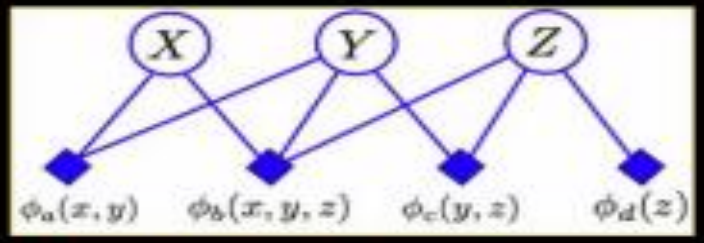


OptoPC - Pavia XXX

Parallel Optical Computing Systems

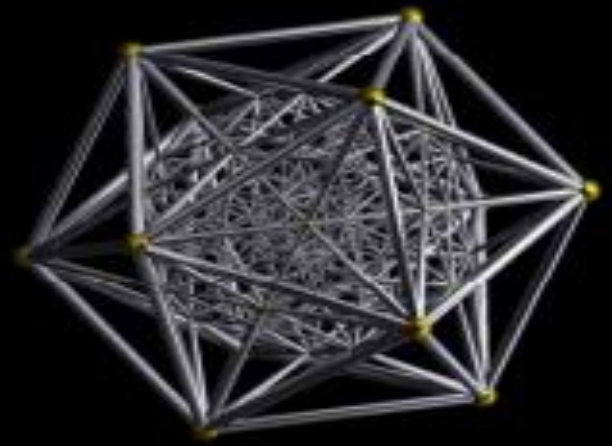
A new Paradigm for AI: HDC

Learning-Based Computational Models

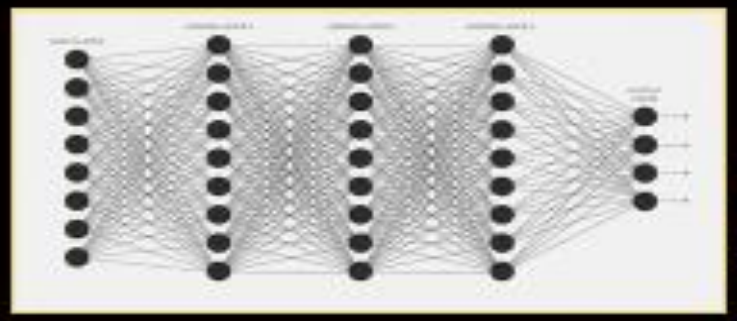


Bayesian Machine learning
(Believe propagation, reinforcement learning, graphical models, support-vector machines)

Model building non-trivial
Executed on standard processors (graph analytics)



High-dimensional computing (SDM, holographic)
Computing with patterns, one-shot learning



Deep Neural Nets
Learning compute and data hungry
Separate from execution
Complex

Privileged and Confidential Information

High-Dimensional Computing* as Another Approach

Cognitive processing that

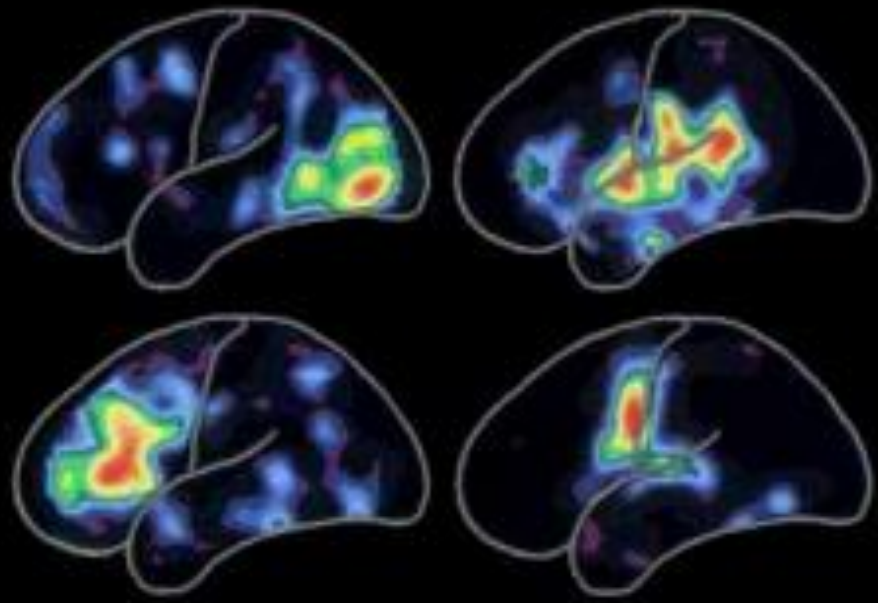
- provides simple and efficient on-line (one-shot) learning
- supports reasoning
- is embarrassingly parallel and memory-centric
- is extremely robust against most failure mechanisms
- offers ultra-low energy potential
- amenable to nanoscale 3D technologies

*: This is just one of many options being explored today

Hyper-Dimensional Computing (HDC)

- Hyperdimensional vectors (N > 10000) as basic computational symbols
  - represent patterns rather then numbers
  - Can be *approximate – that is,* can be compared for similarity

- Mathematical properties of high-dimensional spaces in remarkable agreement with behaviors observed in brain

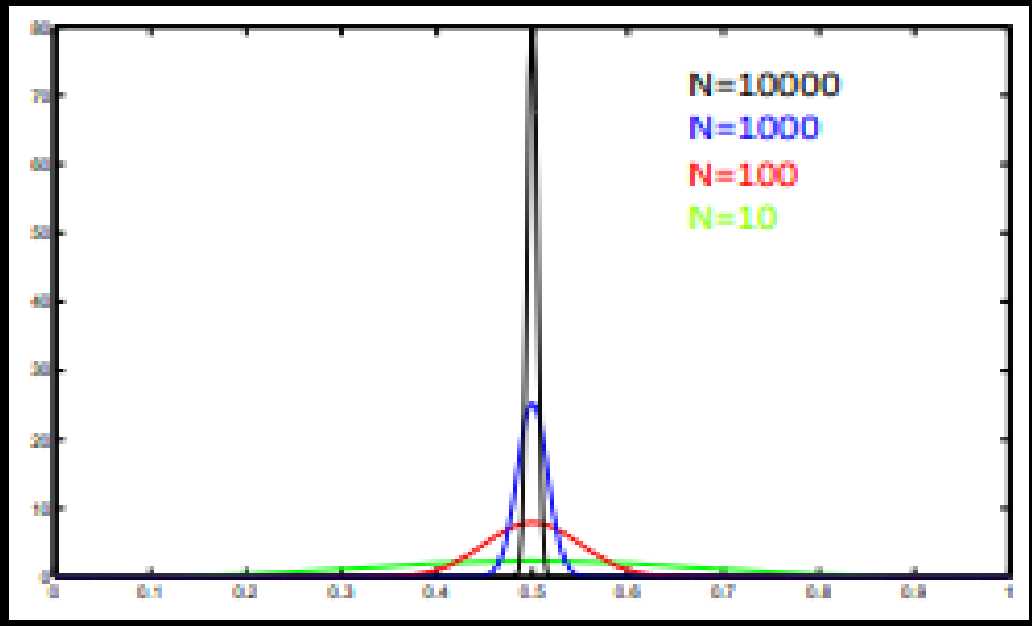


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Hyperdimensional Vectors – The Concept

Probability that two N bit vectors, randomly chosen, are different by at least N/2 bits (or normalized Hamming Distance >= 0.5)

n	Norm. Hamming Distance
10	>= 0.400 for 82.8125%
100	>= 0.450 for 86.4373%
1000	>= 0.453 for 99.8671%
10000	>= 0.485 for 99.8694%



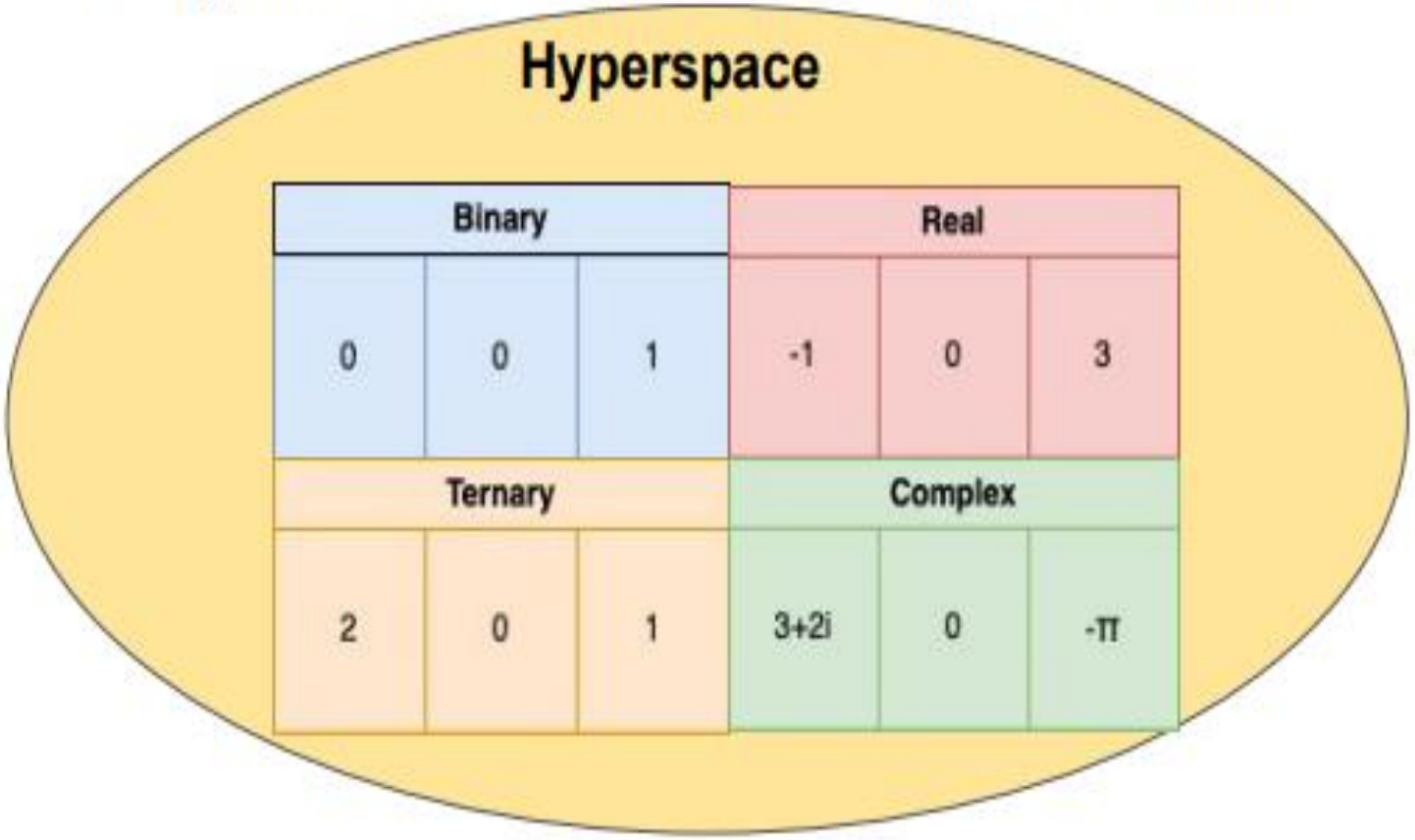
Distance histogram of vectors in N-dimensional space

99.9% probability that normalized Hamming distance between two randomly chosen vectors of length of 10k bits (0's and 1's) > 0.485!

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Hyperdimensional Representation

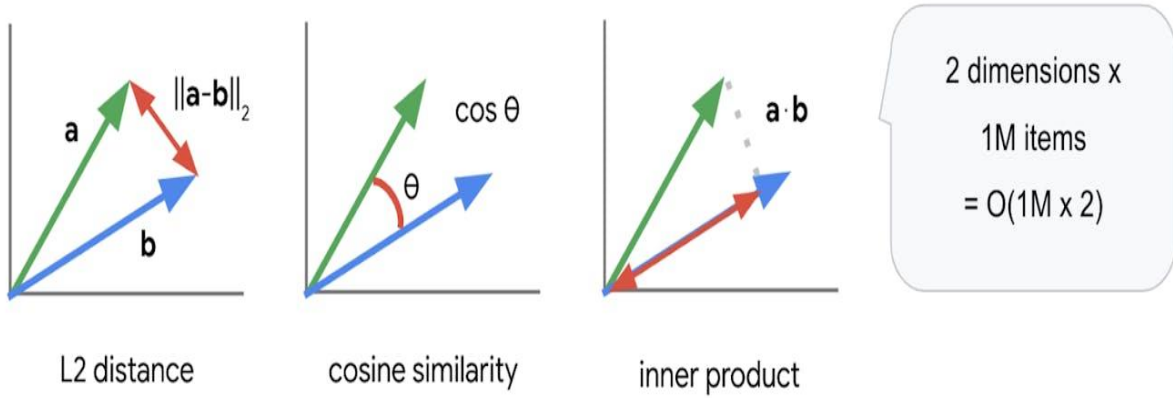
- Hyperdimensional representational space unit: **vector**

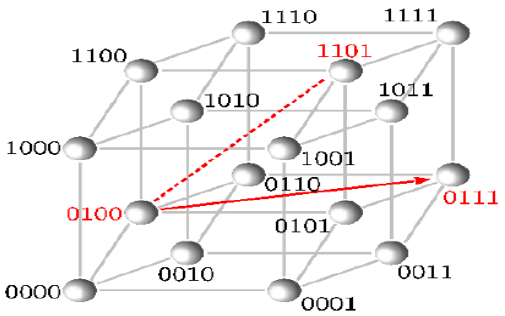


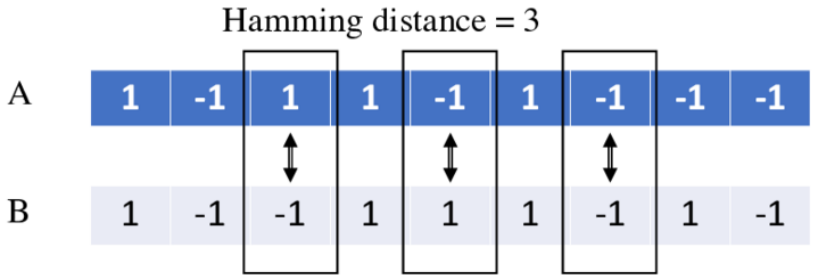
[Neuroscienze 299: Computing with High-Dimensional Vectors - Autunno 2021 - Redwood Center for Theoretical Neuroscience (berkeley.edu)]

Distance (similarity) as a metric for HVi

- Ortogonalità
- Distanza
- Sparsità e densità
- Distribuzione spaziale
- Operazioni su vettori







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Computing with Patters (the HD Algebra)

- Addition (+) is good for representing sets (bundling), since sum vector is similar to its constituent vectors.
  - $\langle A+B, A\rangle=0.5$
- Multiplication(*) is good for binding, since product vector is dissimilar to its constituent vectors.
  - $\langle A*B, A\rangle=0$
- Permutation (ρ) makes a dissimilar vector by rotating, and is good for representing sequences.
  - $\langle A, \rho A\rangle=0$

  NOTE: * and ρ are invertible and preserve the distance
- Distance Measurement (<>) computes distance between 2 vectors
  - Parallel search for closest match performed in Associative Memory

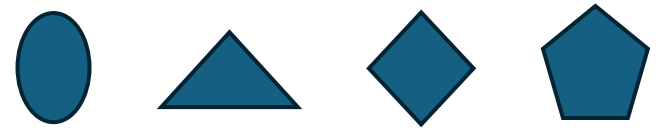
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Somma di HV

- La **somma** di HV vuol dire **associazione** o **sovrapposizione**
- Genera un vettore **simile** ai suoi componenti
- Il risultato della somma viene **normalizzato**
- La somma è **commutativa** HV1+HV2= HV2+HV1

Addizione (+): coordinata per coordinata

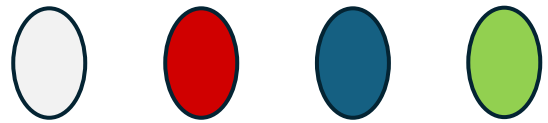
```
1.    = +1 -1 -1 +1 -1 -1 .... +1 +1 -1 +1
2.    = +1 +1 +1 +1 -1 +1 .... -1 +1 +1 +1
3.    = -1 -1 +1 -1 -1 +1 .... -1 -1 -1 +1
-------------------------------------------
A+B+C = +1 -1 +1 +1 -3 +1 .... -1 +1 -1 +3
```



HV1 HV2 HV3 HV4

Forma= HV1+HV2+HV3+HV4

Il vettore **Forma** è simile ai vettori HV1, HV2, HV3, HV4



HV5 HV6 HV7 HV8

Colore= HV5+HV6+HV7+HV8

Il vettore **Colore** è simile ai vettori HV5, HV6, HV7, HV8

I vettori **Forma** e **Colore** sono dissimili (quasi ortogonali)

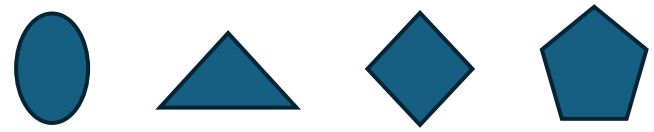
Privileged and Confidential Information

Moltiplicazione di HV

- La **moltiplicazione** vuol dire **legame** o associazione **Chiave-Valore**
- Genera un vettore **dissimile** dai suoi componenti (quasi ortogonali)
- Nei vettori binari (0-1) viene eseguita da uno **XOR**
- È **commutativa** rispetto alla somma A*(B+C) =A*B +A*C

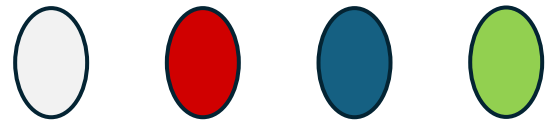
```
 Moltiplicazione (*): coordinata per
coordinata
    1.   = +1 -1 -1 +1 -1 -1 .... +1 +1 -1 +1
    2.   = +1 +1 +1 +1 -1 +1 .... -1 +1 +1 +1
     ------------------------------------------
   A*B = +1 -1 -1 +1 +1 -1 .... -1  +1 -1 +1

NOTA: A*A = 1 1  1 1 ... 1 1 -> auto-inverso
```



HV1 HV2 HV3 HV4

Forma= HV1+HV2+HV3+HV4



HV5 HV6 HV7 HV8

Colore= HV5+HV6+HV7+HV8

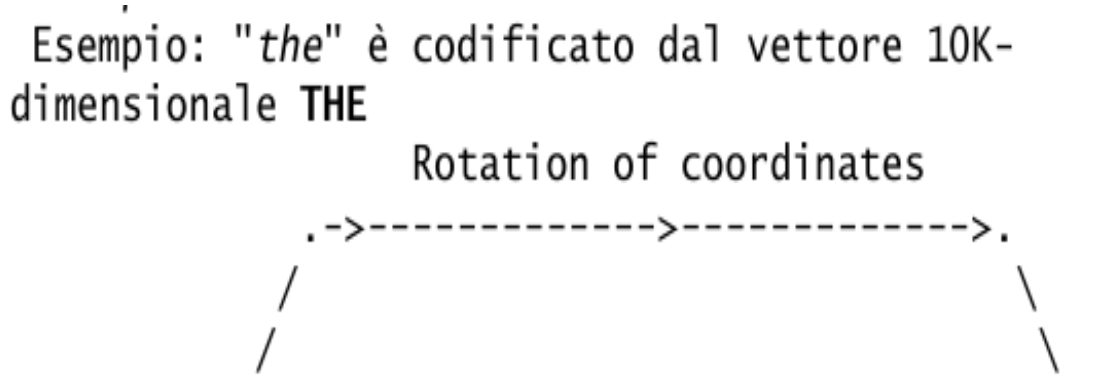
TR= HV2 *HV5 triangolo rosso

CV= HV1* HV8 cerchio verde

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Permutazione: sequenze spaziali e temporali

Esempio: "*the*" è codificato dal vettore 10K-dimensionale **THE**



THE = (+1 +1 -1 +1 . . . . . +1 +1 -1 -1)

In symbols:

THE = *rr***T** * *r***H** * **E**

dove

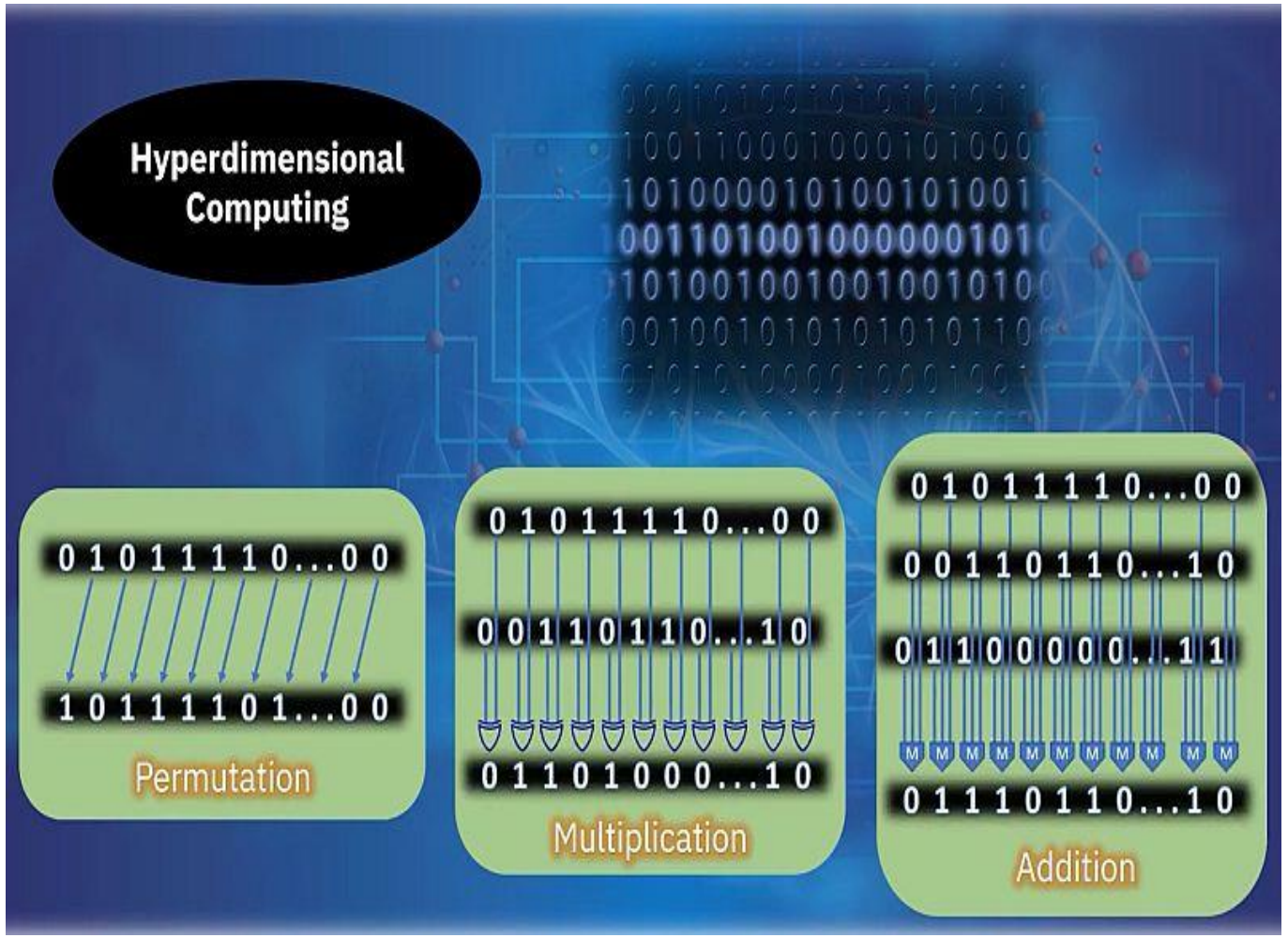
r è una rotazione di 1 posizione (è una *permutazione*)

Permutazione (*r*): Rotazione dellecoordinate

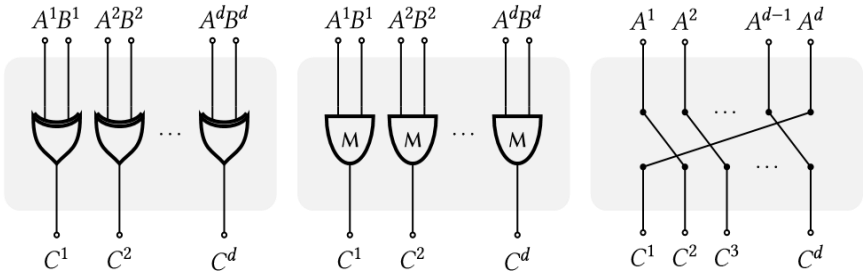
A = +1 -1 -1 +1 -1 -1 .... +1 +1 -1 +1

rA = -1 -1 +1 -1 -1 .... +1 +1 -1 +1 +1 .

MAP: Multiply, ADD, Permute come operatori



- Multiply: XOR
- ADD: Adder
- Permute: Shift



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Codifica: coppie e insiemi di dati

Codifica di una **coppia** con moltiplicazione (associando la variabile *x* al *valore* a, detta anche associazione): p = (x,a)

P = X*A

Estrazione del valore di *x* dalla coppia:

X*P = X*(X*A) = (X*X)*A = A
(X*X canali fuori)

Codifica di un **insieme** con addizione:
s = {a,b,c}

S = A + B + C

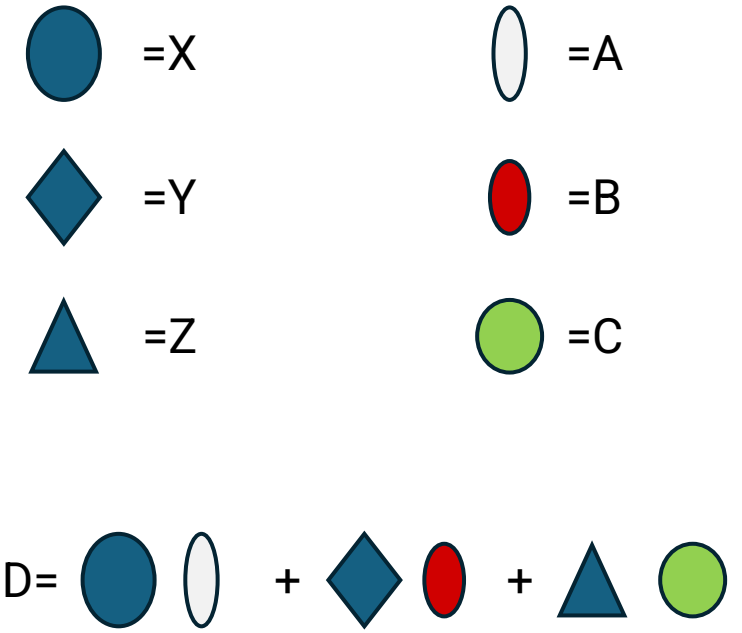
Codifica record di dati

Codifica di **un record di dati** con un set di coppie associate: *d* = '(x = a) & (*y* = *b*) & (*z* = *c*)'

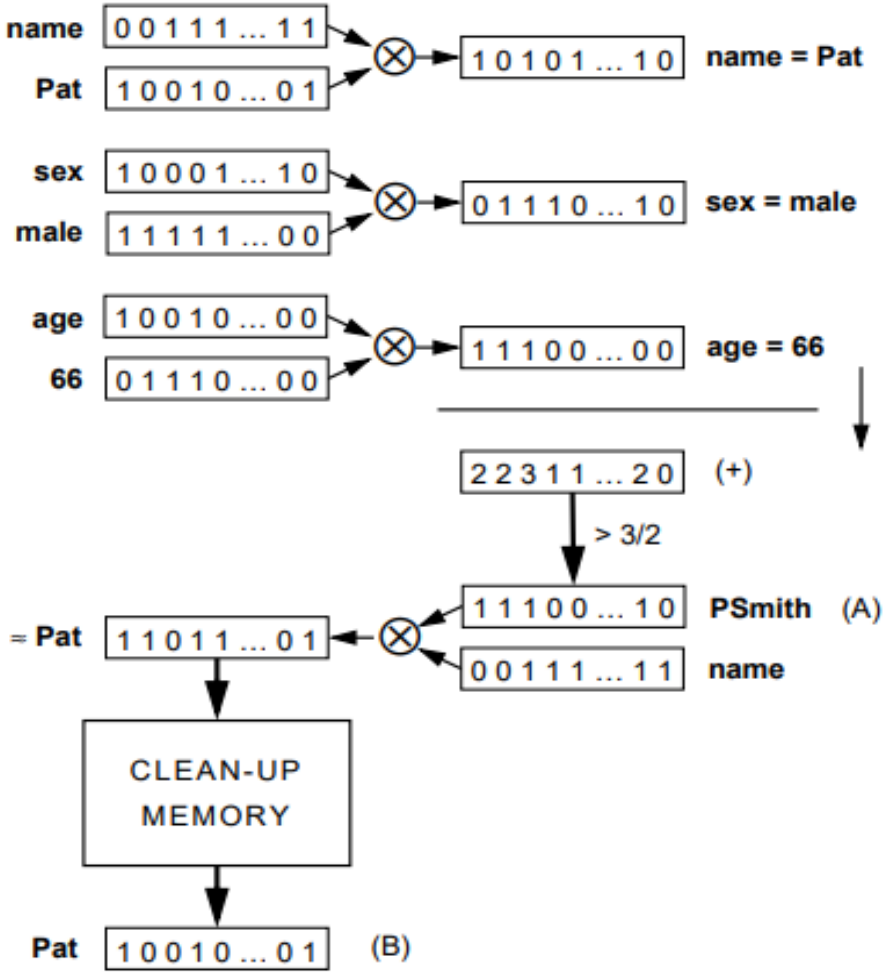
D = X*A + Y*B + Z*C

Estrazione del valore di *x* dal record:

$$
\begin{aligned}
\mathbf{X*D} &= \quad X * (\mathbf{X*A} + \mathbf{Y*B} + Z*C) \\
&= X*\mathbf{X*A} + \mathbf{X*Y*B} + \mathbf{X*Z*C} \\
&= X*\mathbf{X*A} + (\mathbf{X*Y*B} + \mathbf{X*Z*C}) \\
&= \quad \mathbf{A} + \text{rumore} \\
&\approx \mathbf{A}
\end{aligned}
$$



Moltiplicazione: legame Chiave-Valore



Psmith = name * Pat + sex * Male + age * 68

Dal vettore **Psmith** si può estrarre qualsiasi valore moltiplicandolo per il vettore **name** si ottiene
Pat + rumore, e può essere recuperato confrontando
Il risultato della moltiplicazione con la memoria
degli elementi e cercando il vicino più prossimo

Example: Text Processing
(language recognition, text classification)

- Each symbol (letter) is represented by 10,000-D hypervector chosen at *random:*

A = -1 +1 -1 -1 -1 +1 -1 -1 …
B = +1 -1+1 +1+1 -1 +1 -1 …
C = -1 -1 -1 +1 +1 -1 +1 -1 …
D = -1 -1 -1 +1 +1 -1 +1 -1 …
…
Z = -1 -1 +1 -1 +1 +1 +1 -1 …



- Every letter hypervector is dissimilar to others, e.g., $\langle A, B \rangle = 0$
- This assignment is fixed throughout computation

Computing a Profile Using HD Arithmetic

- Trigram (3-letter sequence) : HD vector computed from its *Letter Vectors* with permutation (cyclic shift) and pointwise multiplication.

example: "EAT" versus "ATE"

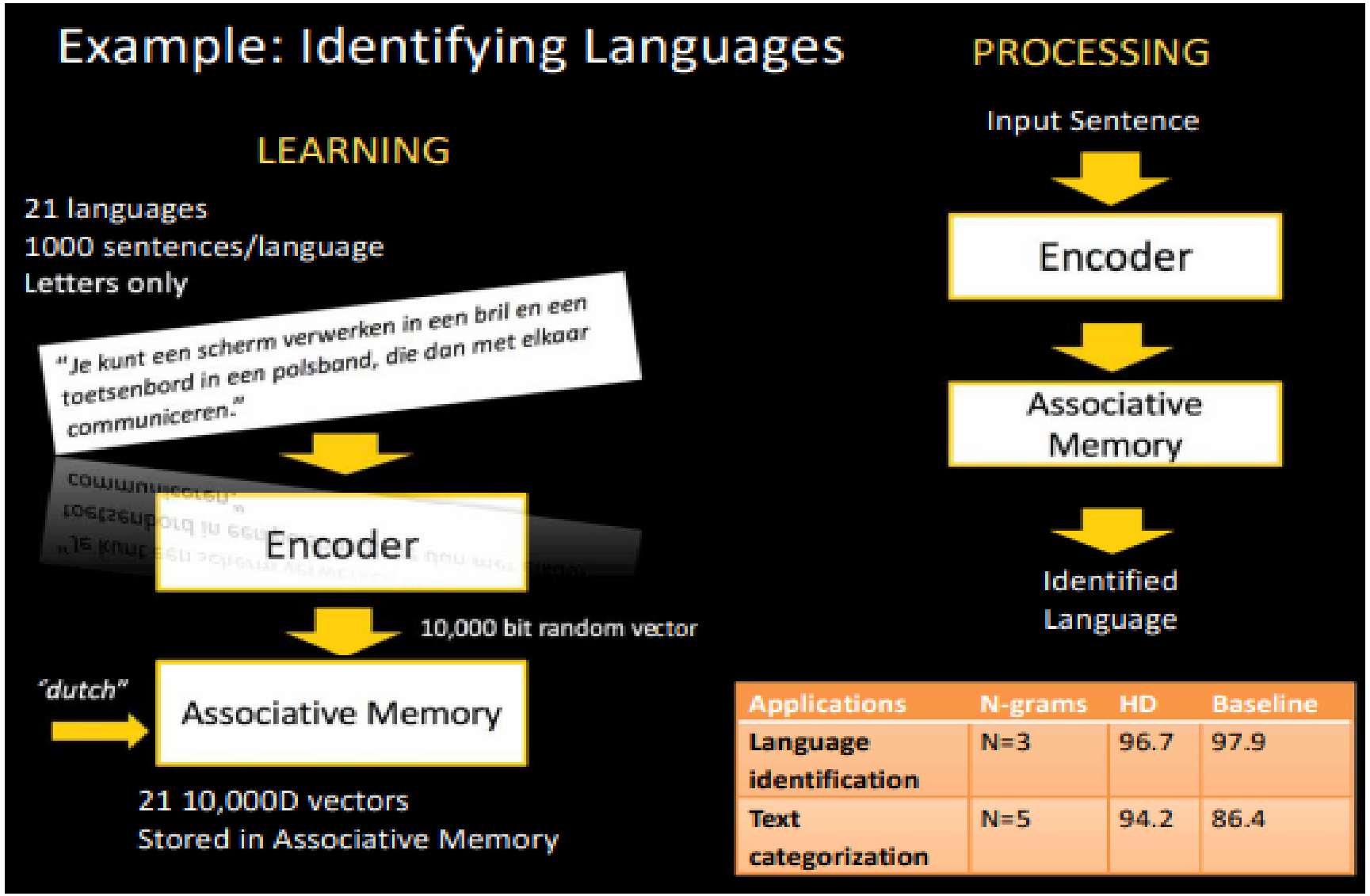
E =		-1	-1	-1	+1	+1	-1	+1	-1	...	
	A =		-1	+1	-1	-1	-1	+1	-1	-1	...
		T =		-1	-1	+1	-1	+1	+1	+1	-1	...
E	A	T =		+1	+1	-1	-1	+1	+1	...		

A =		-1	+1	-1	-1	-1	+1	-1	-1	...	
	T =		-1	-1	+1	-1	+1	+1	+1	-1	...
		E =		-1	-1	-1	+1	+1	-1	+1	-1	...
A	T	E =		-1	+1	-1	+1	-1	+1	...		

New HD vector representing sequence of characters

HD vector of complete text: Sum of trigrams created by sliding window

Example: Identifying Languages



Applications	N-grams	HD	Baseline
Language identification	N=3	96.7	97.9
Text categorization	N=5	94.2	86.4

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From Classification to Reasoning

A simple example

What is the Dollar of Mexico?

Learning (HD database representation)

R1 = Country * USA + MoneyUnit * Dollar + Population * 320M + …
R2 = Country * Mexico + MoneyUnit * Peso + Population * 120M + …
…

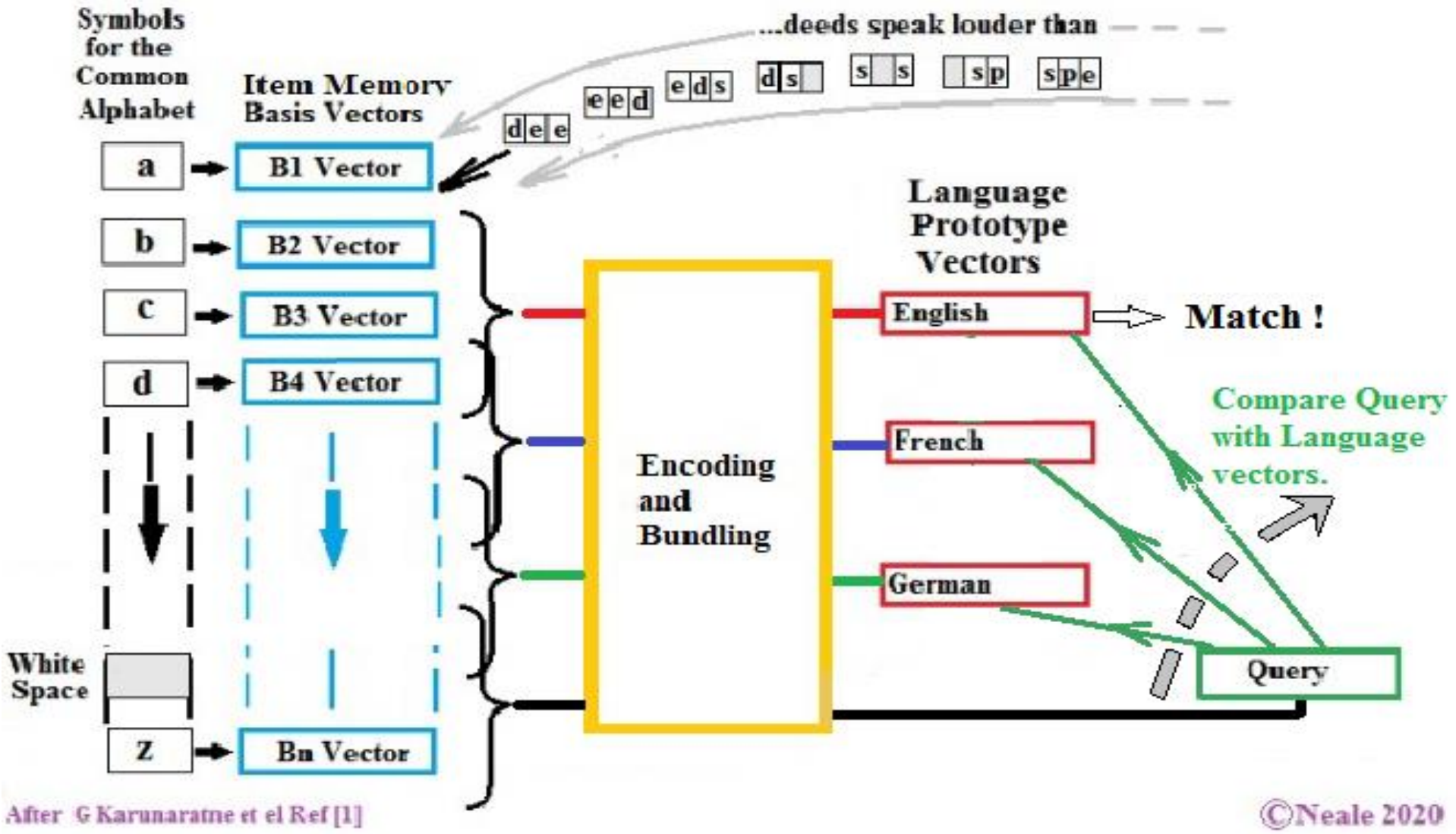
Data stored in superposition

Queries

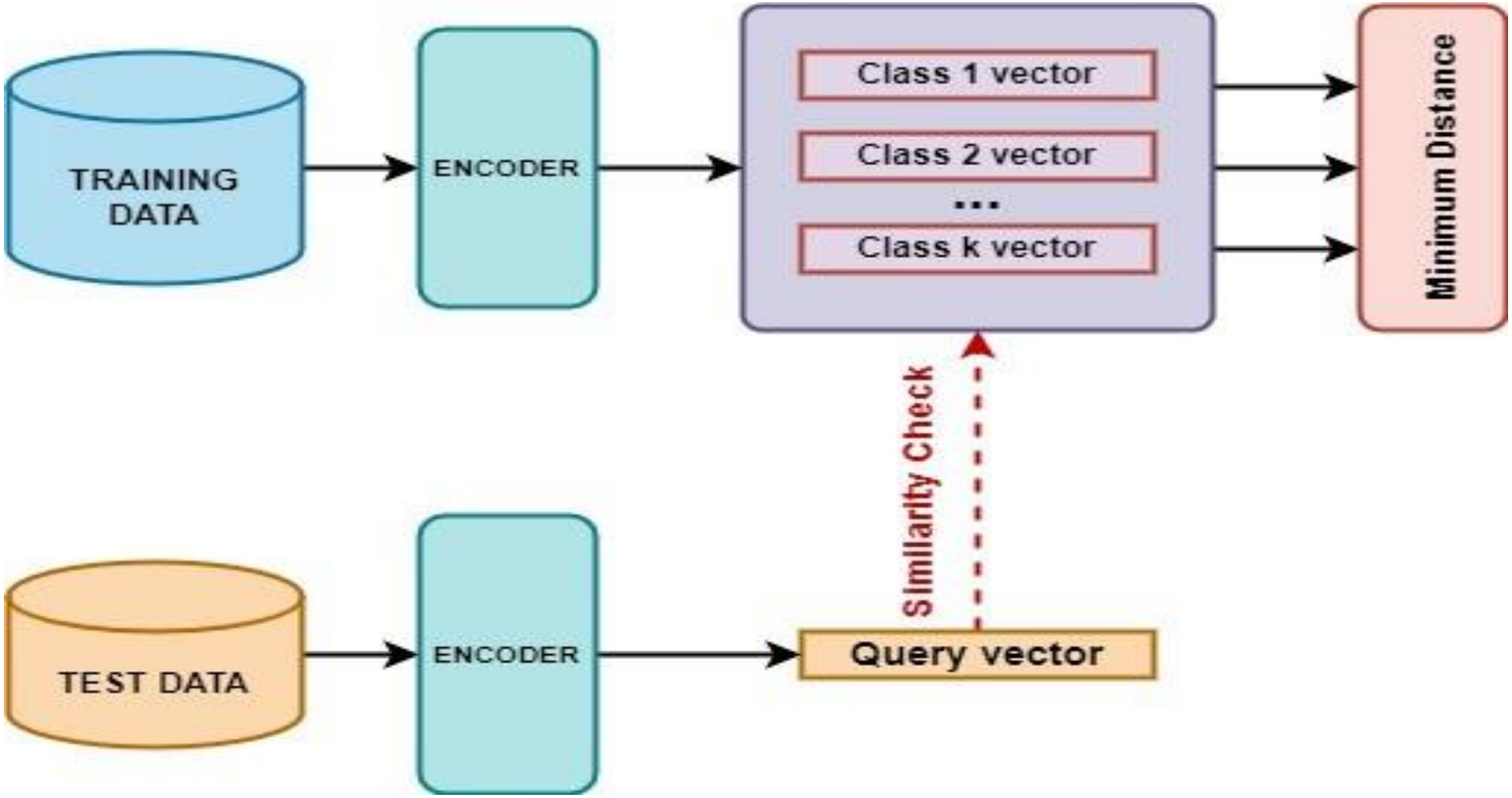
<R2 * Country> = Mexico
<R2 * <R1 * Dollar> > = Peso
…

- Yellow color codes components operating with HD distributed representation.
- <> stand for associative match

Riconoscere il linguaggio



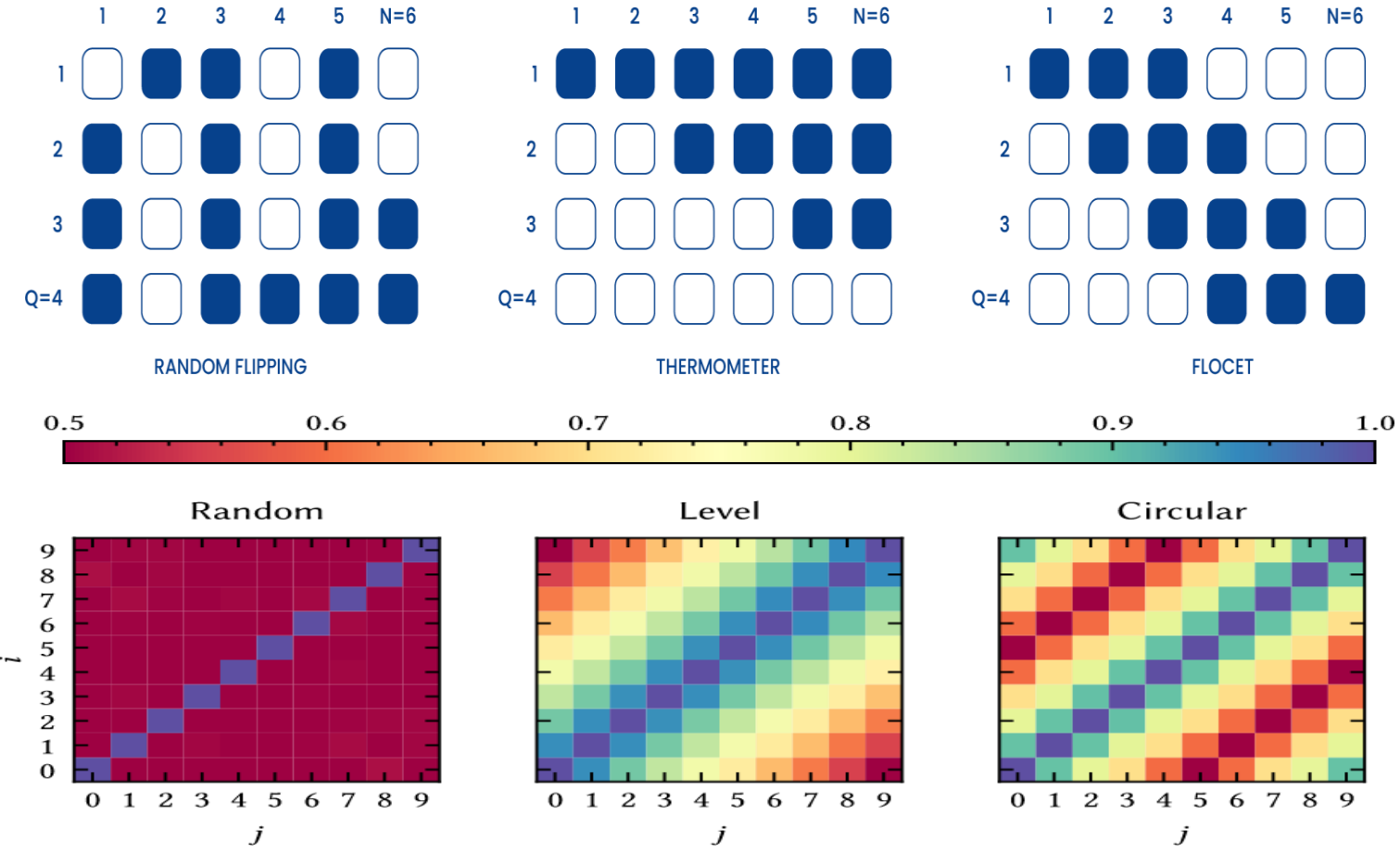
3 operazioni: Mappatura, Codifica, Ricerca



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Mappatura: ipervettori di livello

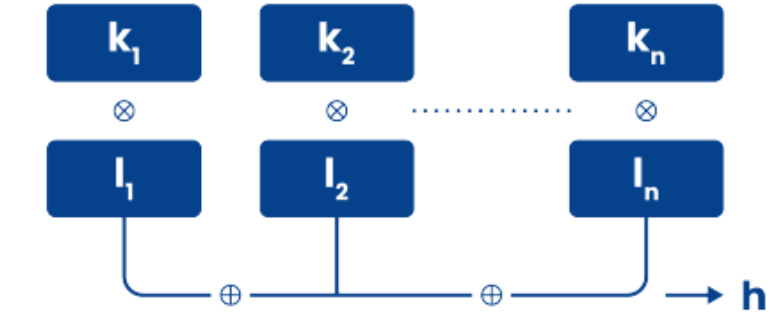
- Vettore iniziale casuale, inversione ciclica, random, circolare

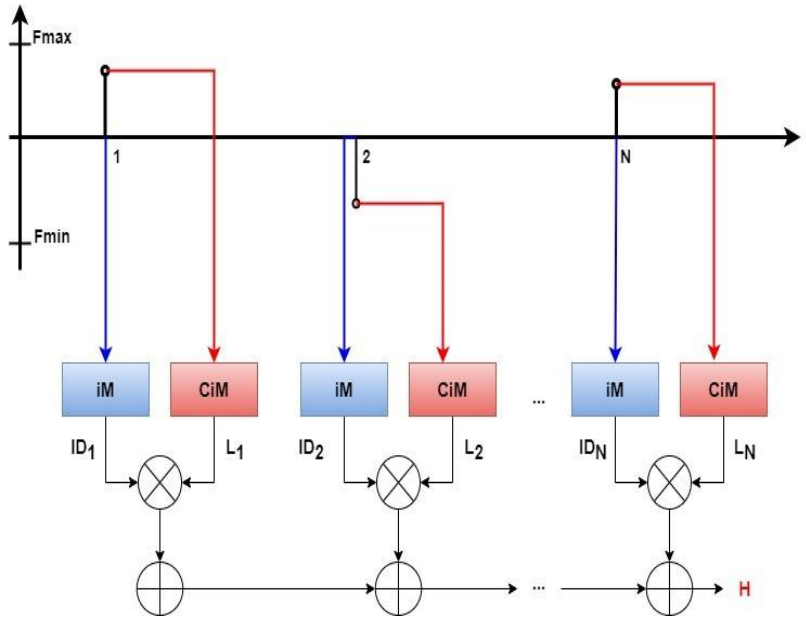


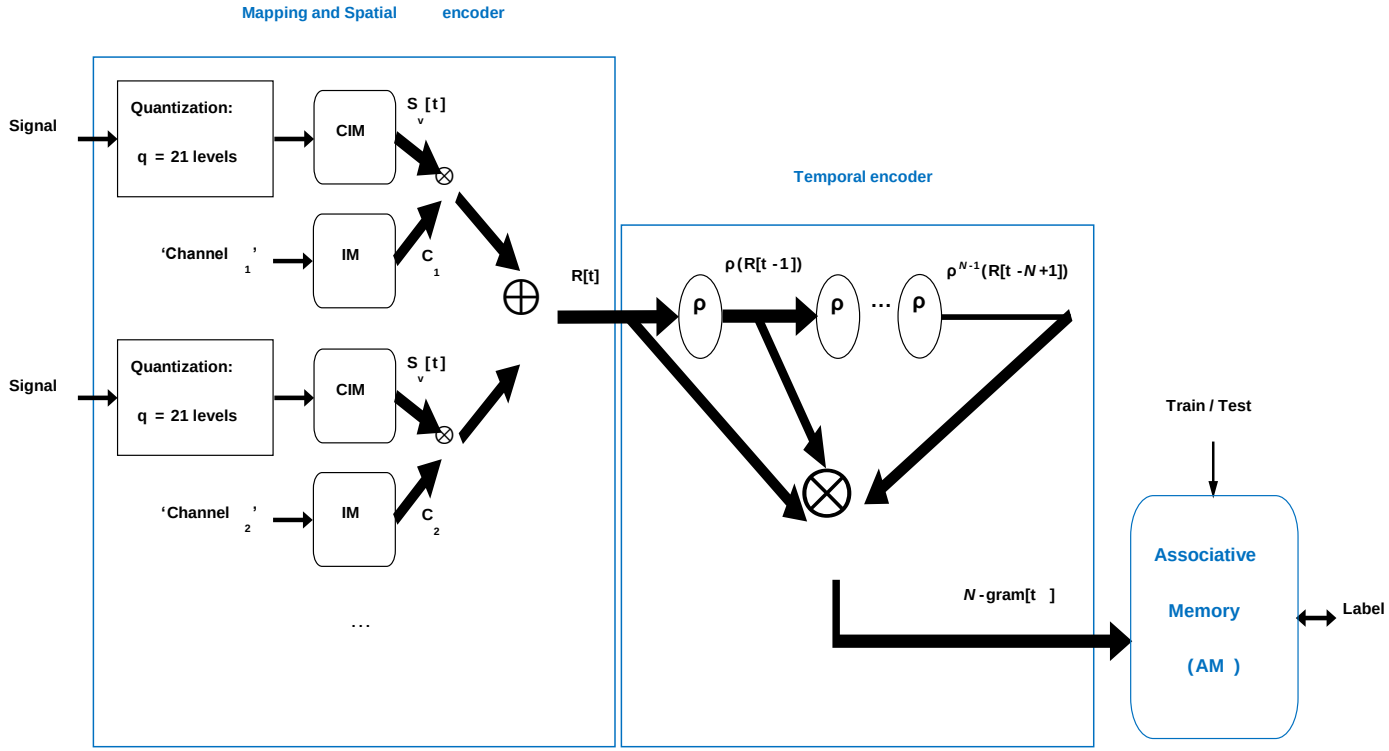
Privileged and Confidential Information

Mappatura: Legame di HV di livello e HV simbolici

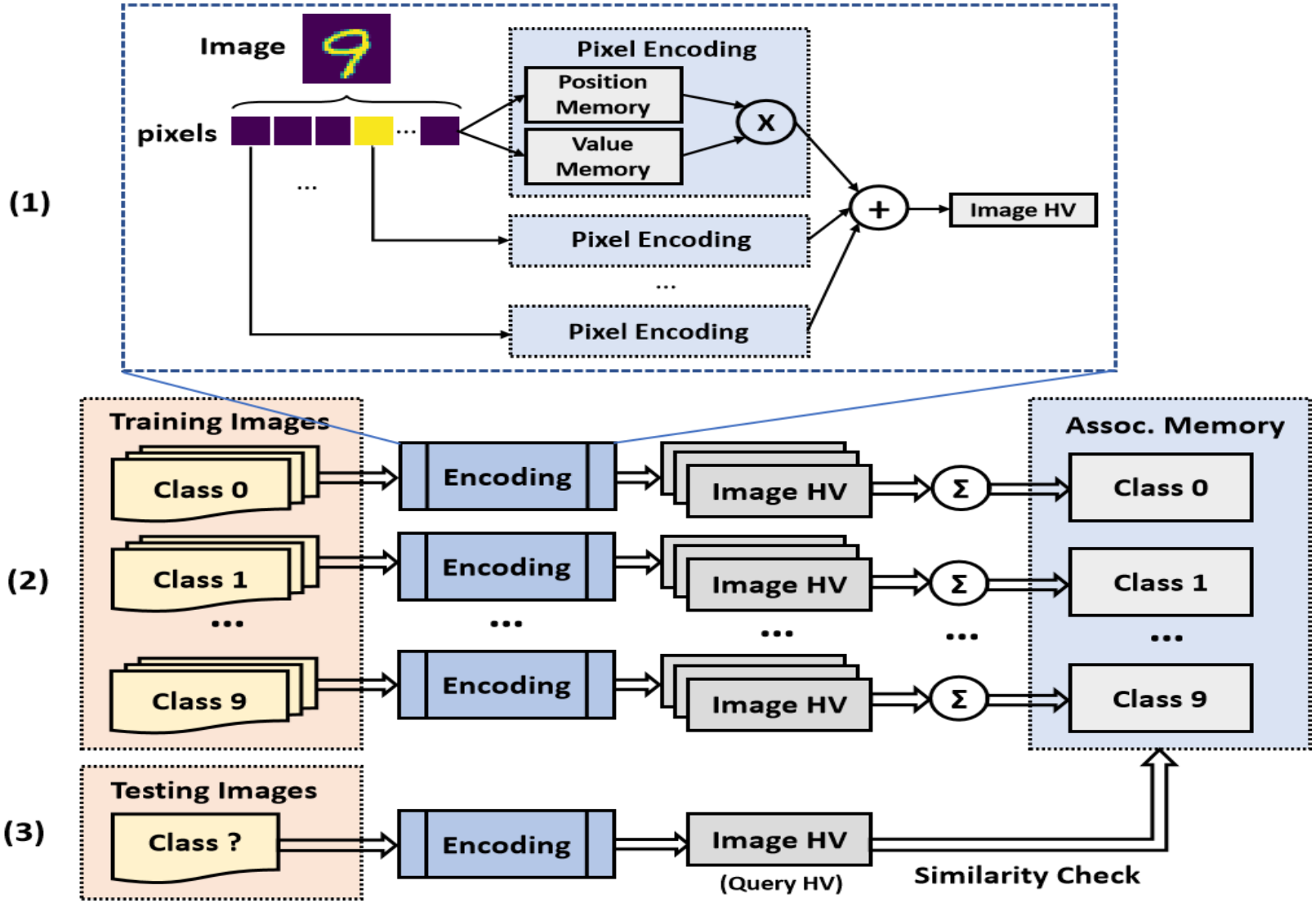
$$h = (k_1 \otimes v_1) \oplus (k_2 \otimes v_2) \oplus \cdots \oplus (k_n \otimes v_n)$$



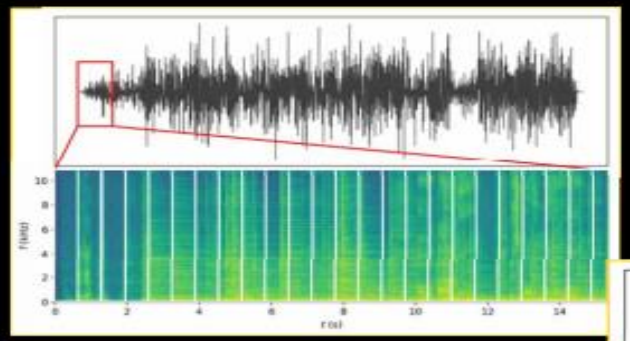




Mappatura: immagini-HV di livello e di posizione

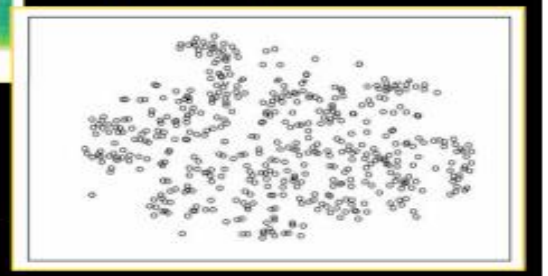


HD applied to streaming signals



Example: Music signal

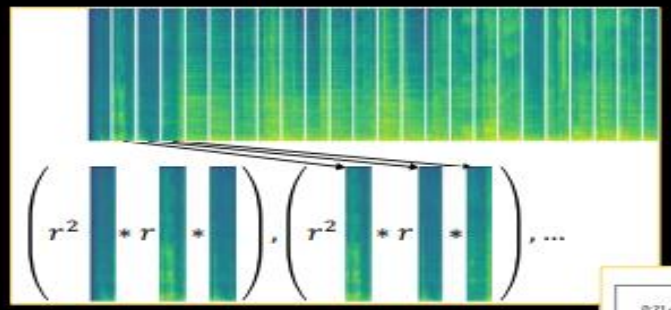
Mapped in HD space:
no visible structure



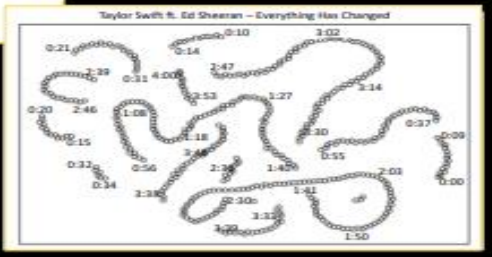
Mapping from high-dimensional to 2-dimensional space
Using t-SNE algorithm

[Courtesy: Justin Wong]

Imposing structure with HD



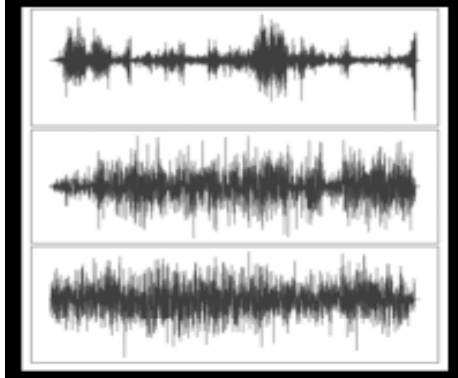
Sliding trigram representation
reveals underlying structure



HD song map

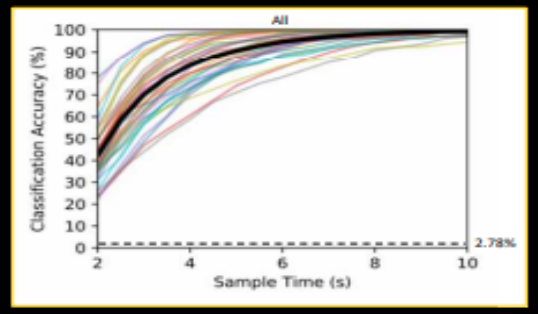
[Courtesy: Justin Wong]

Classifying Music with HD



In which song does segment occur?

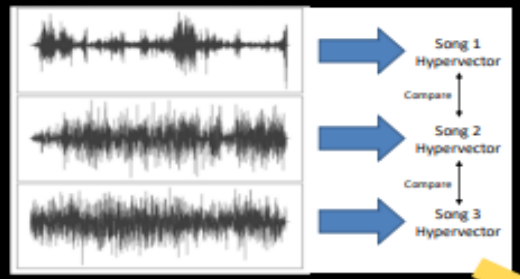




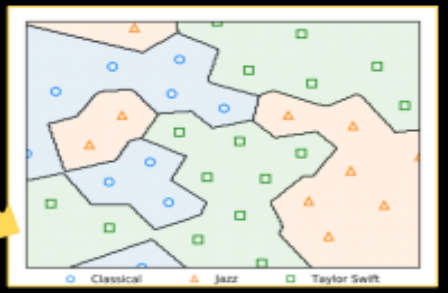
Hypervector size (per song): 86 kB
Compression rate between 65 and 335

[Courtesy: Justin Wong]

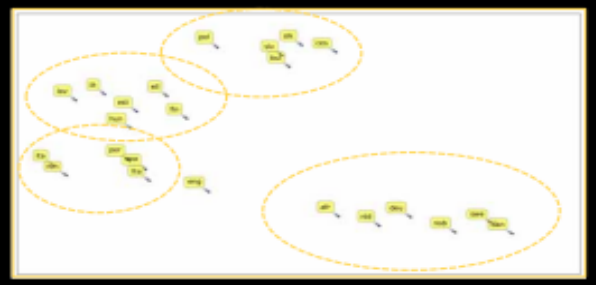
HD provides insights



For music classification

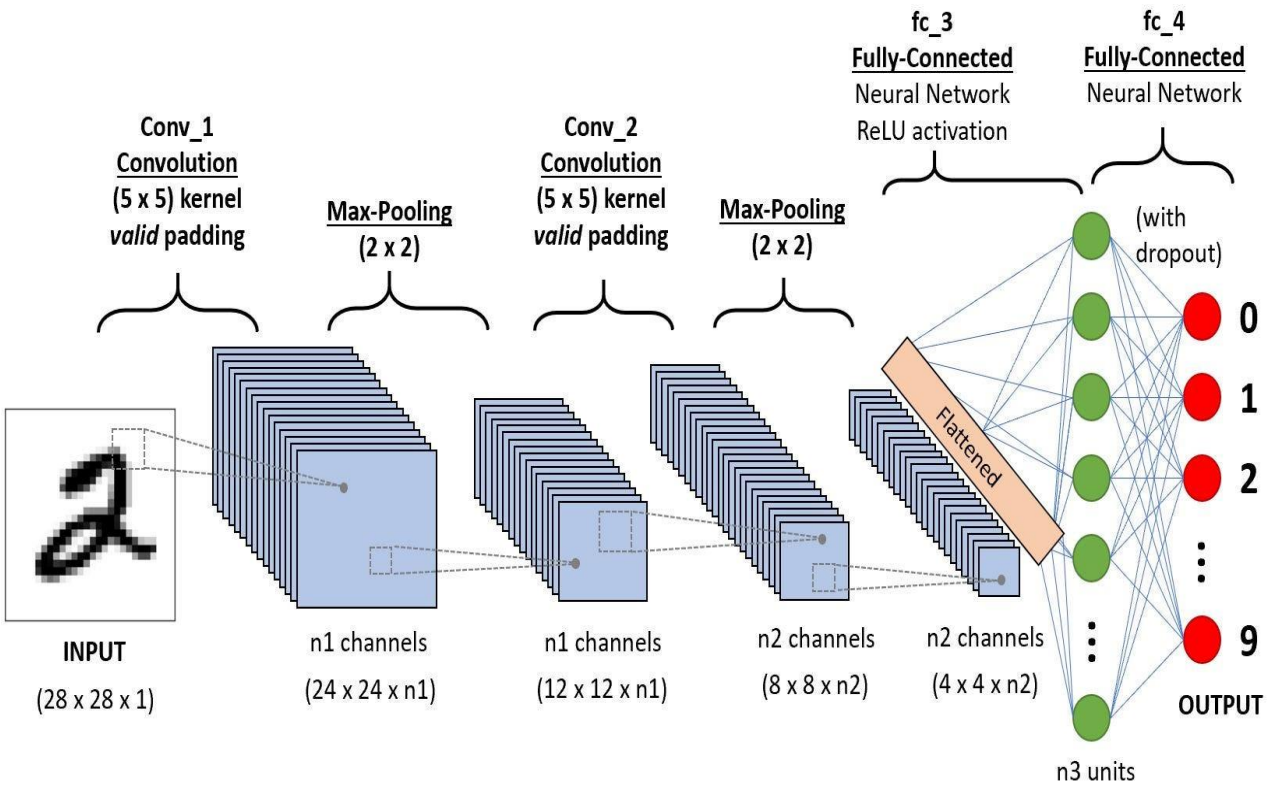


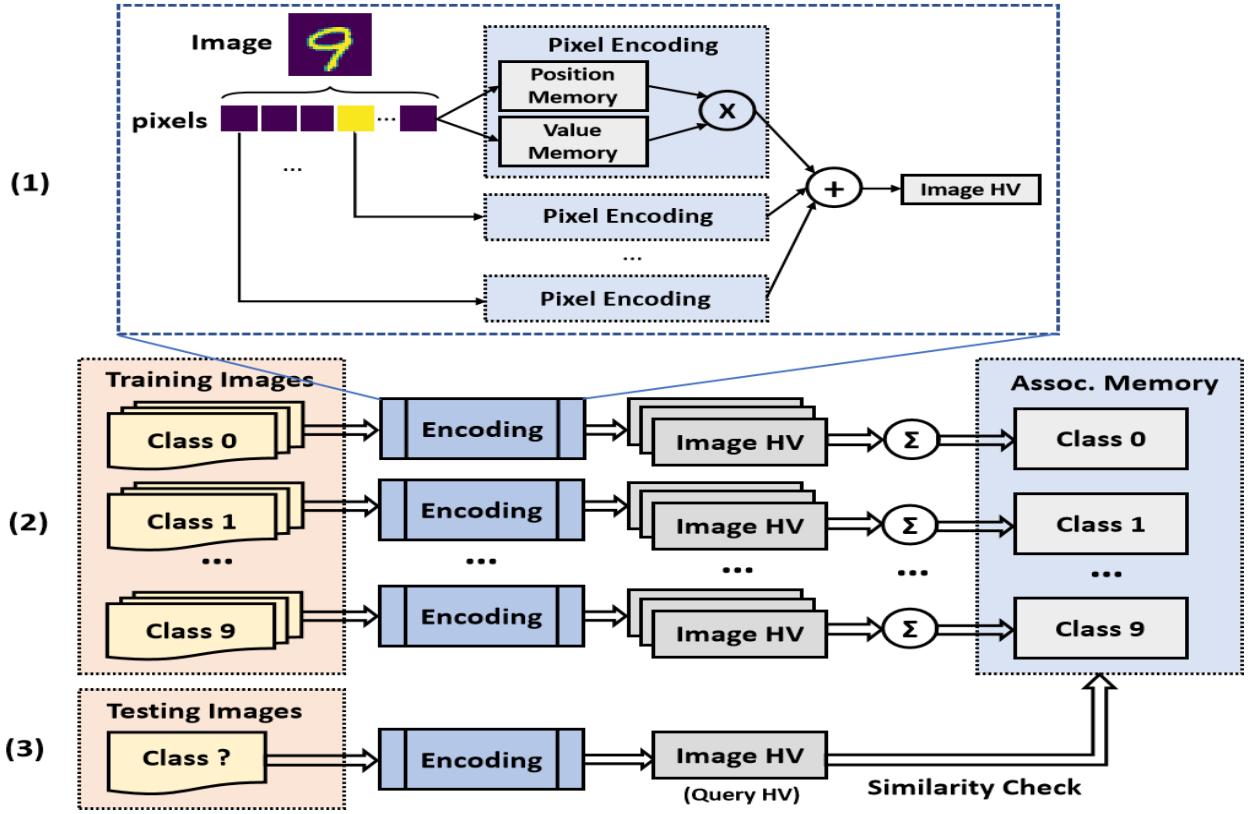
Or languages ...



[Courtesy: J. Wong and P. Kanerva]

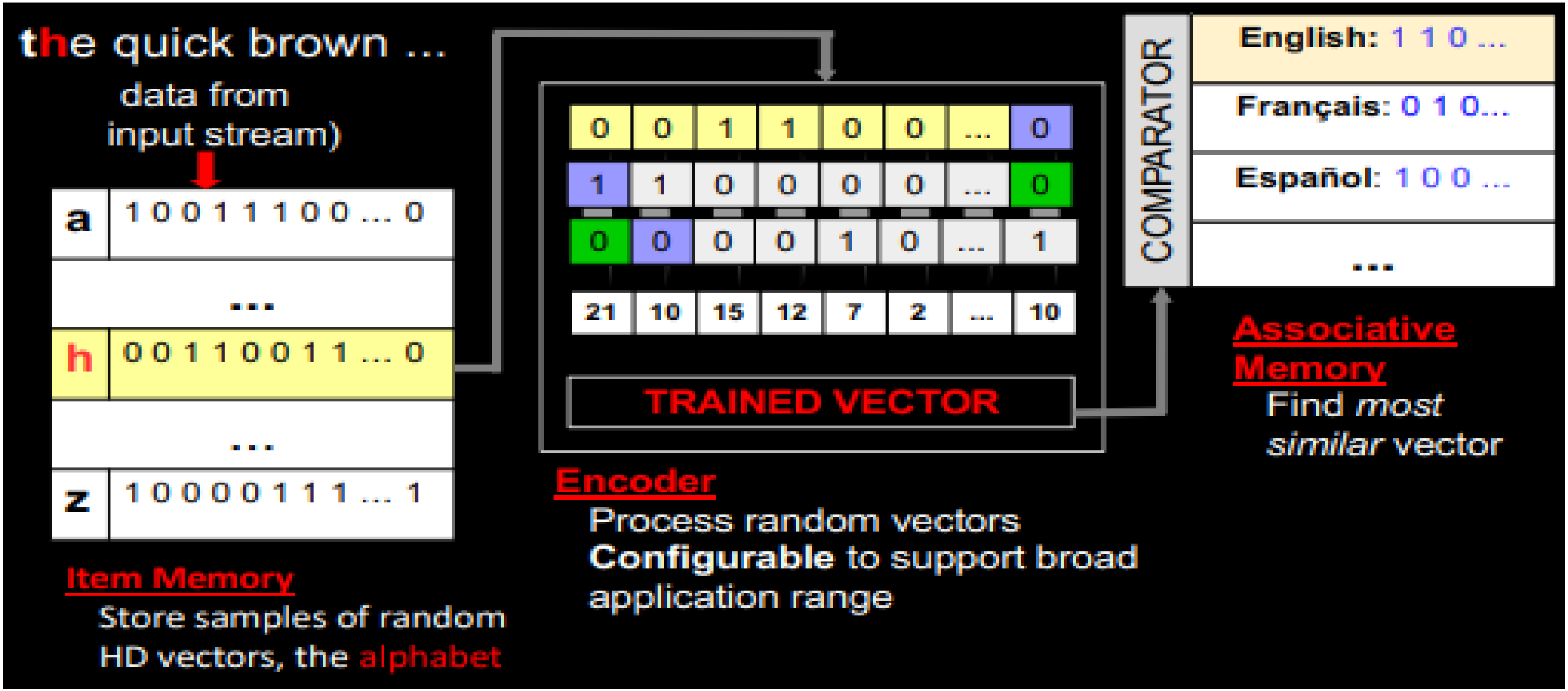
DNN vs HDC





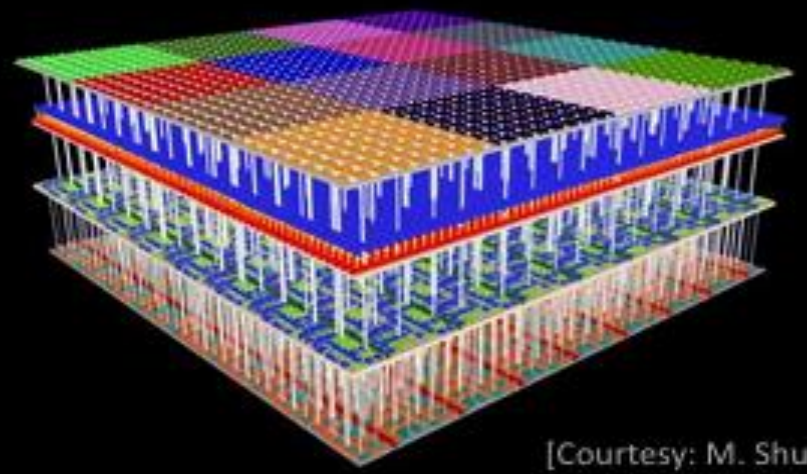
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Building a Generic HD Processor



HDC maps well into 3D nanostructures

- Tight interweaving of memory and logic
  - True in-memory computing
- Approximate
  - Extremely robust against failures and errors
  - Allows for low SNR computing
- Scalable

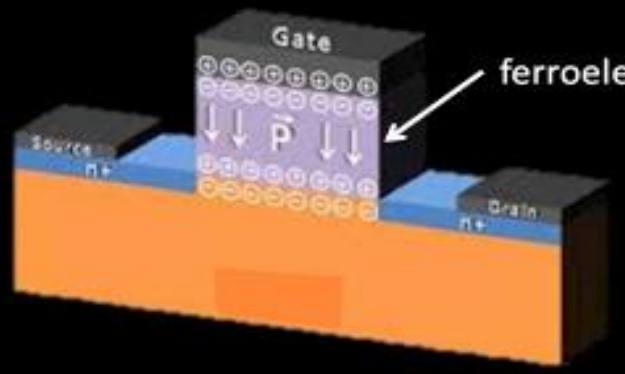


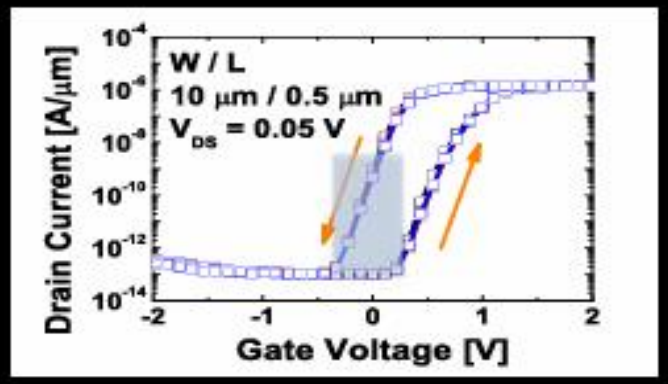
[Courtesy: M. Shulaker]

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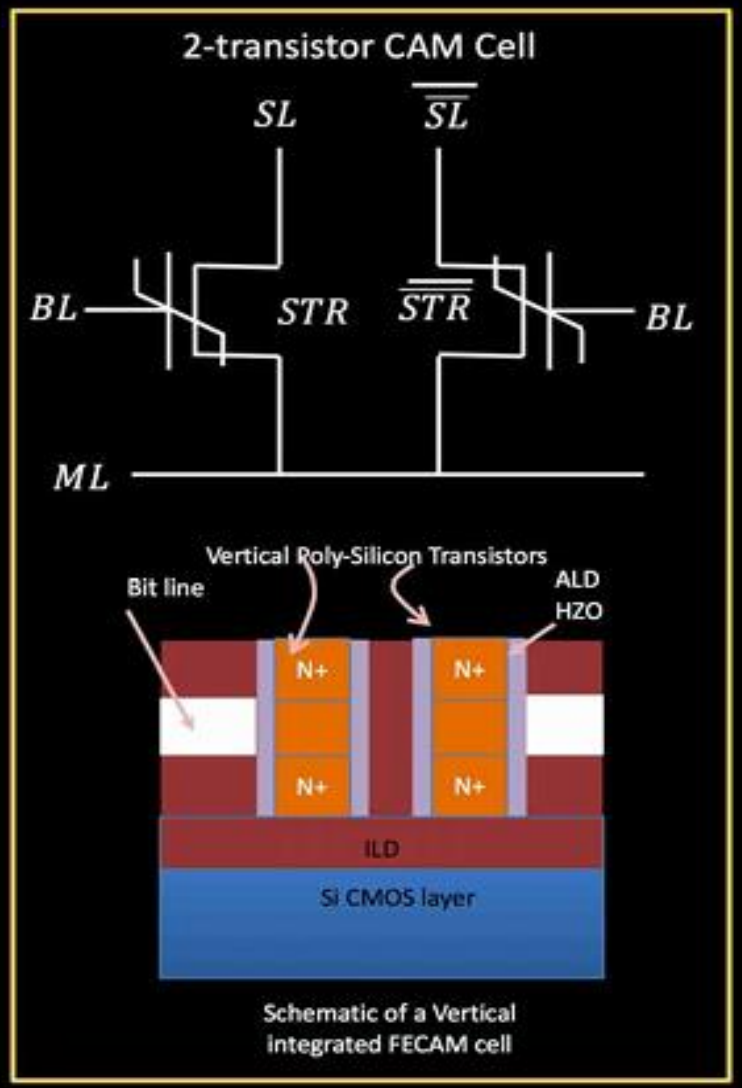
Device Opportunity: Ferroelectric AM

Device opportunity: Ferroelectric AM



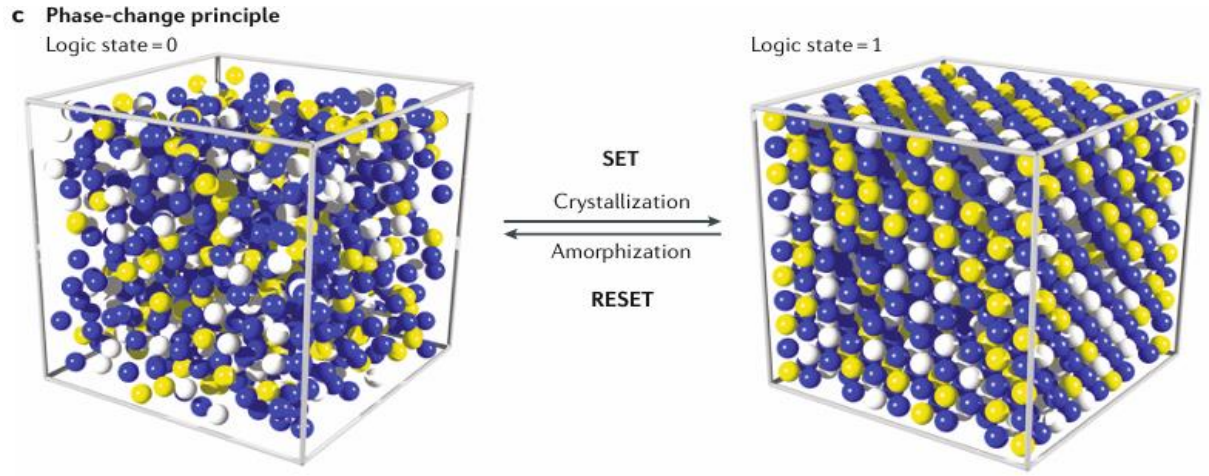


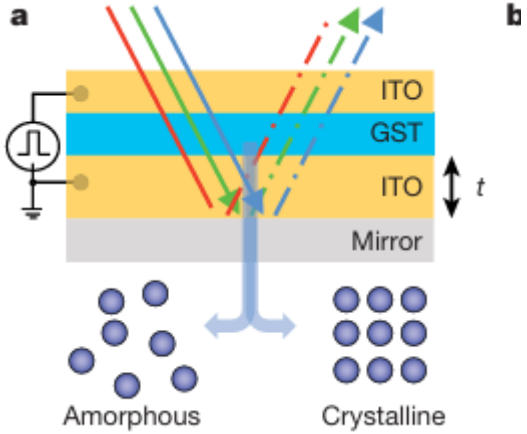
[Courtesy: Sayeef Salahuddin, UCB]

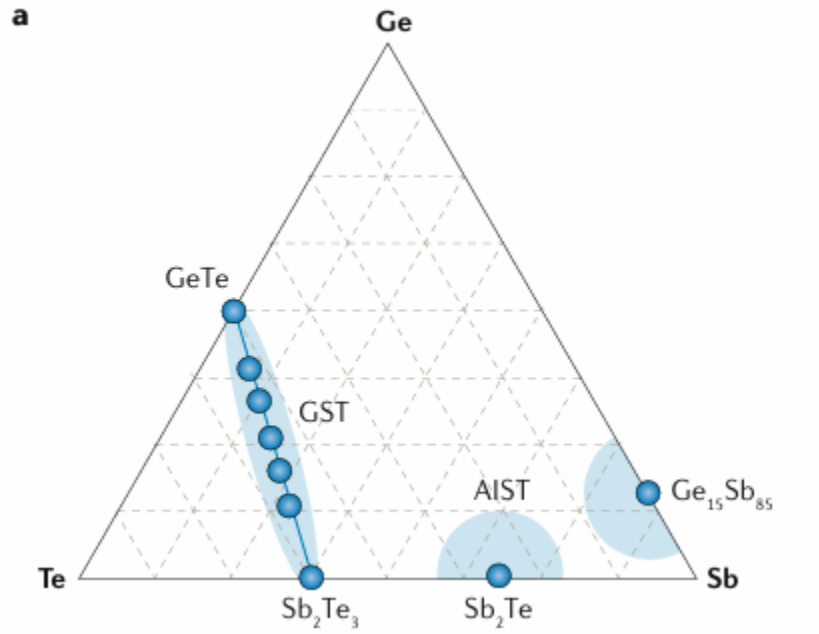


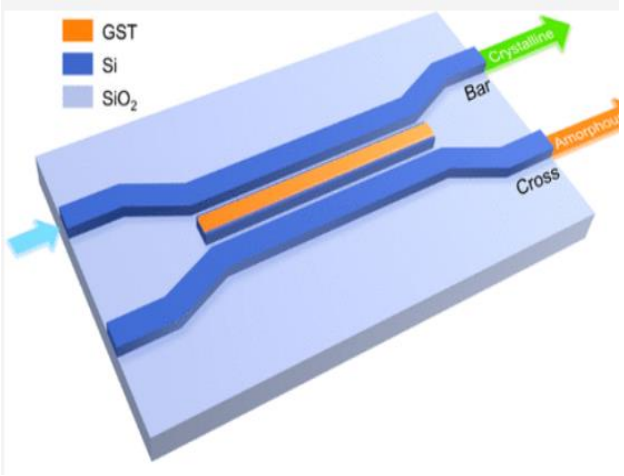
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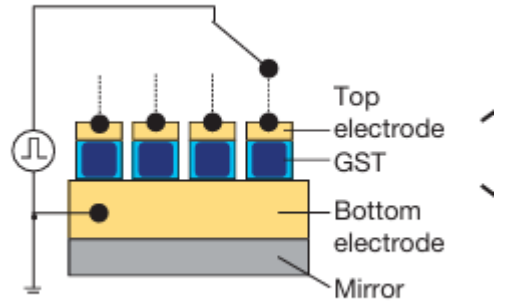
Optical-Phase Change Materials

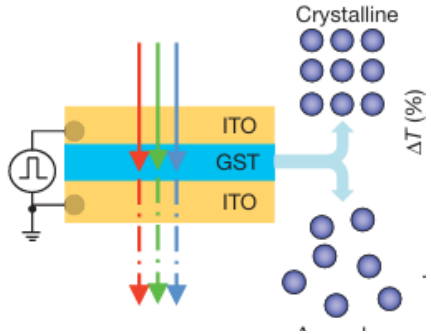






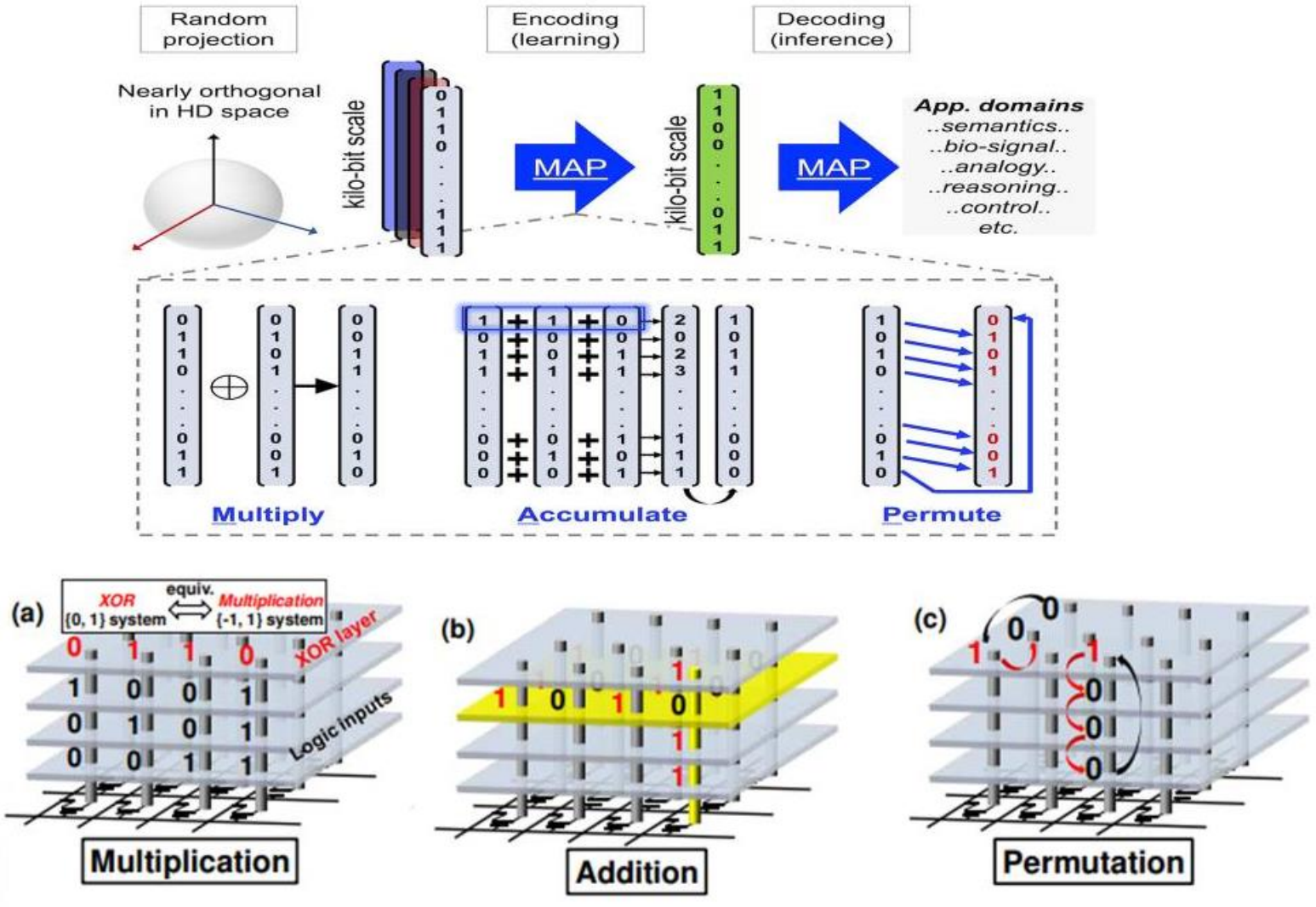




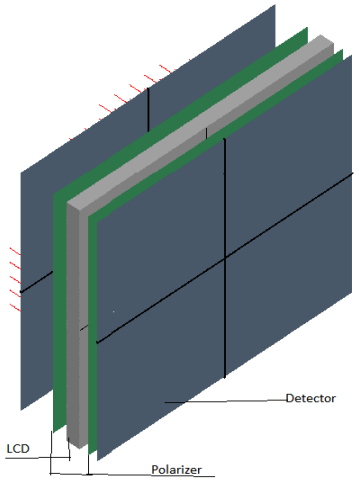


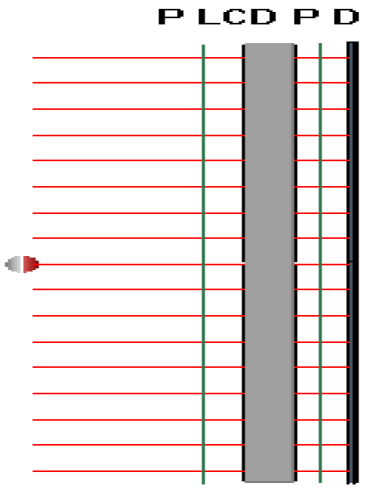
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HDC needs Parallelism: OptoPC can do it

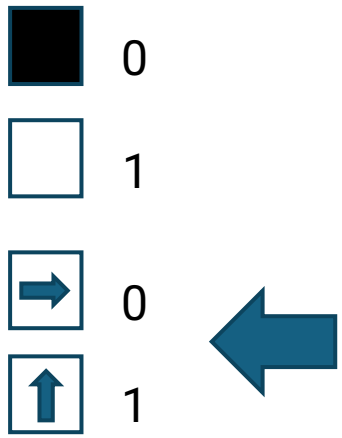


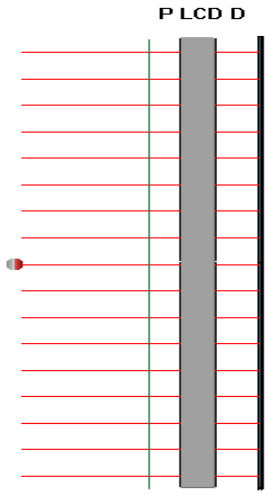
LCDs Parallelism

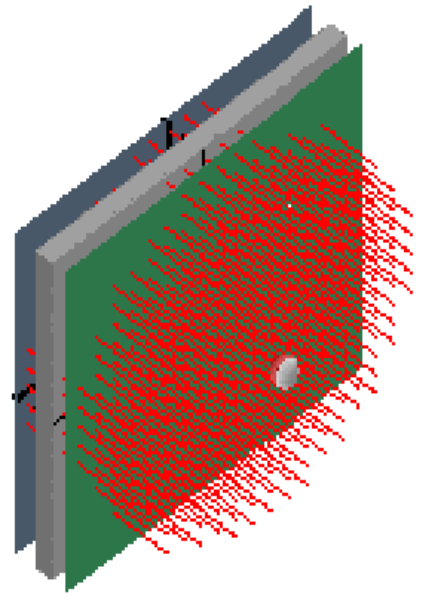


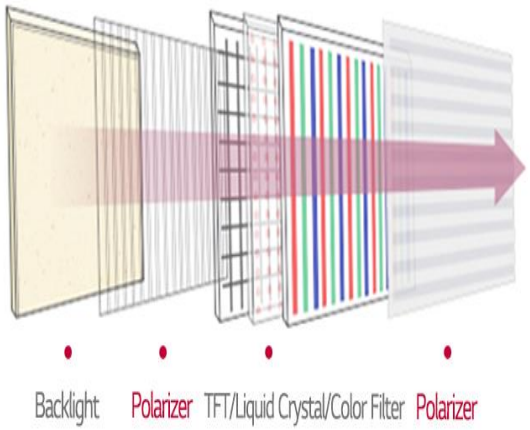


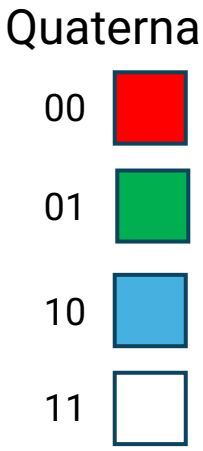








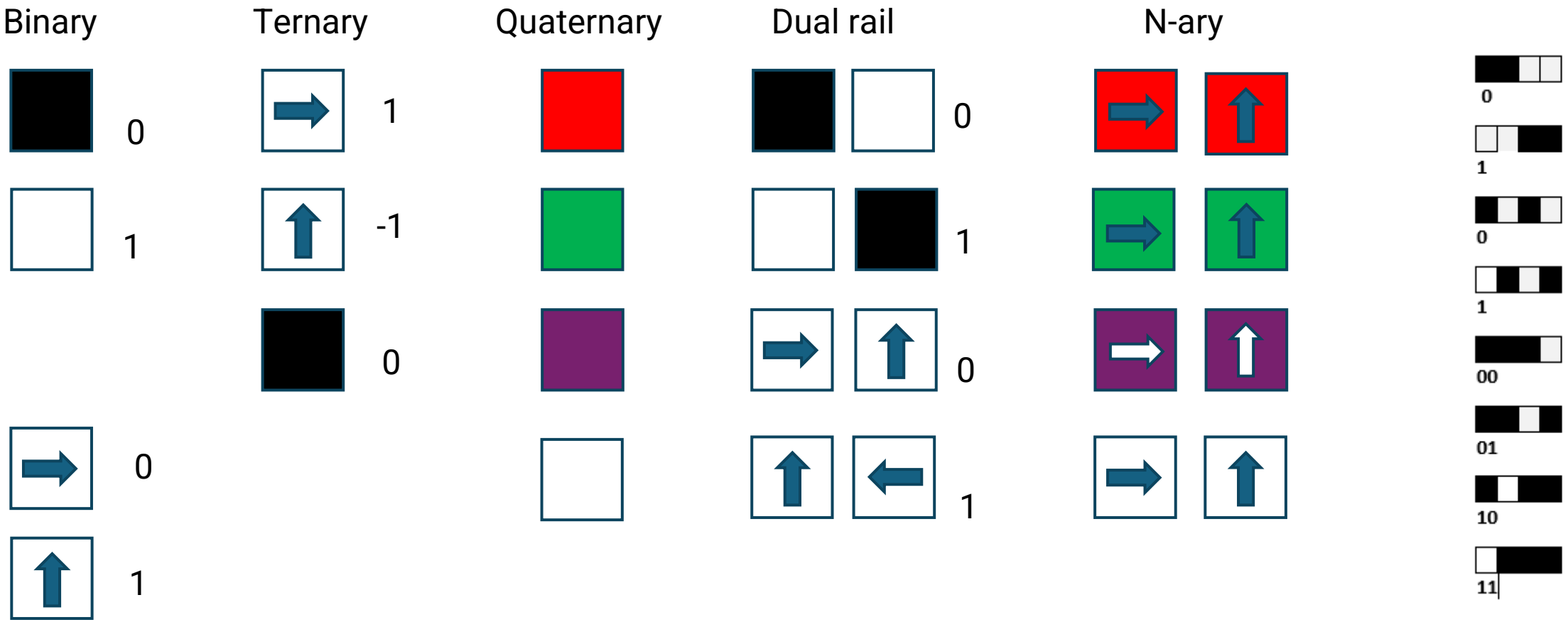




- LCDs can manipulate millions rays in parallel and each ray can have 2, 3, 4… 32 symbols

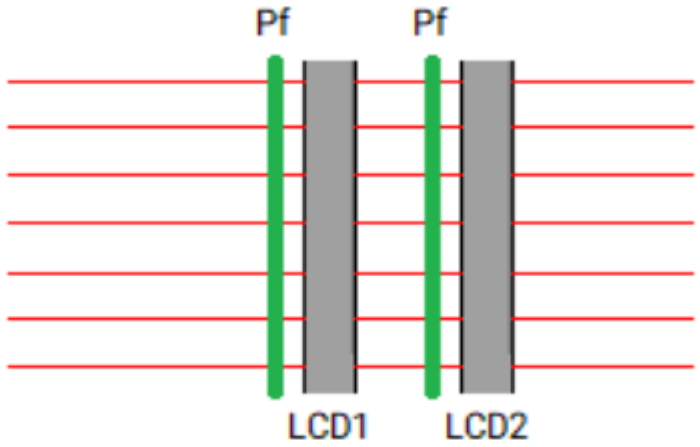
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Data Processing Logic



How Data is Encoded for Each Pixel

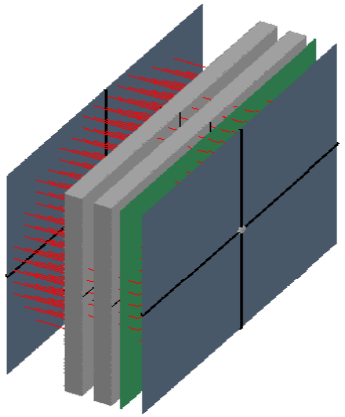
Adding a Second LCD Means Manipulate Data Out

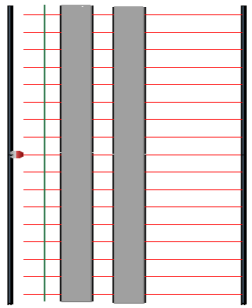


Pf	LCD1	Pf	LCD2	out
V	0	V	0	V
V	0	V	1	H
V	1	V	0	Black
V	1	V	1	Black

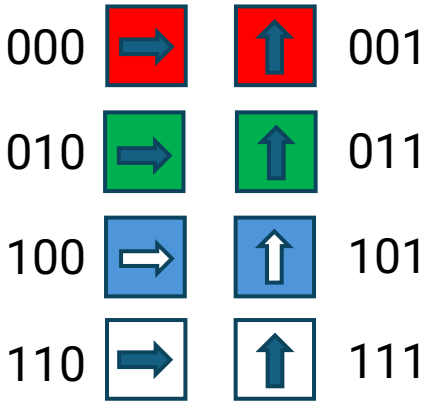
Ternary





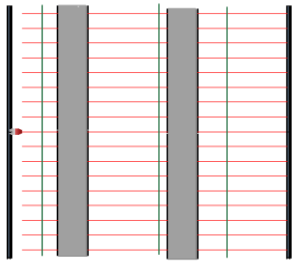


N-ary



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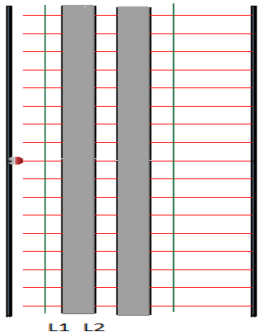
With Two LCDs We Can Make Logic Gates



AND gate
Incoming V pol light
is detected (1) only if the 2 LCDs
are in 1 state (inactive)

Pf	LCD1	Pf	LCD2	out
V	0	V	0	0
V	0	V	1	0
V	1	V	0	0
V	1	V	1	1

LCD=0 active V->H H->V
LCD=1 inactive V->V H->H

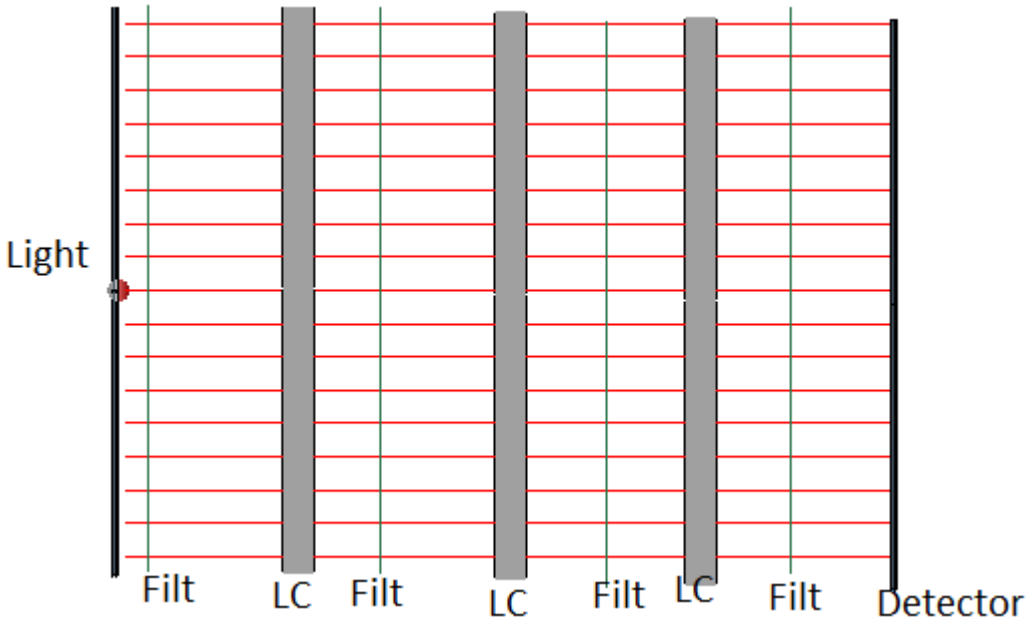


XOR gate
Incoming V pol light
is detected (1) only if both LCDs
are in the same state

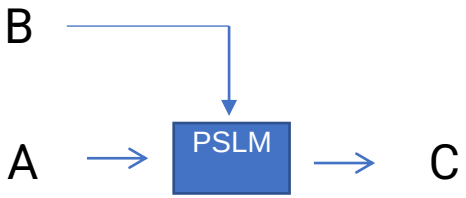
Pf	LCD1	Pf	LCD2	out
V	0	V	0	1
V	0	V	1	0
V	1	V	0	0
V	1	V	1	1

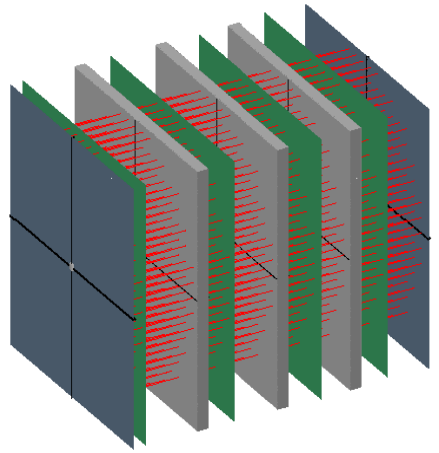
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Input Table for Horizontally Polarized Light



VALORI STATO MODULATORE					USCITA	TERNARY CODE
LCD3	Pol1	LCD4	Pol2	LCD5		
0	Vp	0	Hp	0	V	1
0	Vp	0	Hp	1	H	-1
0	Vp	1	Hp	0	W	0
0	Vp	1	Hp	1	W	0
1	Vp	0	Hp	0	W	0
1	Vp	0	Hp	1	W	0
1	Vp	1	Hp	0	W	0
1	Vp	1	Hp	1	W	0



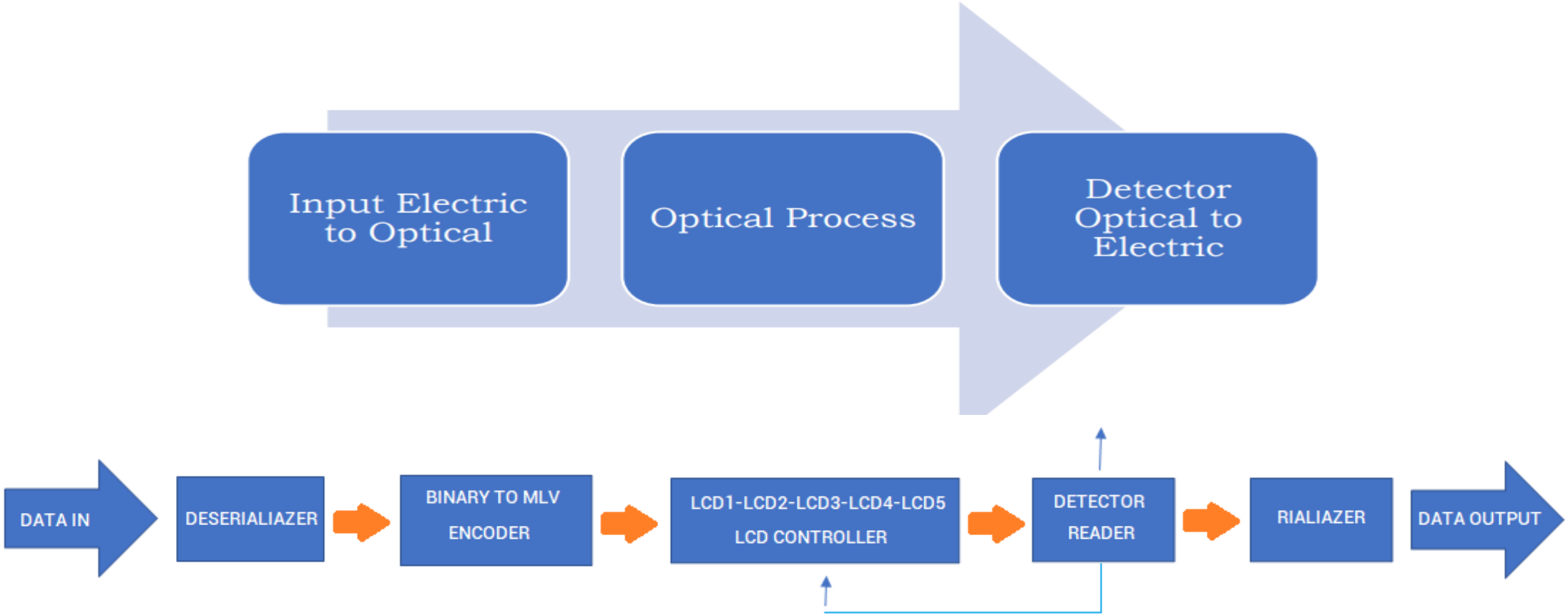


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Some Number Systems Applied in Optical Computing

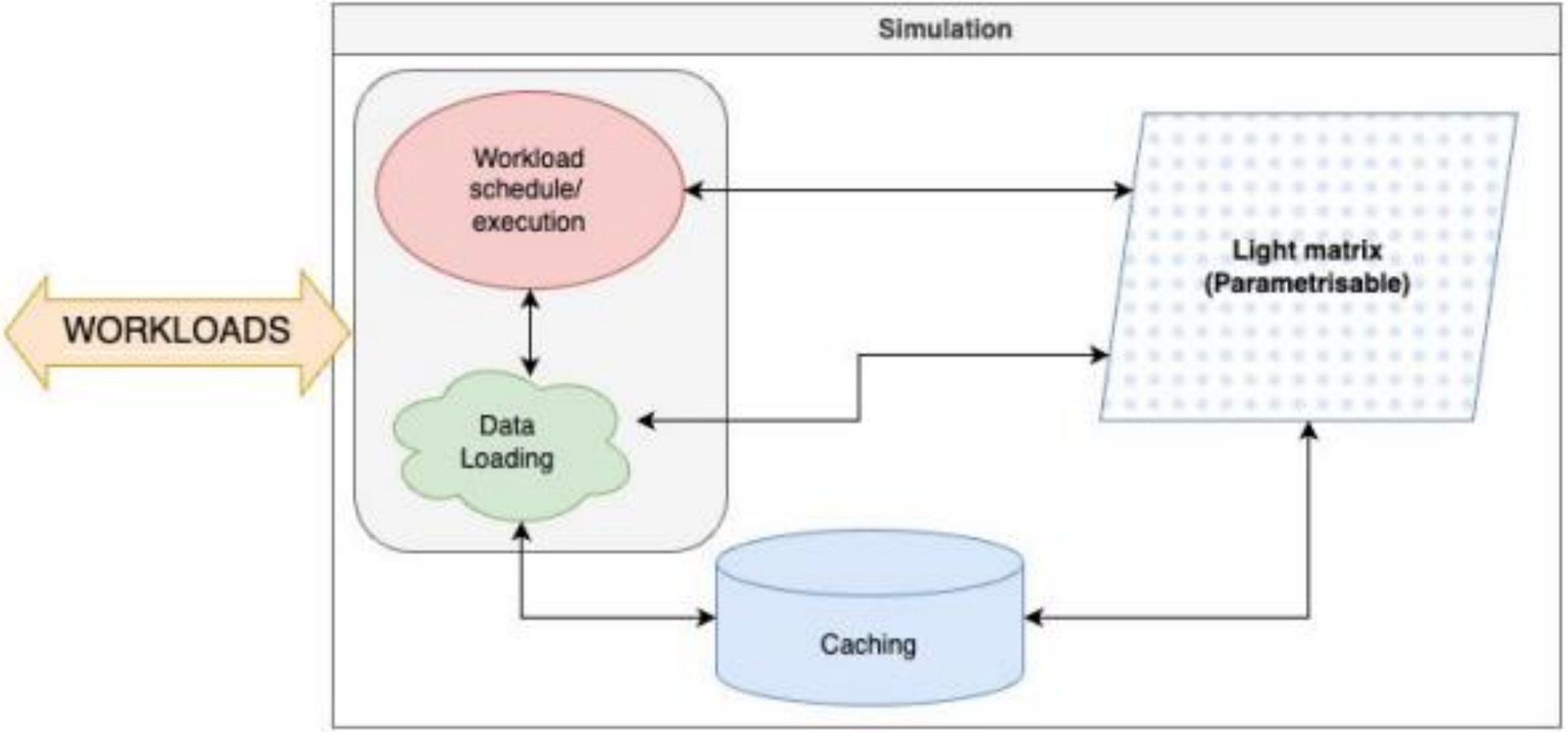
- Negabinary number system
- Redundant number system (RNS)
- Modified Signed Digit (MSD)
- Modular Arithmetic
- Residue Number System
- Ternary Number System
- Hyperdimensional Vector (HDC/VSA)

Data Processing: OptoPC Data Flow



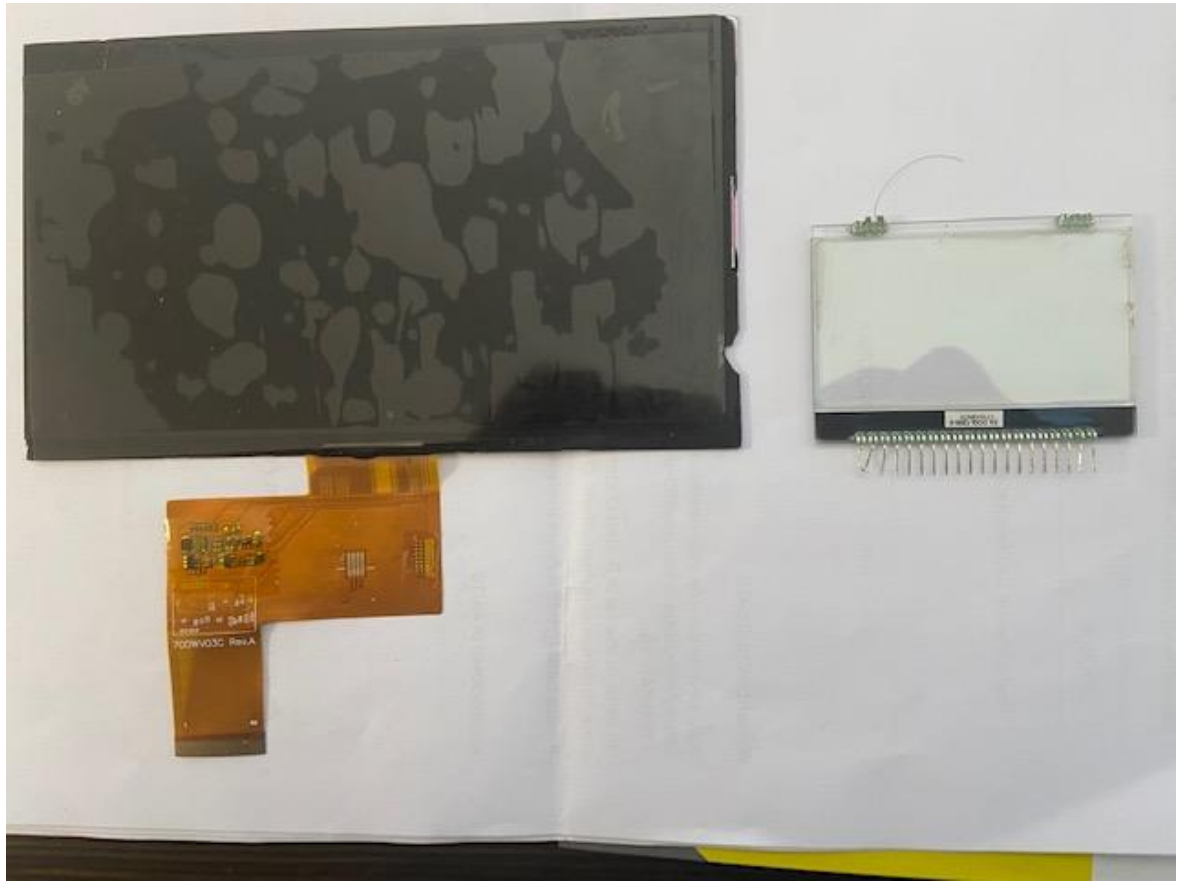
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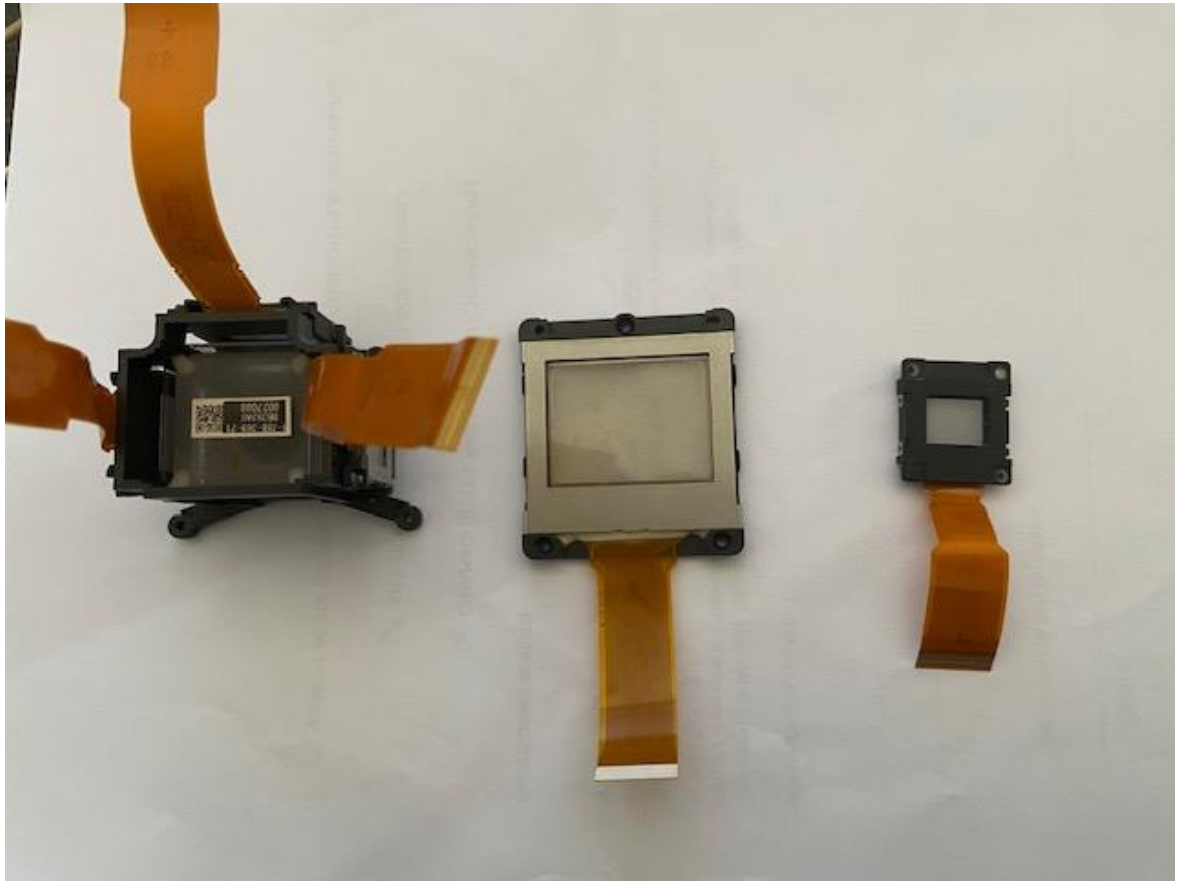
Simulation Overview



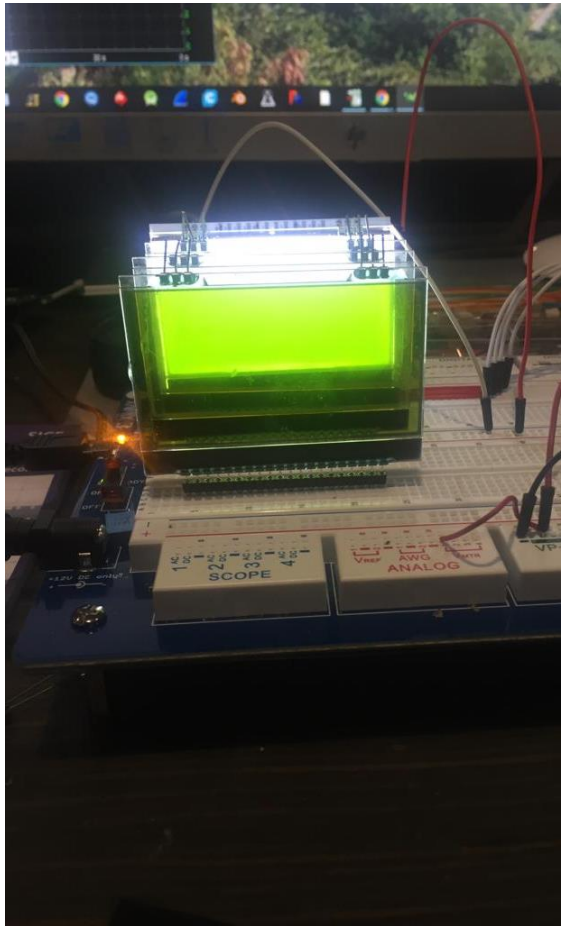
SUPSI

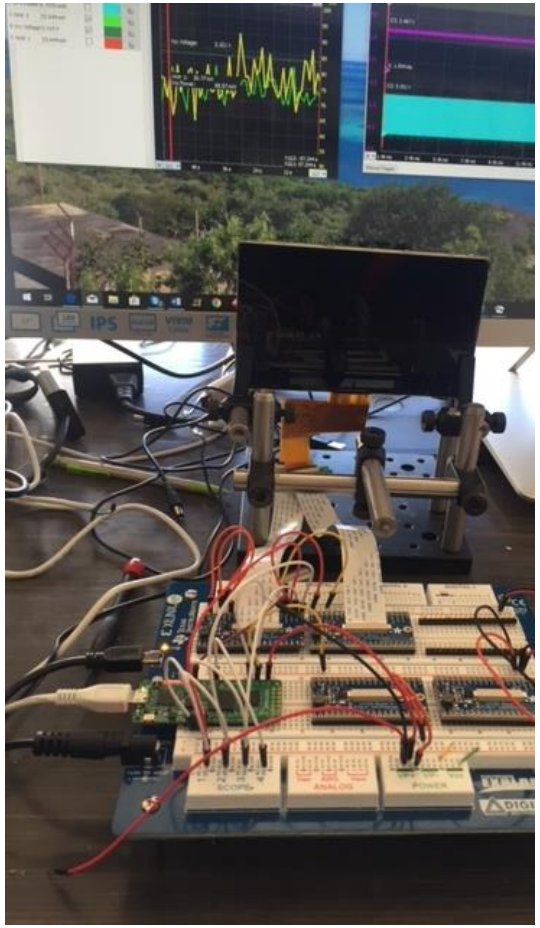
Feasibility Study: Testing and Prototyping (1)

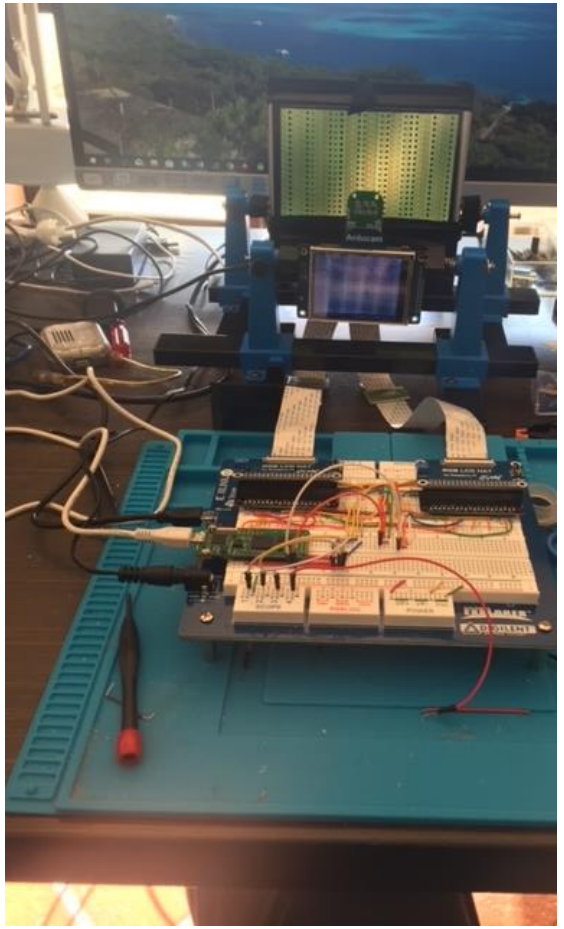




Feasibility Study: Testing and Prototyping (2)

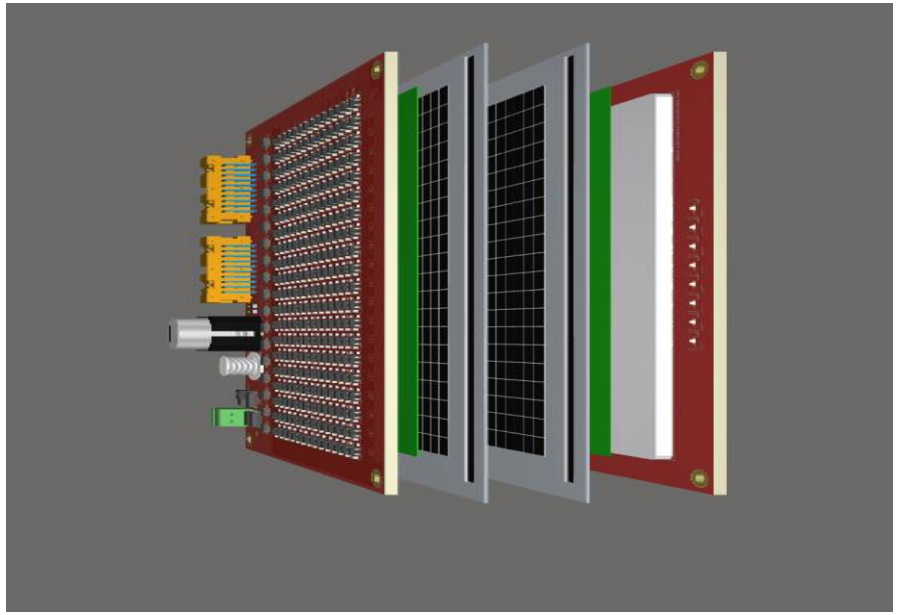


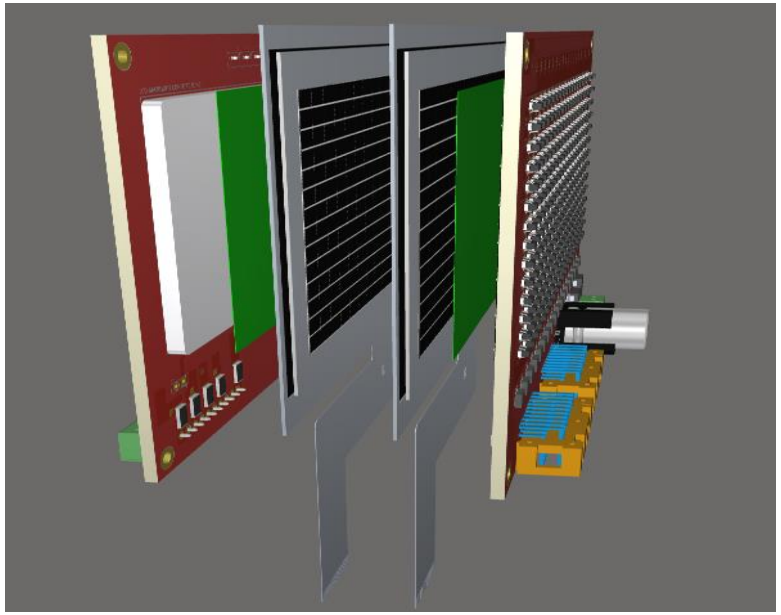


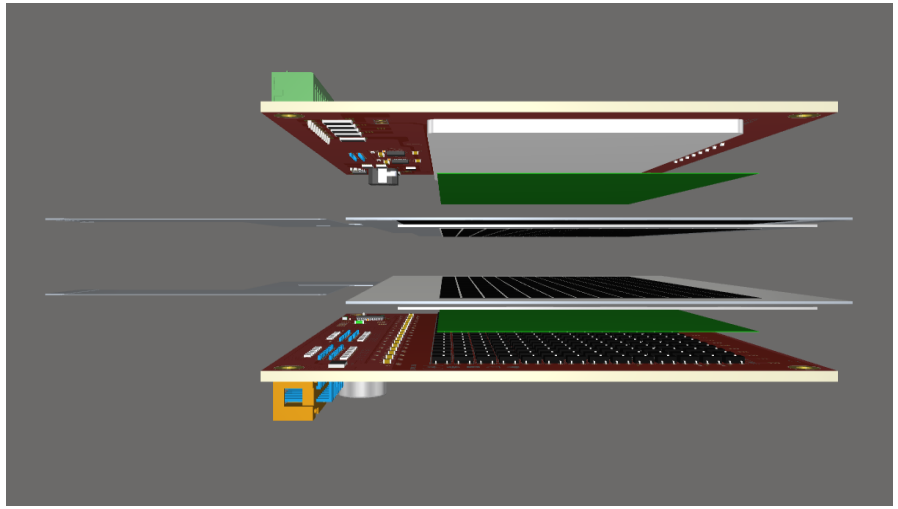


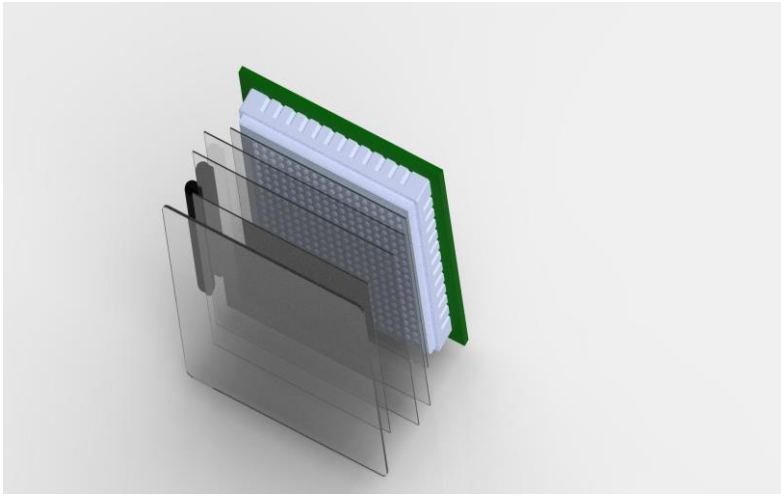
OptoPC

A Silicon Sensor for Each Cell

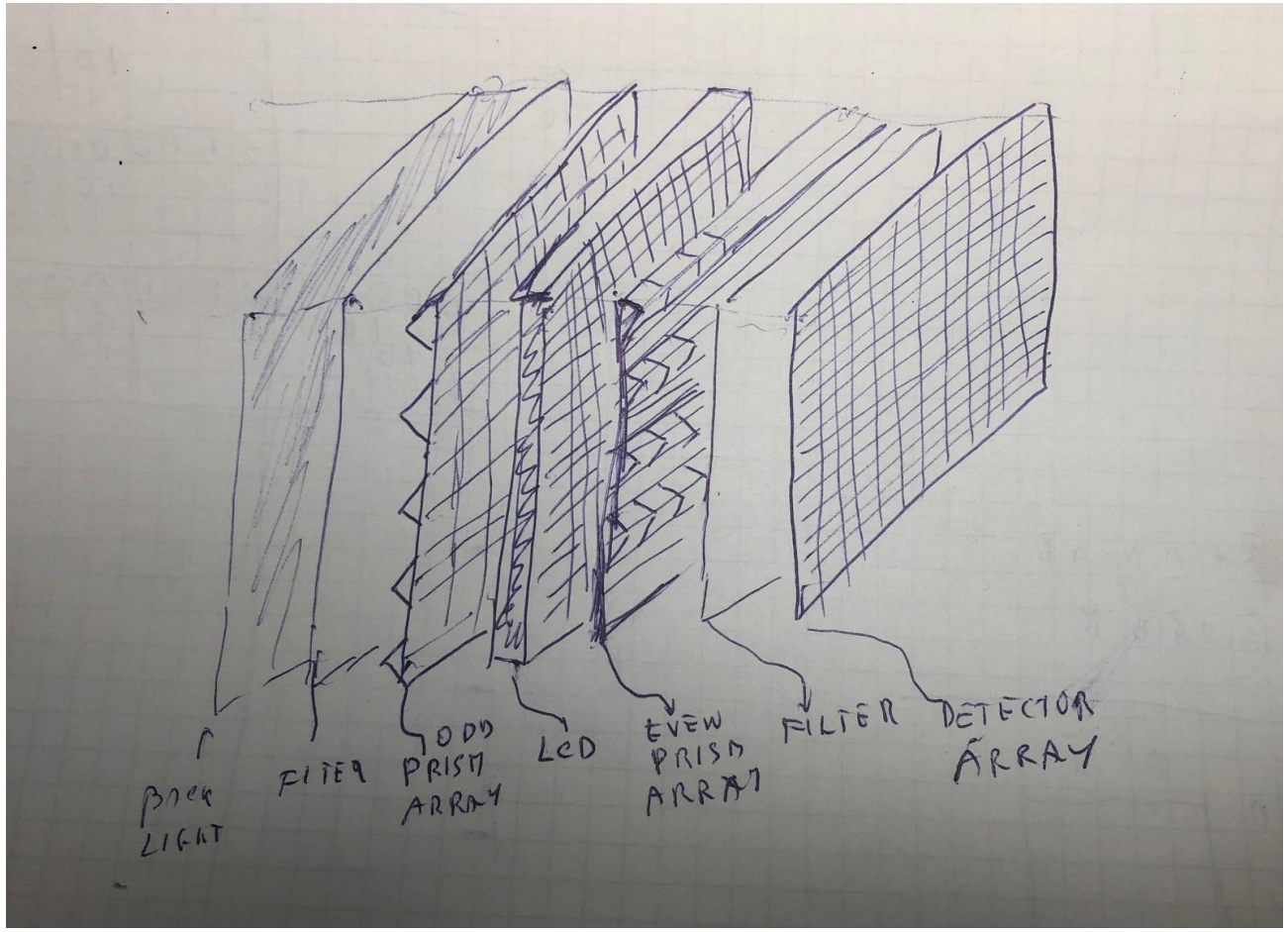








The Concept



The first steps

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Device Simulation (1)

UNIVERSITY of Pavia

Ray Optics Simulations

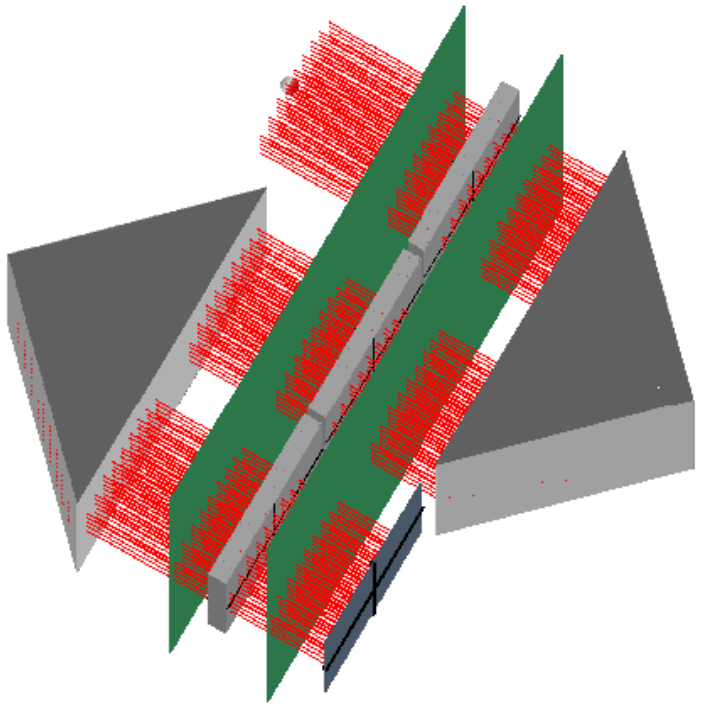
Using COMSOL

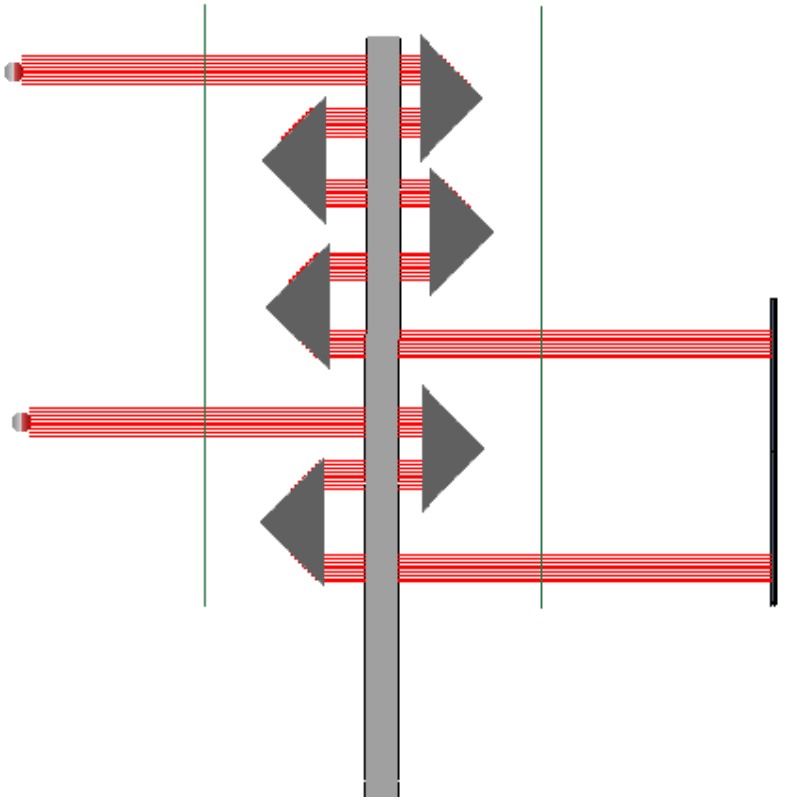
I. Cristiani,

A. E. Kaplan,

C. Lacava,

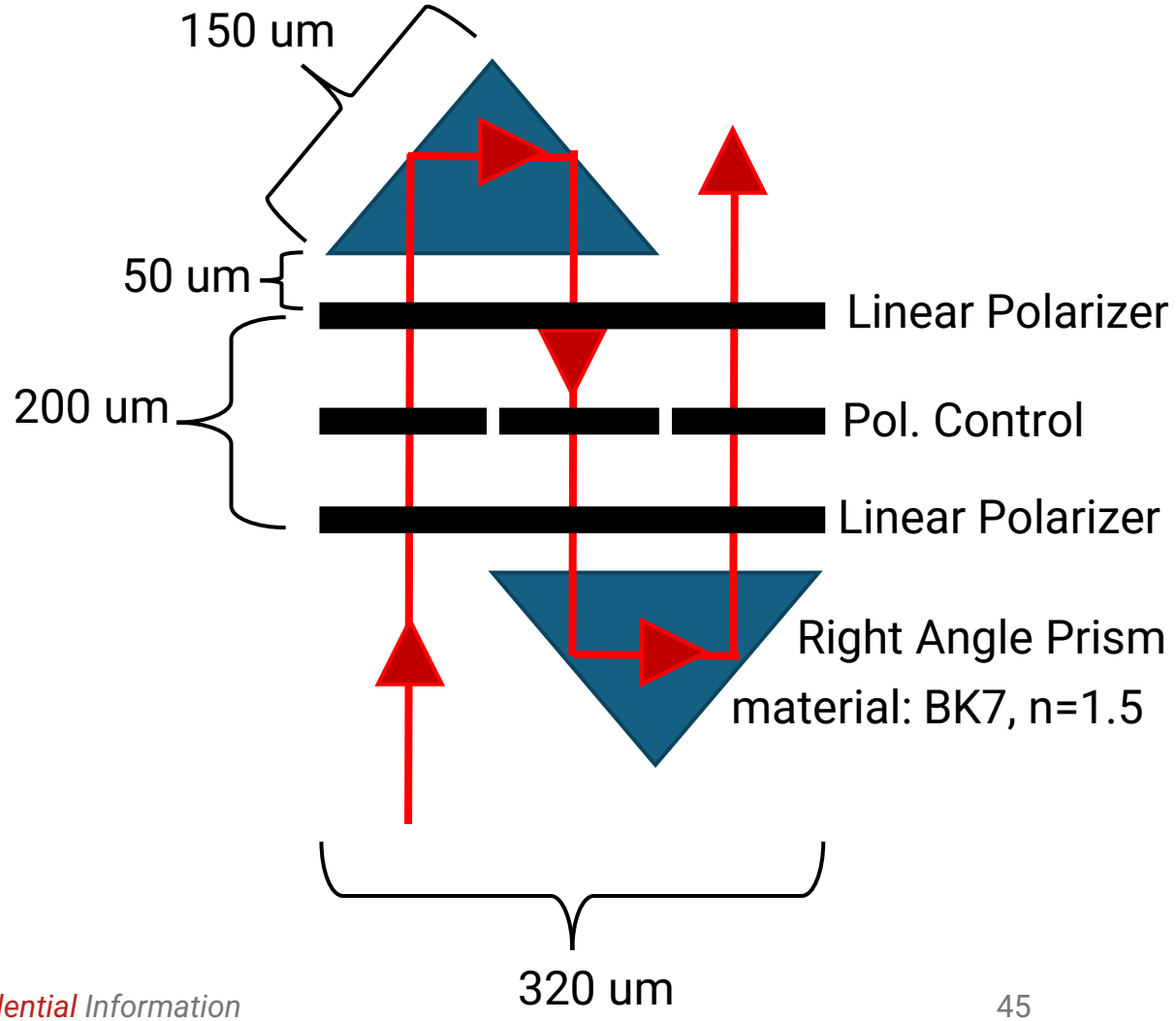
P. Minzioni





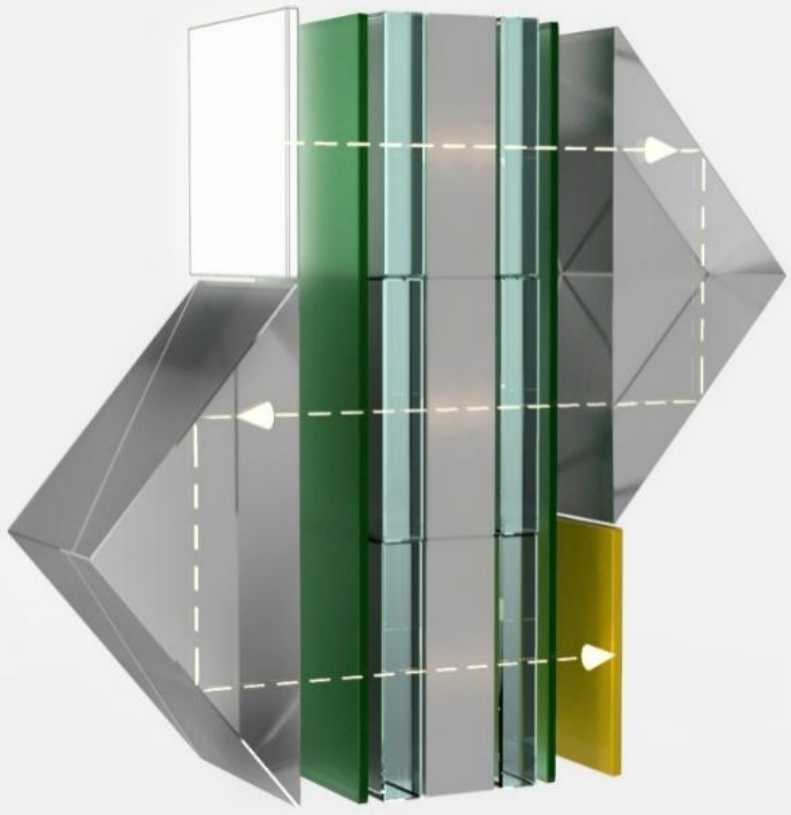
Device Simulation (2)

- Simulated Structure (not to scale)
- Main characteristics of the simulations
  - ✓ Commercial software: COMSOL
  - ✓ Ray-tracing method
- Studied parameters
  - ✓ Emission angle of the source
  - ✓ Refractive index of material (prisms)
  - ✓ Position of the prisms

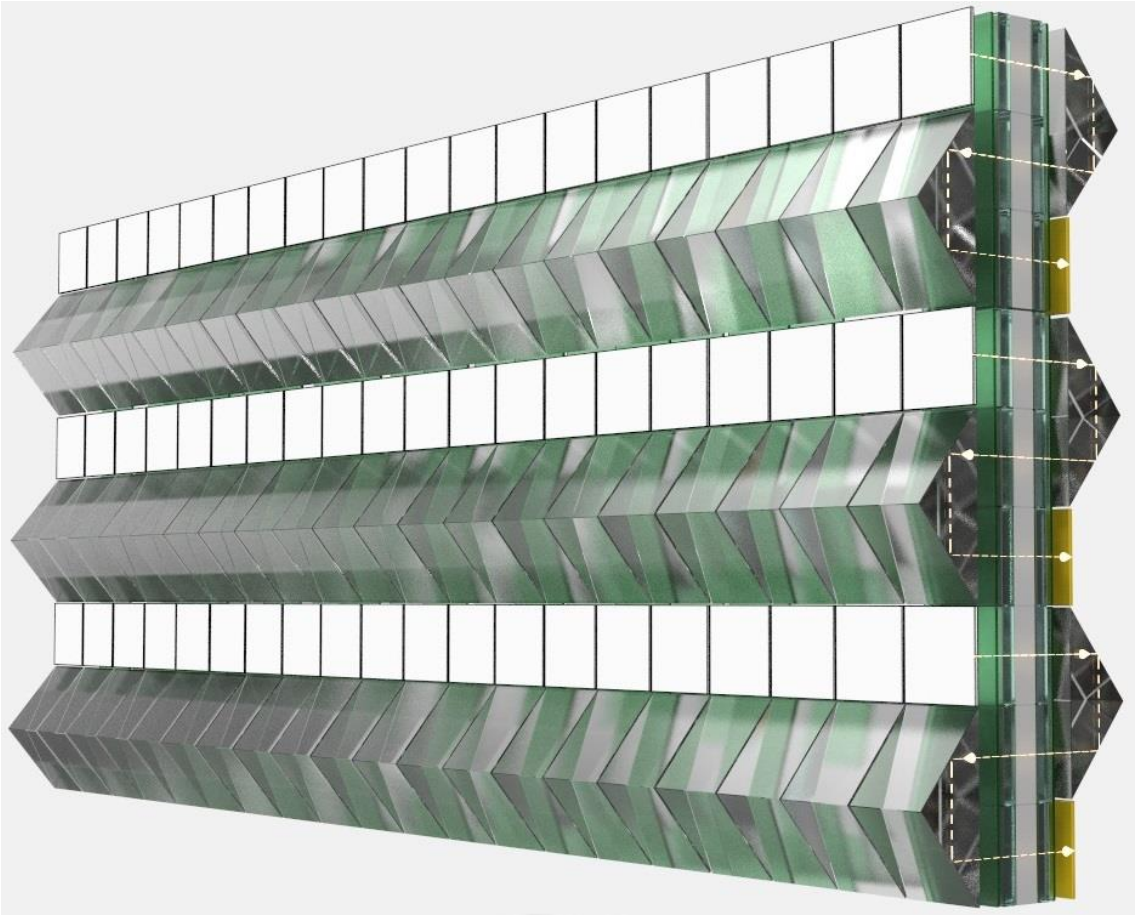


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Photonic Processor: Element Matrix



single element



element matrix

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(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
14 October 2021 (14.10.2021)

WIPO | PCT

(10) International Publication Number
WO 2021/205213 A1

(51) International Patent Classification:
G06E 3/00 (2006.01)

(21) International Application Number:
PCT/IB2020/053388

(22) International Filing Date:
09 April 2020 (09.04.2020)

(25) Filing Language: Italian

(26) Publication Language: English

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(74) Agent: **ZARDI, Marco**; Via G. B. Pioda, 6, 6900 Lugano (CH).

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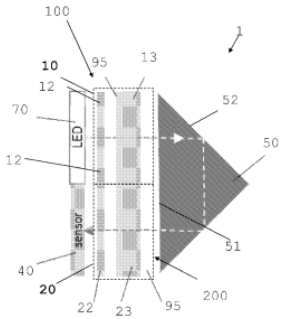
(84) Designated States *(unless otherwise indicated, for every kind of regional protection available)*: ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, ST, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

Published:
— *with international search report (Art. 21(3))*
— *in black and white; the international application as filed contained color or greyscale and is available for download from PATENTSCOPE*

(54) **Title:** PARALLEL OPTICAL COMPUTING SYSTEM

(57) **Abstract:** A parallel optical computing system is described, said system comprising: at least one first module (10) comprising at least one polarization filter (12) and at least one liquid crystal cell (13), the first module (10) being configured as an optical modulator (100) for receiving light from a light source (70) and for encoding the light output from the liquid crystal cell (13) into optical data to be processed; at least one second module (20) comprising at least one polarization filter (22) and at least one liquid crystal cell (23), the second module (20) being able to be configured as an optical processor (200) for receiving the optical data to be processed and for outputting an optical result of the processing; at least one optical detector (40), designed to receive the optical result of the processing and convert the optical result into a corresponding electrical result.

Fig. 1



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INTERNATIONAL PRELIMINARY REPORT ON PATENTABILITY

International application No.
PCT/IB2020/053388

6. ☒ With regard to top-up searches (Rules 66.1 *ter* and 70.2(f)):
   ☒ A top-up search was carried out by this Authority on 06.01.2022 (all discovered documents are listed in the Supplemental Box Relating to Top-up Search).
   ☐ Additional relevant documents have been discovered during the top-up search.
   ☐ No top-up search was carried out by this Authority because it would serve no useful purpose.

7. ☐ Supplementary international search report(s) from Authority(ies) has/have been received and taken into account in establishing this report (Rule 45bis.8(b) and (c)).

* *If item 4 applies, some or all of those sheets may be marked "superseded".*

Box No. V Reasoned statement under Article 35(2) with regard to novelty, inventive step or industrial applicability; citations and explanations supporting such statement

1. Statement

Novelty (N)	Yes:	Claims	1-8
	No:	Claims	
Inventive step (IS)	Yes:	Claims	1-8
	No:	Claims	
Industrial applicability (IA)	Yes:	Claims	1-8
	No:	Claims	

2. Citations and explanations (Rule 70.7):

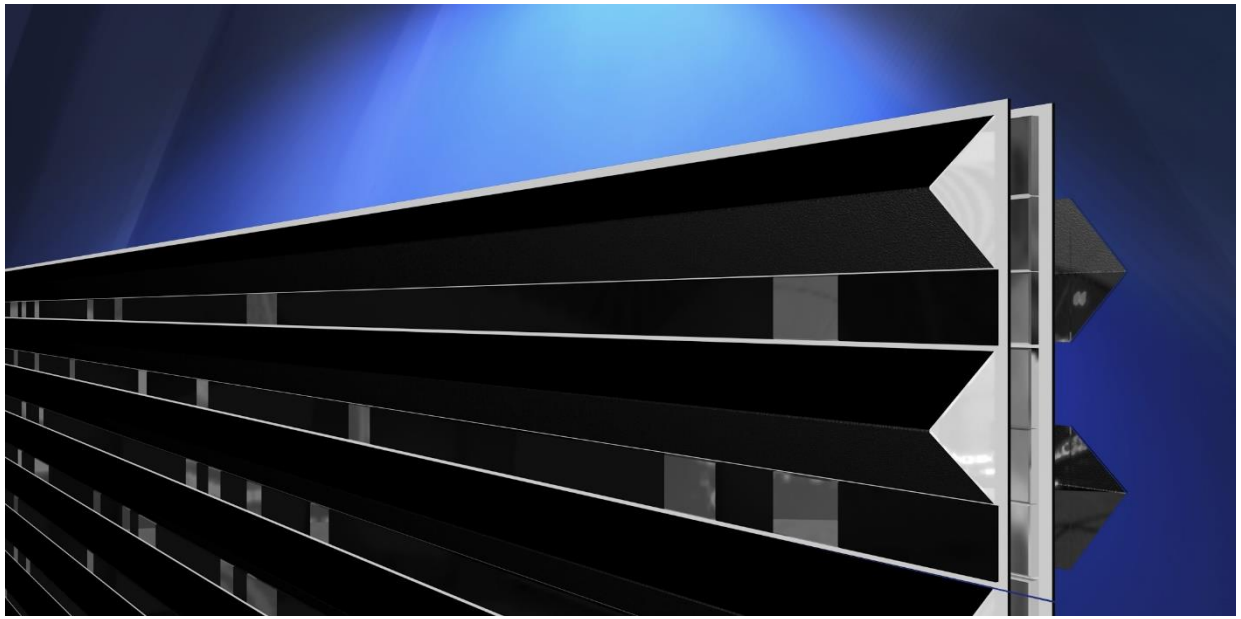
see separate sheet

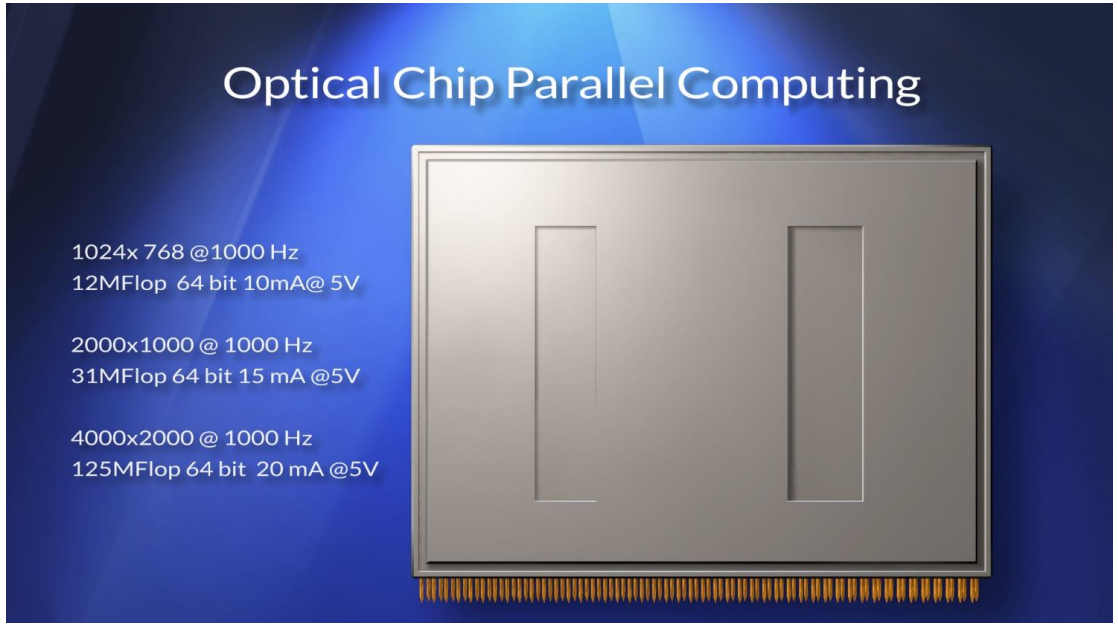
Box No. VII Certain defects in the international application

The following defects in the form or contents of the international application have been noted:

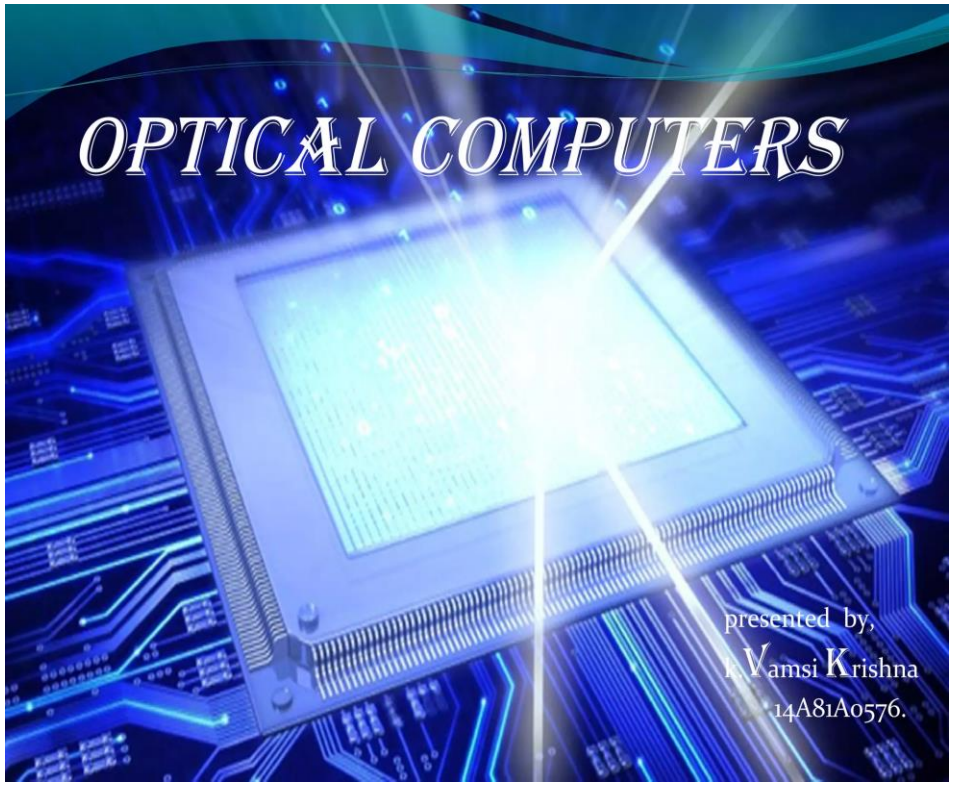
see separate sheet

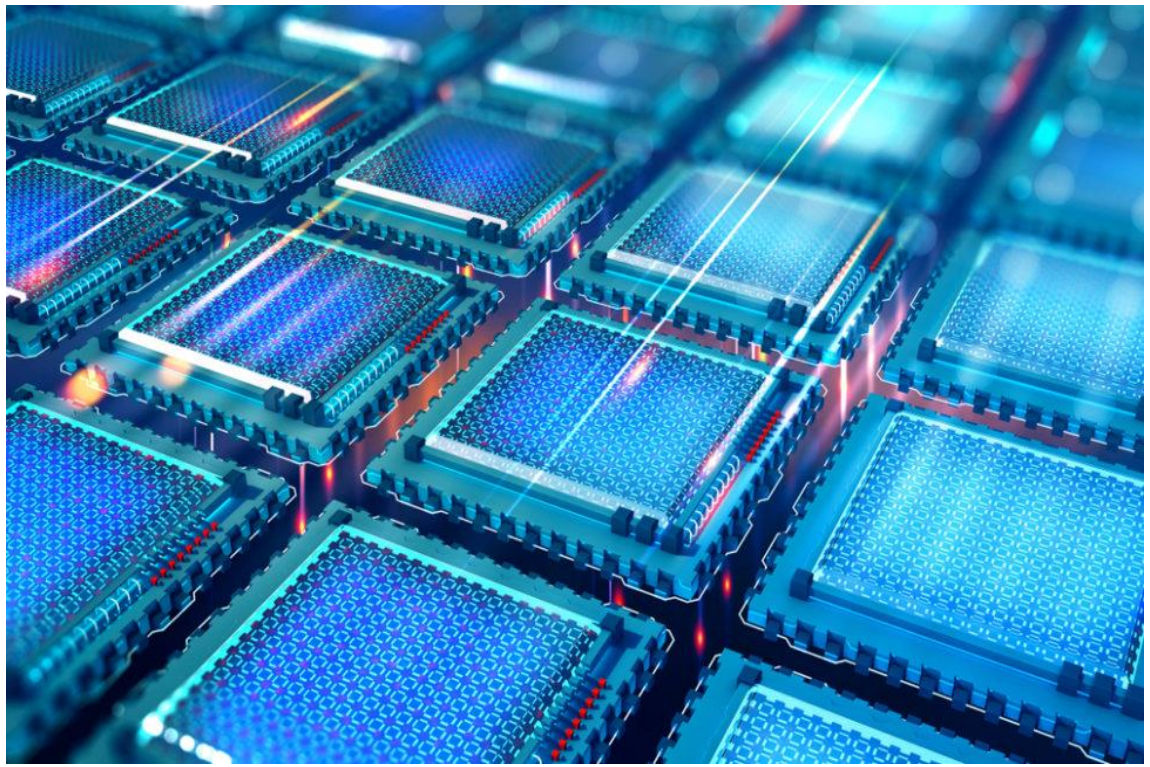
Photonic Processor: Hardware Solutions (1)





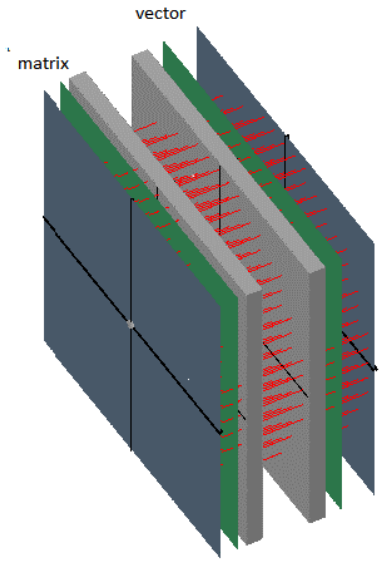
Photonic Processor: Hardware Solutions (2)

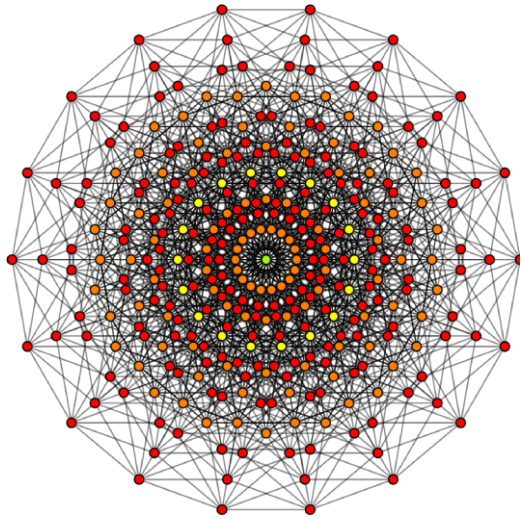


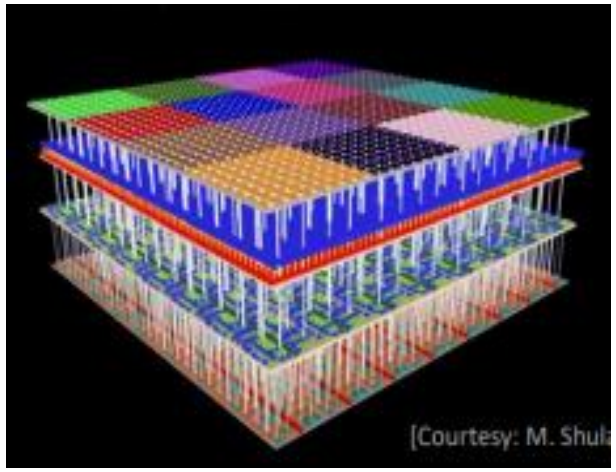


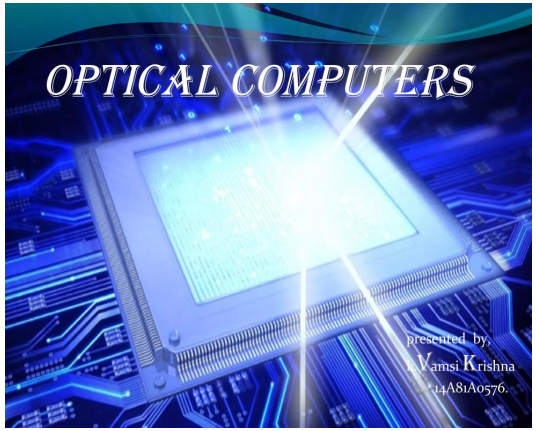
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OptoPC+HDC: OpticalHD a New Concept

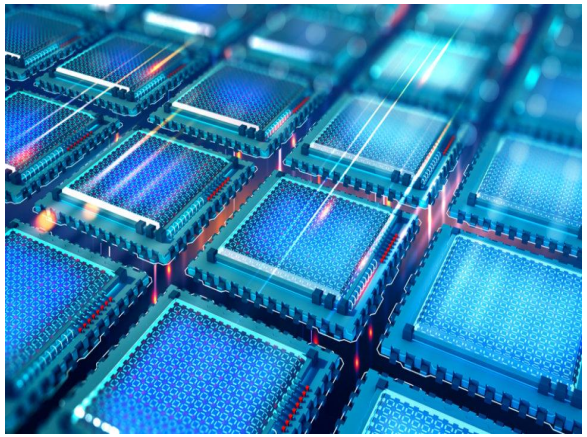








OPTOHDC



OptoPC