with the analog world is limited in its precision by the analog front- and back-ends

There is growing interest in **mixed-signal** (i.e. analog and digital) system design.

Mixed signal systems combine the best of both worlds:

Analog	Digital
High speed	Precision
Continuous-time operation	Noise immunity
Easy interfacing to analog world	Easy interfacing to digital systems
Smaller size, power consumption	Invariance over temperature, time, etc.
Direct realization of some signal operations (integration, multiplication, etc.)	Realization of arbitrary operations on signals

Although the analog component may comprise a small fraction of a mixed-signal system, its design is usually the bottleneck, because of the lack of suitable Design Automation methods and tools.


Design
Automation
MIXED
SYSTEM
analog

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Building analog/mixed-signal systems

Analog/mixed-signal design automation (custom)

Field Programmable Analog/Mixed-signal Arrays (FPA/MAs)

Challenges

- Flexible, **full programmability** of analog medium without compromising the performance:

  i) programmability of **parameters**

  ii) programmability of **structure**

- Integration of analog and digital subcircuits

2. Analog computing then and now

Then:

- Analog computers of the 50-ties
  - bulky
  - unreliable
  - programmable ?
  - ...

Now:

- Artificial Neural Networks (ANNs)
  - dedicated architectures
  - high degree of parallelism
  - analog (= fast) operation
- Cellular Neural Networks (CNNs)
- Fuzzy logic circuits
- ... ?

3. Analog computing with FPA/MAs

- high degree of **parallelism**
- **fast**, analog operation
- **full digital programmability** (no more patch boards !!)
- full **digital communication** with digital processors

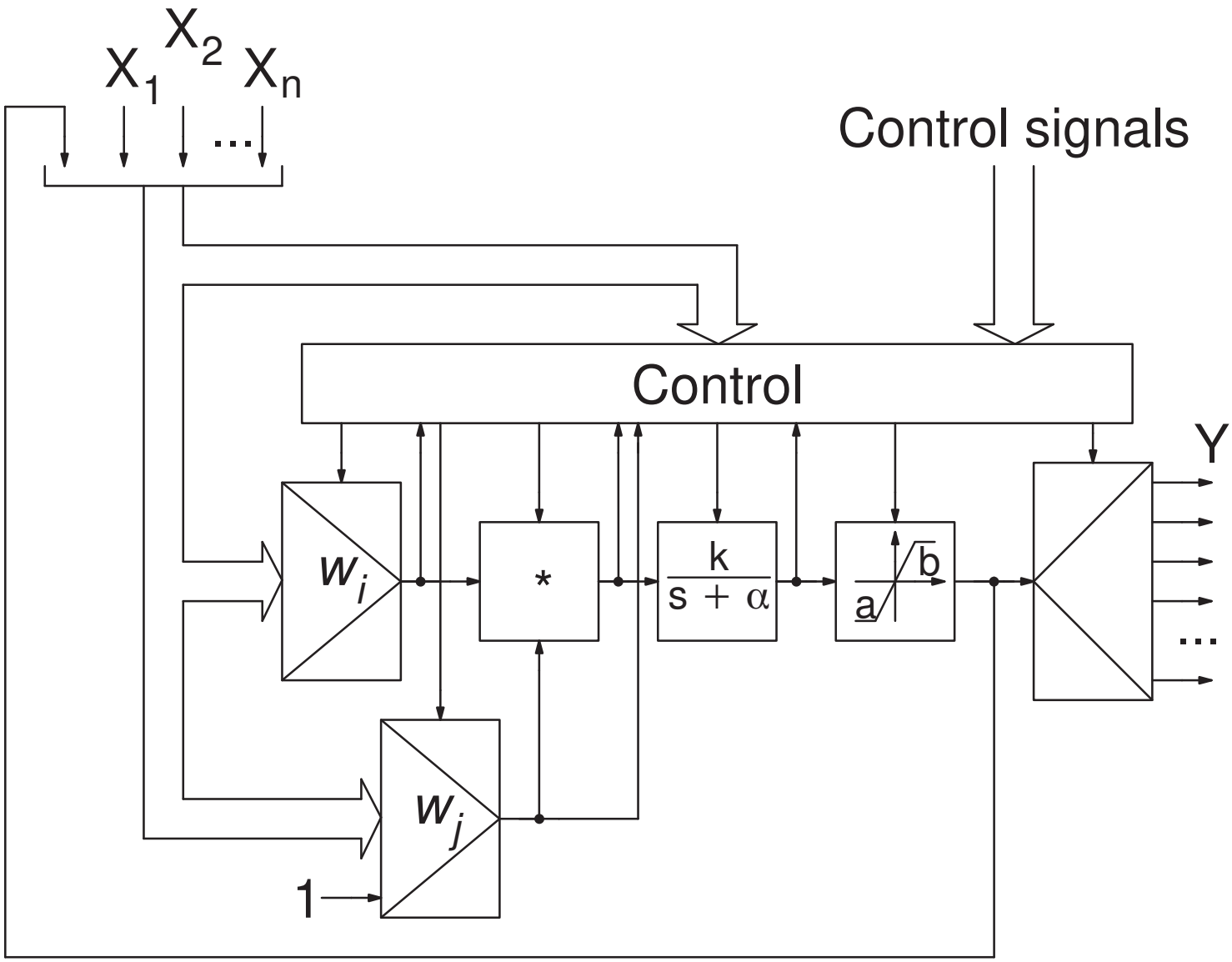
Full programmability requires:

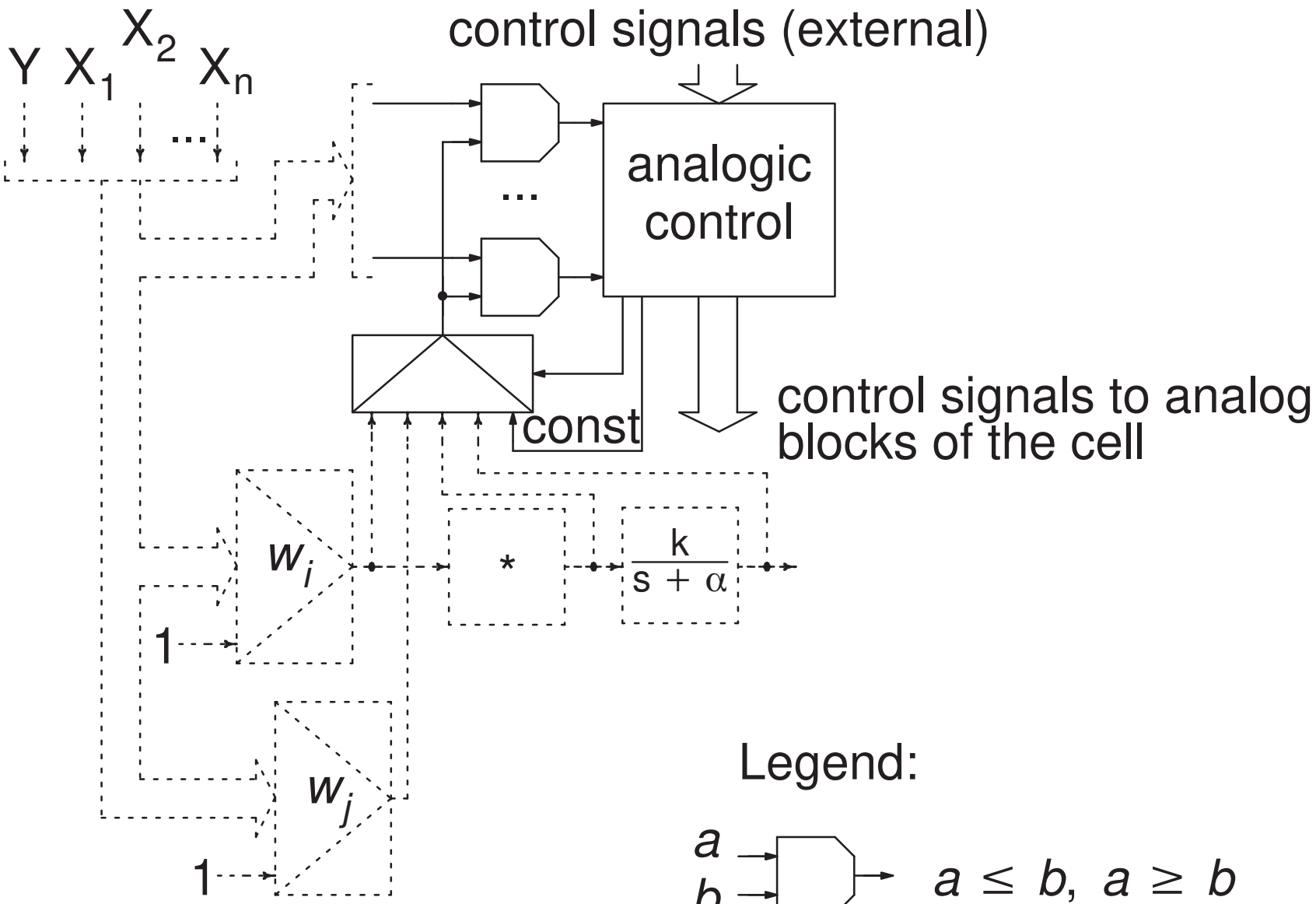
i) flexible cell

ii) efficient architecture (scheme of interaction between cells)

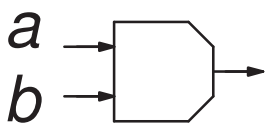
Basic cell functions

- weighted addition/subtraction
- multiplication/phase detection
- integration over time
- clipping (limiting) of the signal level


X1
X2
...
Xn
Control signals
Control
Y
wi
*
k
s + α
a
b
wj
1
...



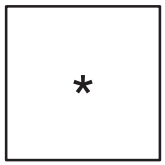
Legend:



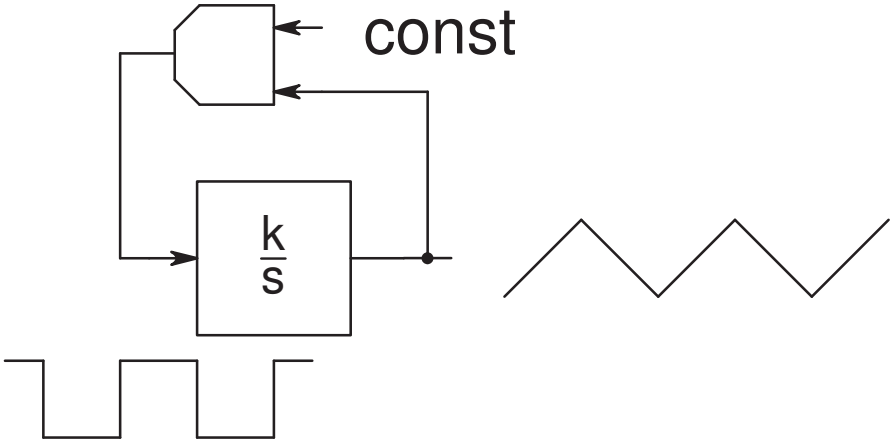
$a \leq b,\ a \geq b$

Analog/logic (analogic) control block enhances functionality of the cell:

- nonlinear operations such as min/max follower
- signal-controlled generation of programmed waveforms
- signal-to-frequency conversion (VCO)
- MVL operations



Gilbert multiplier – it can also be used as a balanced modulator and phase detector



- programmed sine waves can be generated by a linear circuit composed of several cells

Pattern of interconnections between cells

Full (almost full)

- flexibility

Restricted

- performance

Long signal interconnections

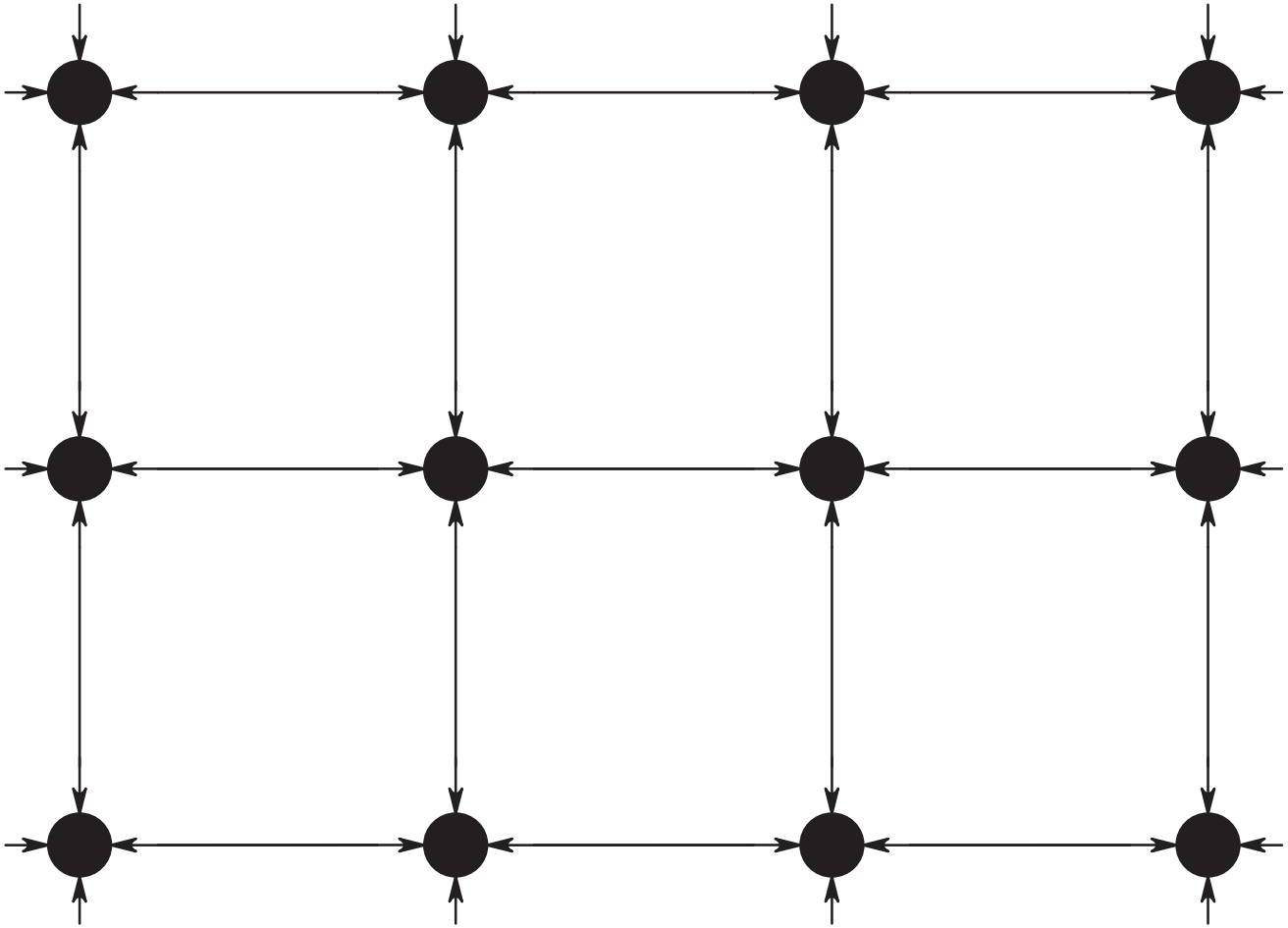
$\Rightarrow$ **parasitics**

$\Rightarrow$ **phase errors** in transmitted signals

$\Rightarrow$ undesired **coupling**

$\Rightarrow$ **noise**

Therefore **local signal interconnections** are preferred.



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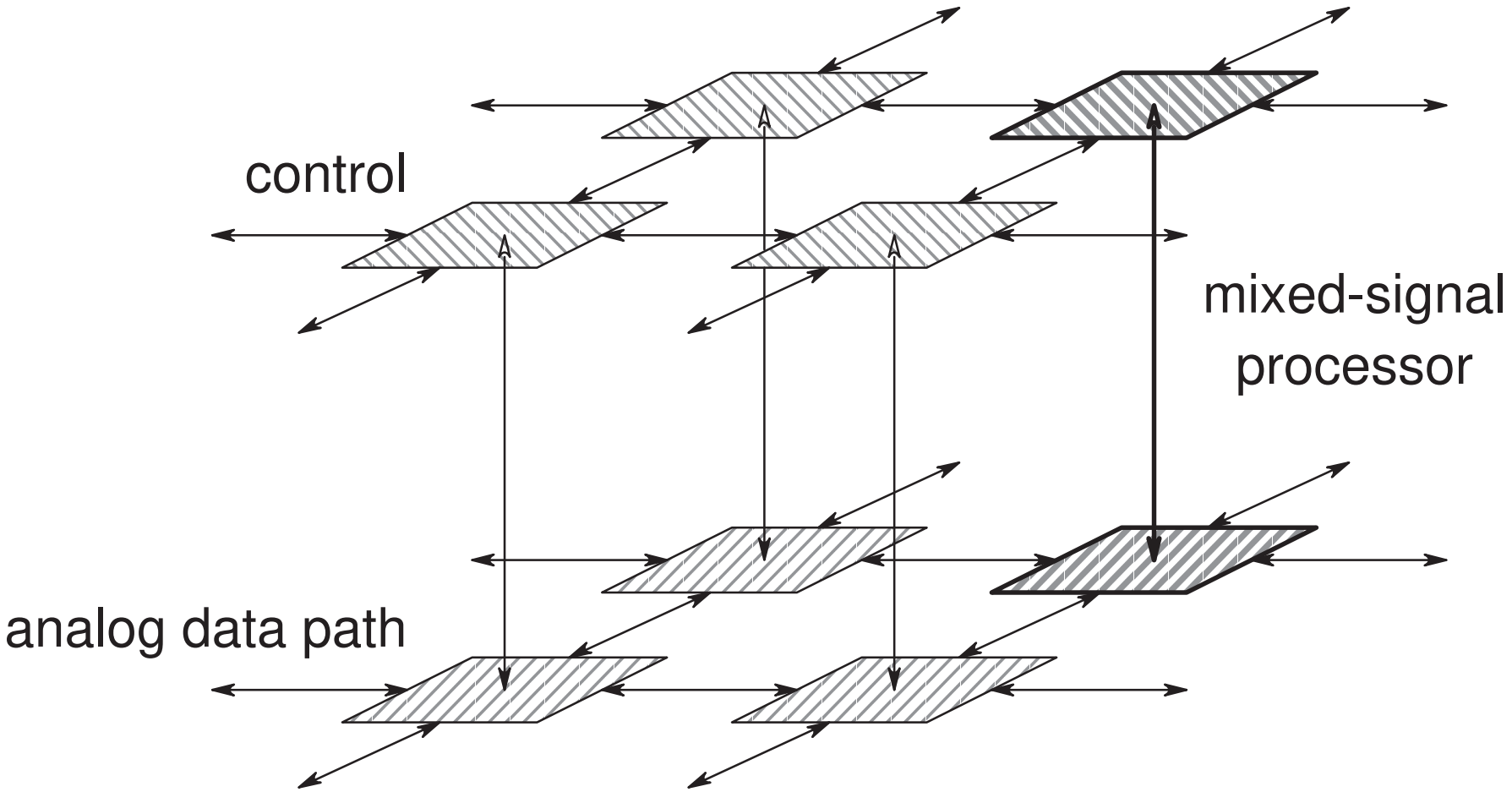
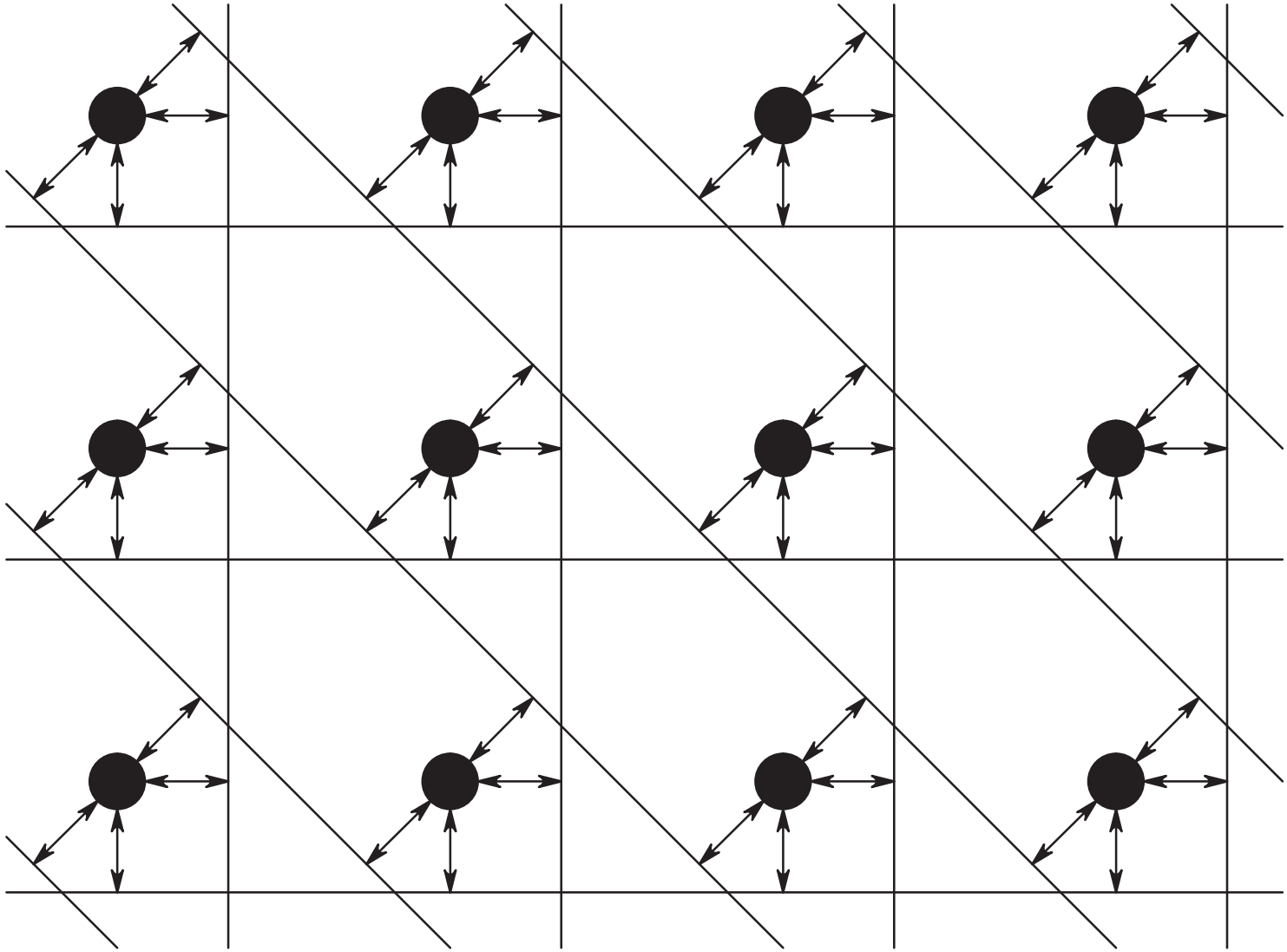


Dual cellular structure

Global interconnections can be used, but only if necessary.



Interaction between cells is

- unilateral
- bidirectional or unidirectional

Signals between cells are exchanged in **current form**

- high speed
- good noise immunity

Information exchange between the **chip** and the **outside world** can be in **digital** form.

We propose a fairly general, universal design of a FPA/MA.

If necessary, it can be tailored to specific needs.

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4. Applications

- Analog “glue circuitry” (including interfaces between analog and digital worlds)
  - A/D and D/A converters
  - signal conditioning
- “Analog-lab-in-a-chip” – linear and nonlinear electronics
  - controlled waveform generators (oscillators)
  - phase detectors
  - phase-locked loops
  - modulators, demodulators

- Linear and nonlinear signal processing systems
  - linear filters
  - adaptive and Kalman filters
  - rank and median filters
- Analog and hybrid computers
  - linear and nonlinear algebraic and differential/integral equations
  - partial differential equations (finite element method)

- Matrix manipulation
  - multiplication
  - inverse
  - LU decomposition
- Combinatorial optimization
  - traveling salesman problem
  - graph coloring
  - covering problem
  - finding shortest paths and maximum flow in networks

- Robotics:
  - fast control systems
  - vision
  - speech processing
- Fast signal and image processing (HDTV)
- Analog pipelined, systolic, regular array and systolizable processors, analog/mixed-signal xputers
- Adaptive control
- Stochastic computers

- Cellular immunological networks (CINs)
- Genetic algorithms, artificial life, adaptive (learning) systems
- Cellular automata
- Cellular neural networks (CNNs)
- Artificial neural networks (ANNs)
- Systems for solving problems by analogy to nature
- Multi valued logic (MVL) and fuzzy logic, Lukasiewicz logic

Since **one structure** can be used to implement all of the above, complex systems containing a variety of different components can be built in one FPA/MA.

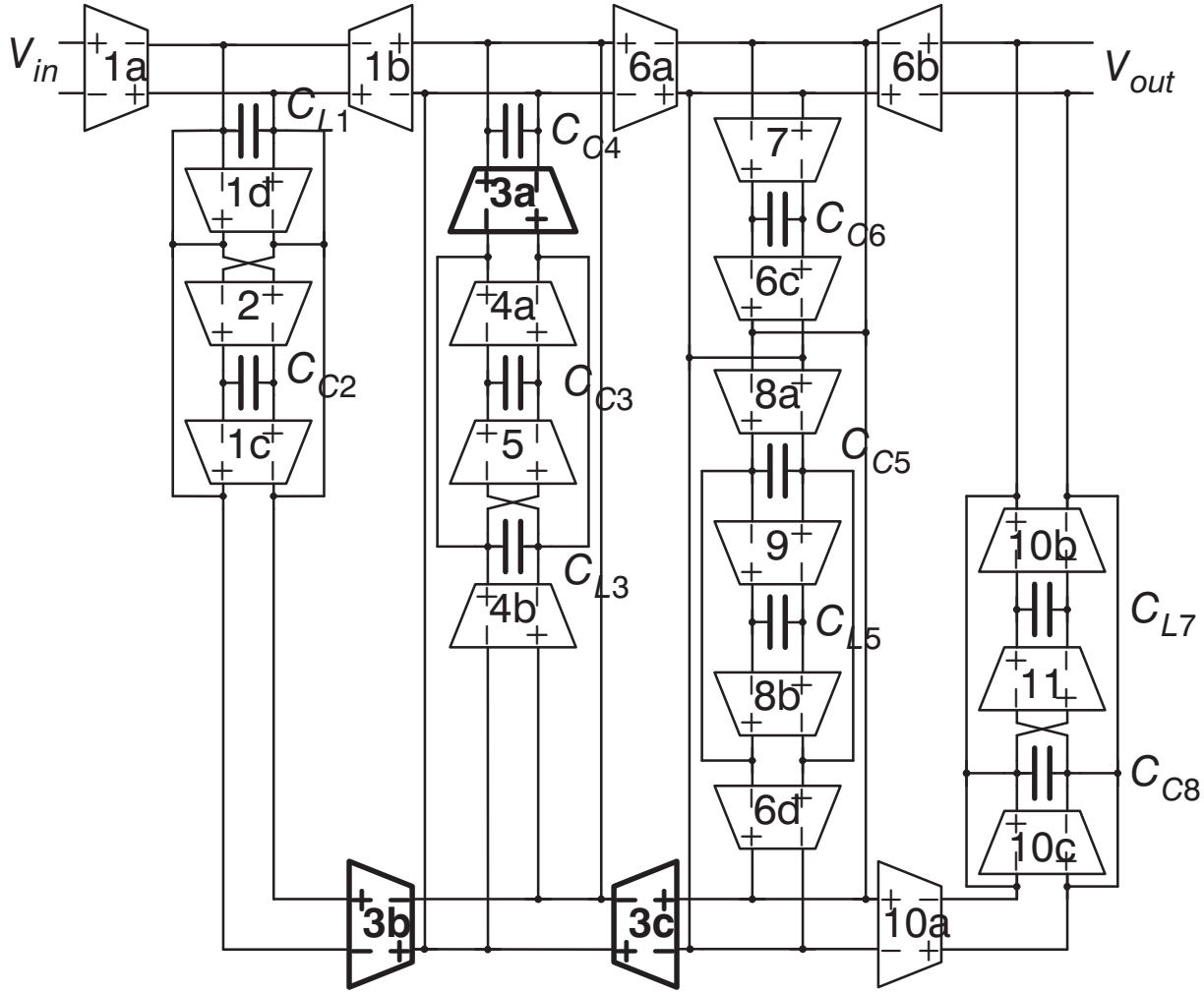
5. Examples

1. Continuous-time linear filter
2. Rank filter cell
3. Matrix multiplication circuit
4. Circuit for solving a system of linear equations
5. Circuit for solving a nonlinear programming problem
6. Fuzzy controller

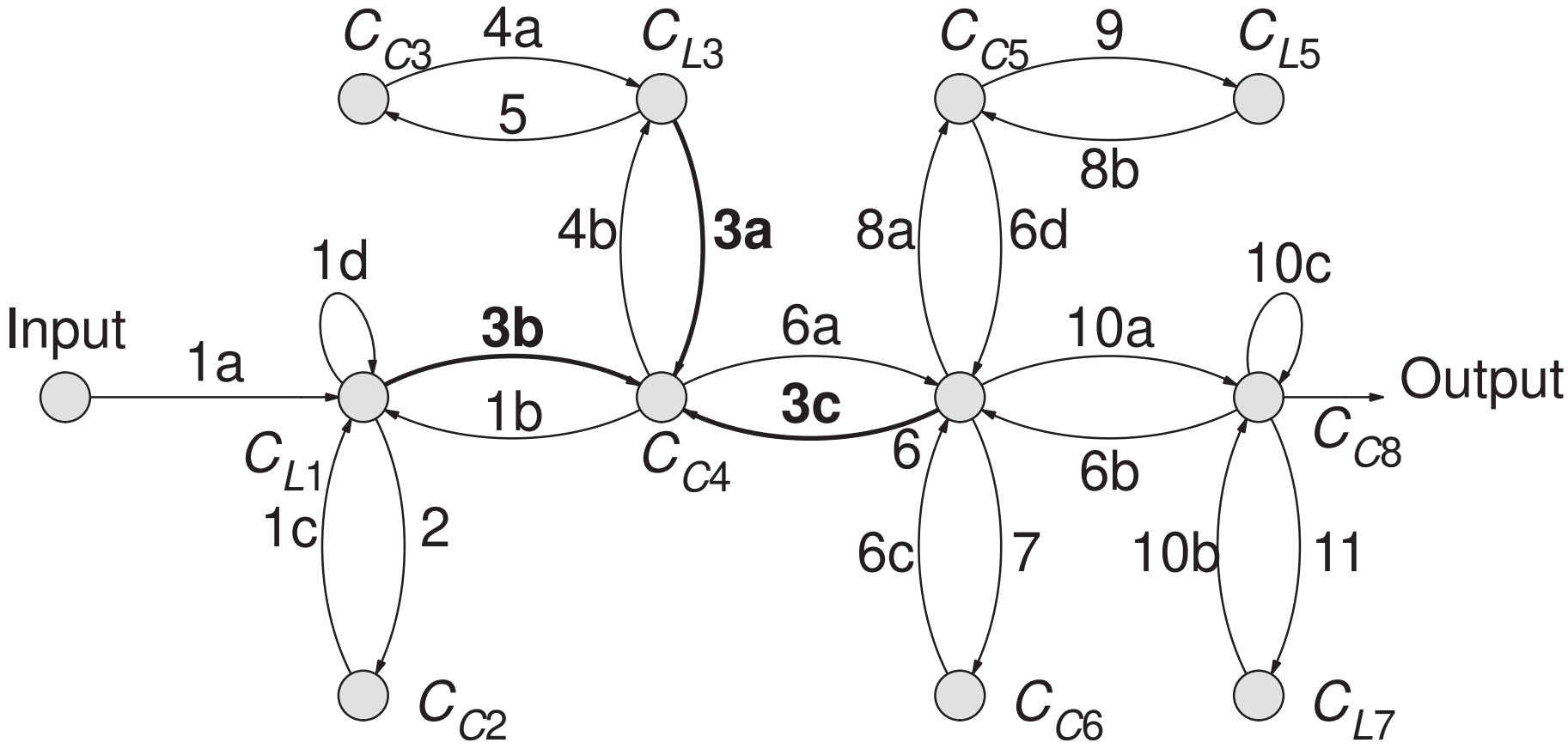
1. **Eight-order elliptic band-pass filter**

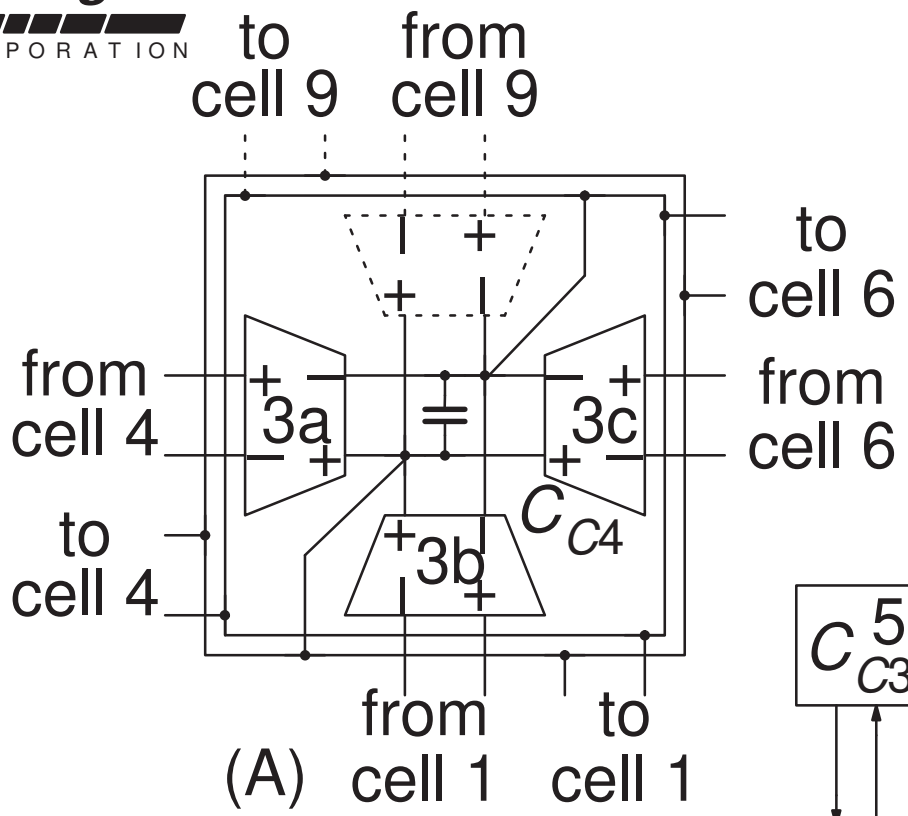
Applications of linear filters:

- video and voice communication
- cellular phones
- signal conditioning in computer disk drives
- modems
- voice recognition, speech systems

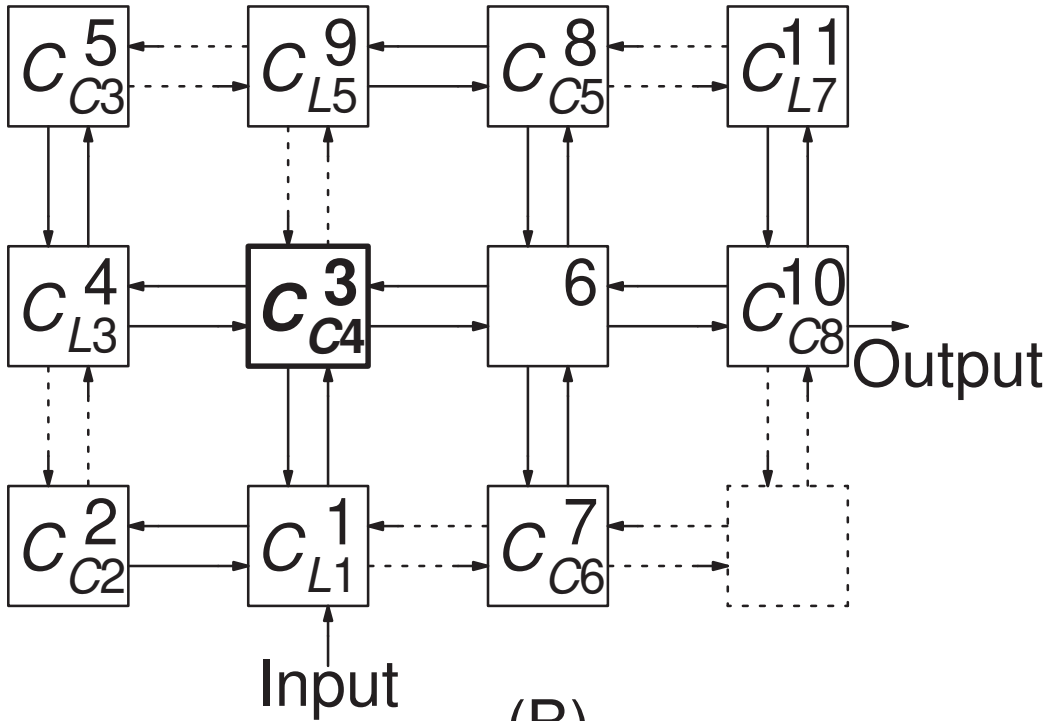


OTA–C technique


C_{C3}
4a
C_{L3}
5
C_{C5}
9
C_{L5}
8b
4b
3a
8a
6d
1d
10c
Input
3b
6a
10a
1a
Output
1b
3c
C_{L1}
C_{C4}
6
C_{C8}
6b
1c
2
6c
7
10b
11
C_{C2}
C_{C6}
C_{L7}


to
cell 9
from
cell 9
to
cell 6
from
cell 4
3a
3c
from
cell 6
C_{C4}
to
cell 4
3b
from
cell 1
to
cell 1

(A)

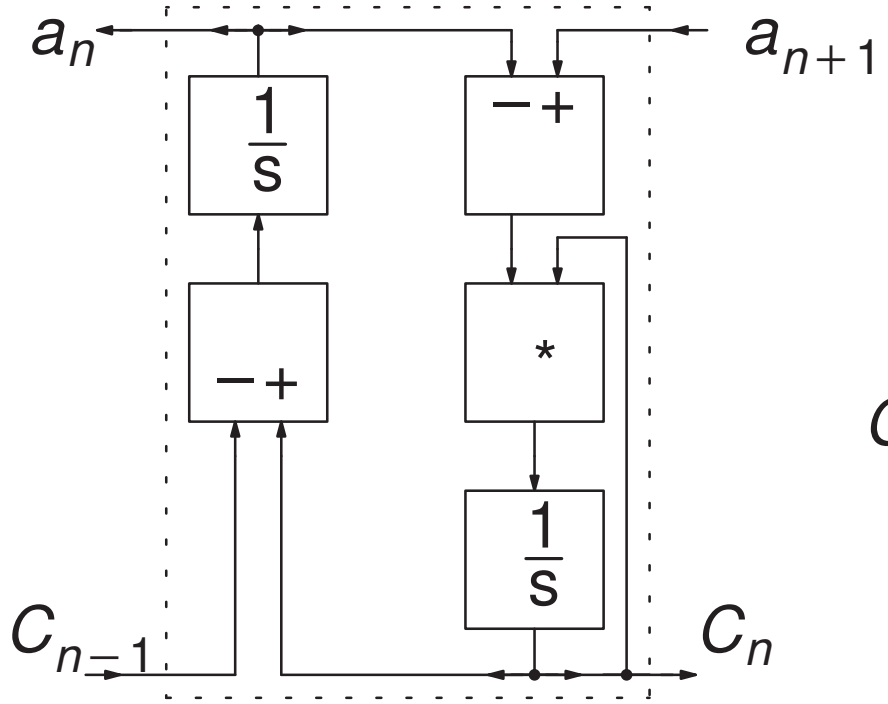

5
C_{C3}
9
C_{L5}
8
C_{C5}
11
C_{L7}
4
C_{L3}
3
C_{C4}
6
10
C_{C8}
Output
2
C_{C2}
1
C_{L1}
7
C_{C6}
Input

(B)

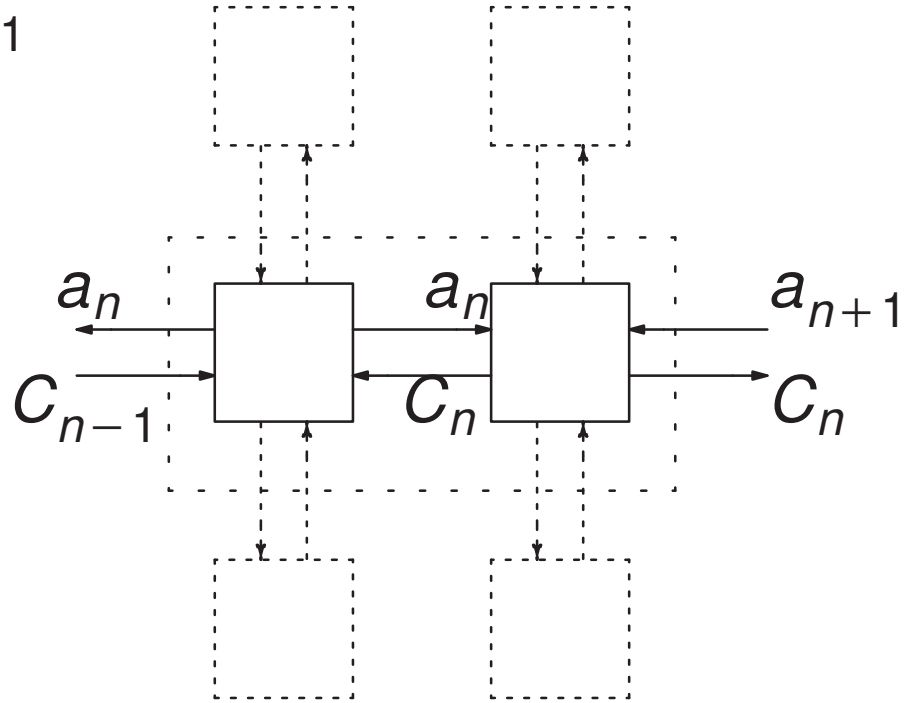
2. **Rank filter cell**

Applications:

- image processing



(A)

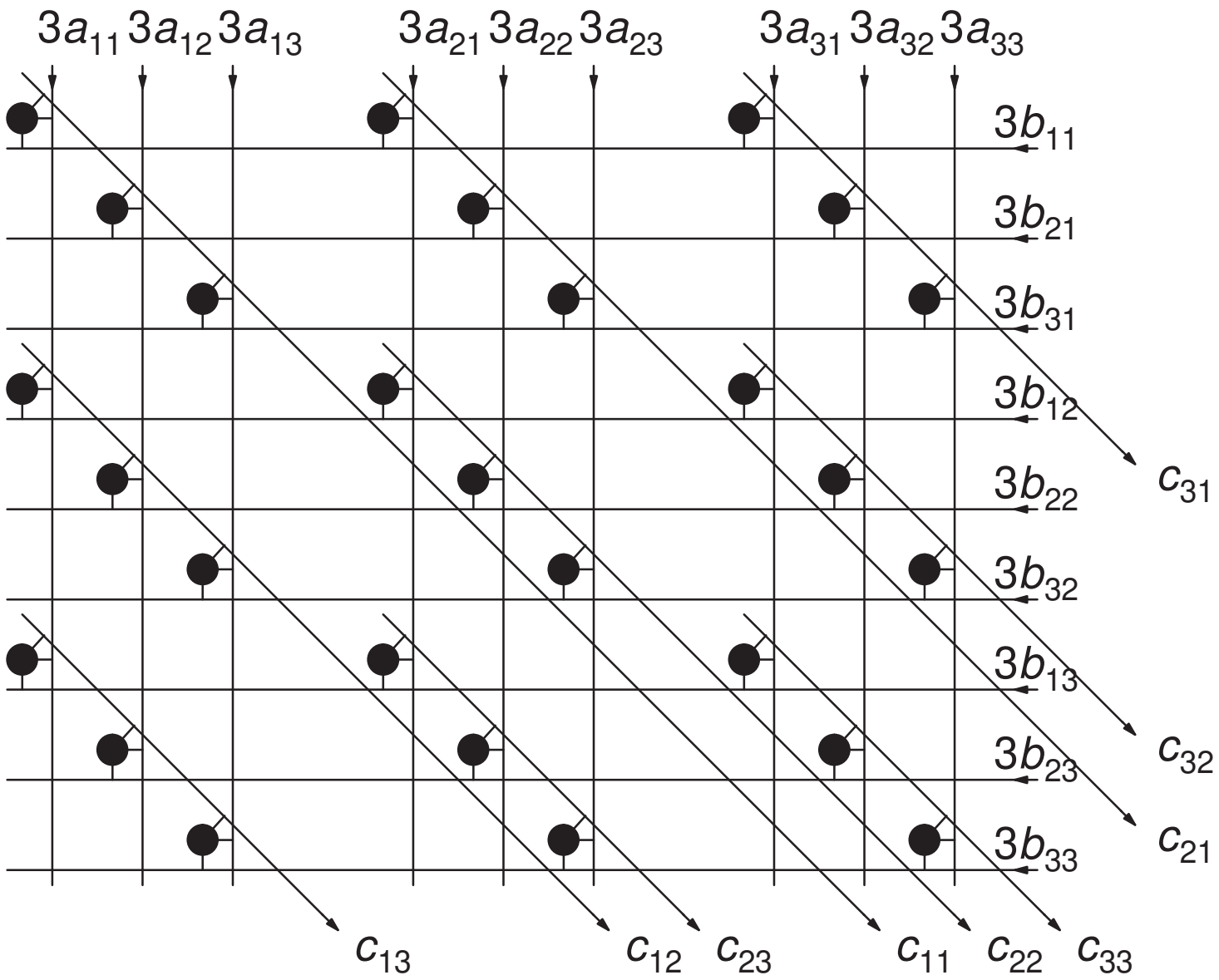


(B)

3. **Matrix multiplication circuit**

Applications:

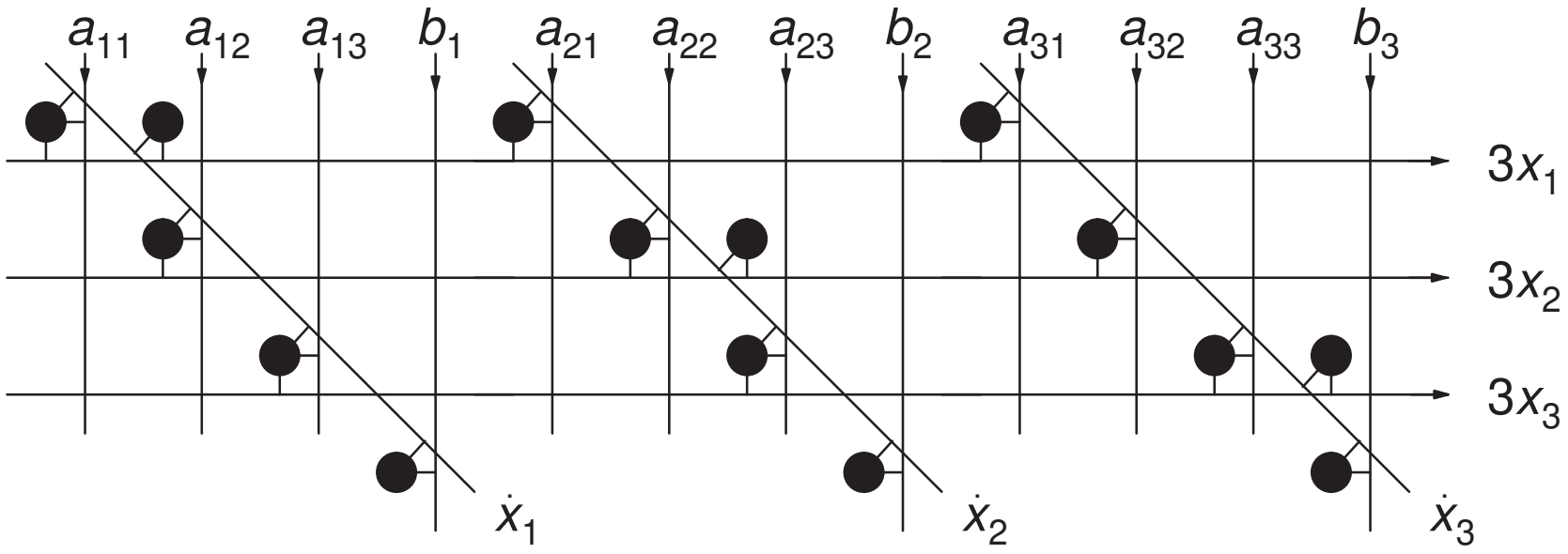
- control (e.g. for robots)
- artificial neural networks


$3a_{11}$ $3a_{12}$ $3a_{13}$
$3a_{21}$ $3a_{22}$ $3a_{23}$
$3a_{31}$ $3a_{32}$ $3a_{33}$
$3b_{11}$
$3b_{21}$
$3b_{31}$
$3b_{12}$
$3b_{22}$
$3b_{32}$
$3b_{13}$
$3b_{23}$
$3b_{33}$
c_{31}
c_{32}
c_{21}
c_{13}
c_{12}
c_{23}
c_{11}
c_{22}
c_{33}

4. **Circuit for solving a system of linear equations**

Applications:

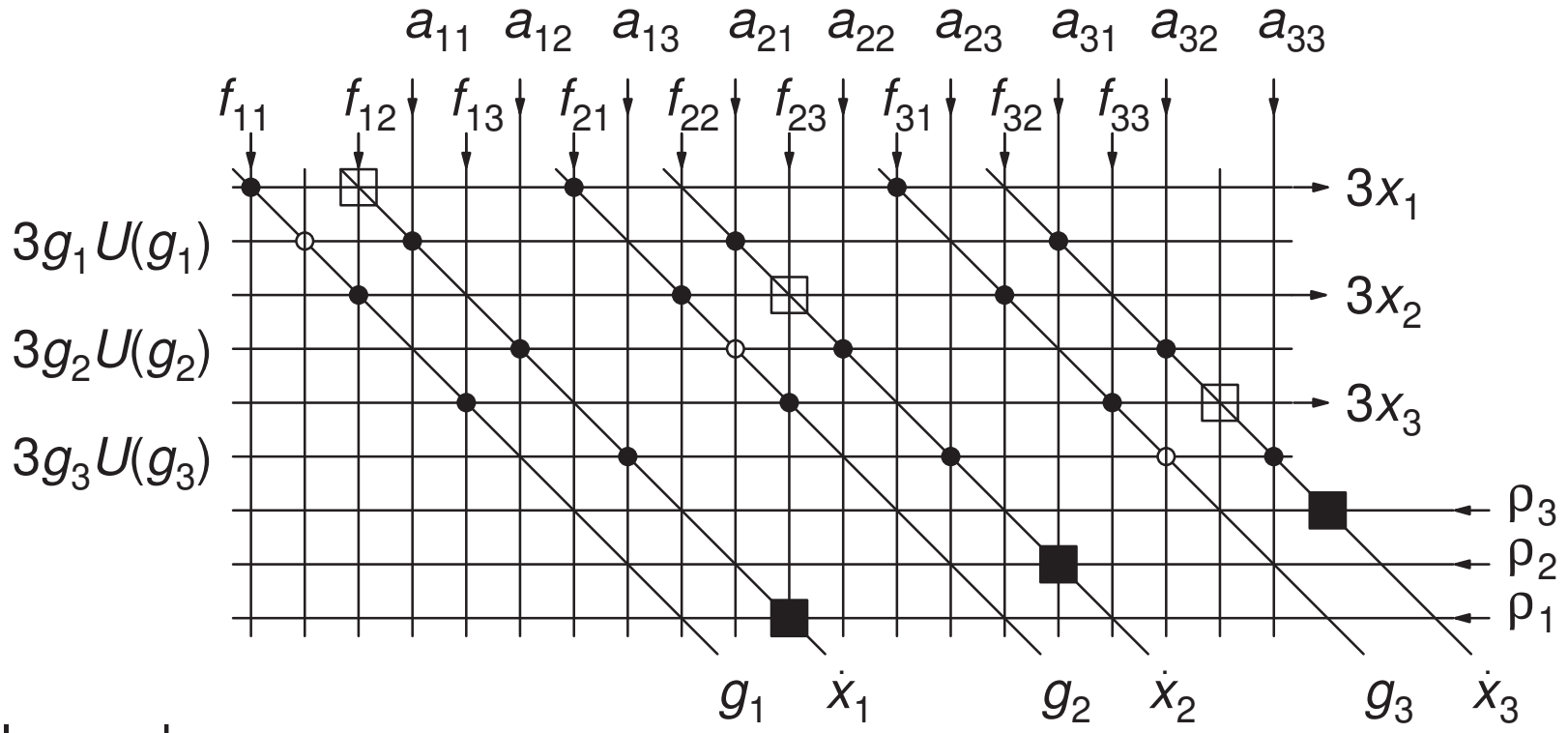
- matrix operations
- circuit simulation
- combinatorial optimization


a_{11}
a_{12}
a_{13}
b_1
a_{21}
a_{22}
a_{23}
b_2
a_{31}
a_{32}
a_{33}
b_3
$3x_1$
$3x_2$
$3x_3$
$\dot{x}_1$
$\dot{x}_2$
$\dot{x}_3$

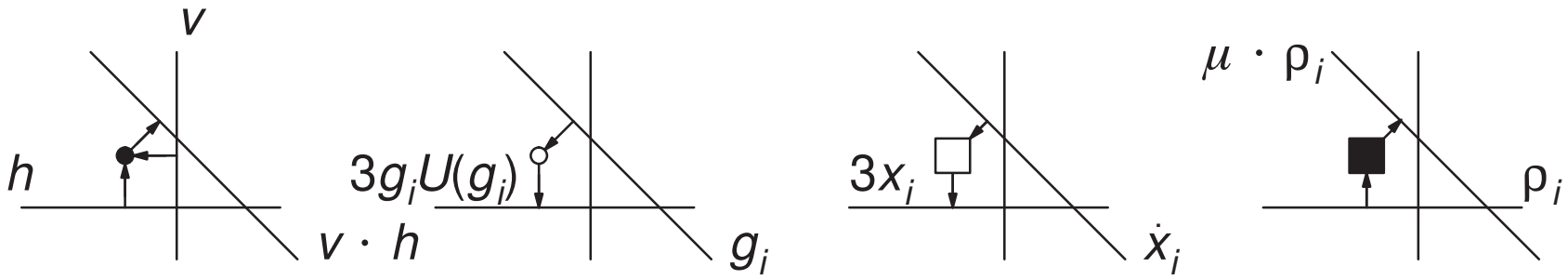
5. **Circuit for solving a nonlinear programming problem**

Applications:

- fast routing of telephone calls
- other combinatorial optimization problems
- CAD accelerator


a_{11} a_{12} a_{13} a_{21} a_{22} a_{23} a_{31} a_{32} a_{33}
f_{11} f_{12} f_{13} f_{21} f_{22} f_{23} f_{31} f_{32} f_{33}
$3g_1U(g_1)$
$3g_2U(g_2)$
$3g_3U(g_3)$
$3x_1$
$3x_2$
$3x_3$
ρ_3
ρ_2
ρ_1
g_1 $\dot{x}_1$ g_2 $\dot{x}_2$ g_3 $\dot{x}_3$

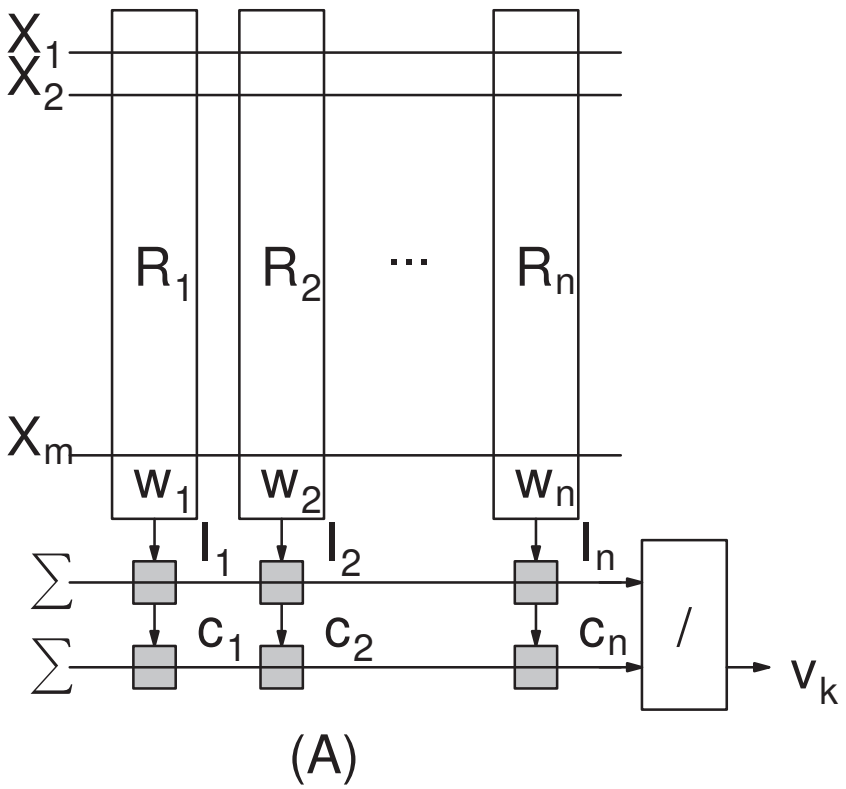
Legend:


v
h
$v \cdot h$
$3g_iU(g_i)$
g_i
$3x_i$
$\dot{x}_i$
$\mu \cdot \rho_i$
ρ_i

6. **Fuzzy controller**

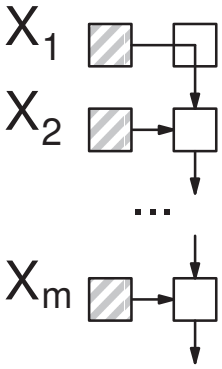
Applications:

- robot control
- home electronics
- intelligent toys

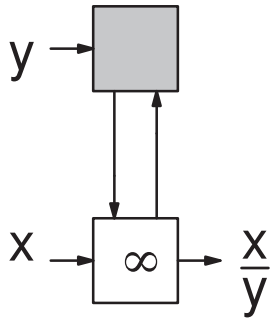


(A)

$$v_k = \frac{\sum_{i=1}^{n} w_i c_i I_i}{\sum_{i=1}^{n} w_i I_i}$$



(B)



(C)

Legend:

- product
- fuzzy set membership
- min

6. Conclusions

- Analog computing may come back, if technical challenges are solved, and a cost effective and flexible technology is available

- Our vision of an FPA/MA with applications in analog computing:
  - functional analog cells forming a data path
  - flexible digital (analog/digital) control forming a control layer coupled with the analog data path
  - a regular array of cells with primarily local interconnections
  - digital interface between the chip and the outside world