encontro CIÊNCIA '16

New Generation Robots

Beyond Moore's Law and Rebooting Computing with Probabilistic Machines

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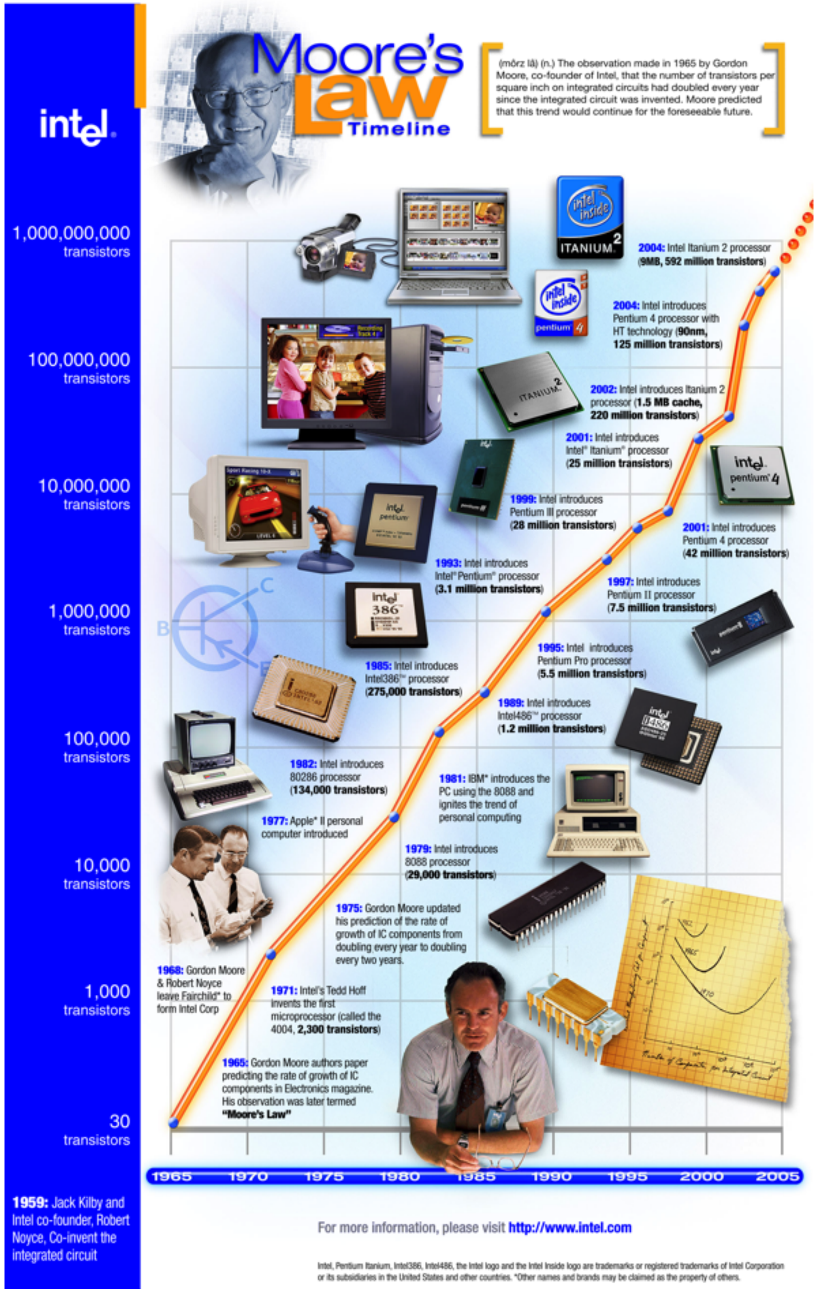
ARTIFICIAL PERCEPTION TEAM
FOR INTELLIGENT SYSTEMS AND ROBOTICS



Moore's Law

- number of transistors doubles every two years
- Fantastic exponential growth
- Enabled the boom in digital electronics and computing

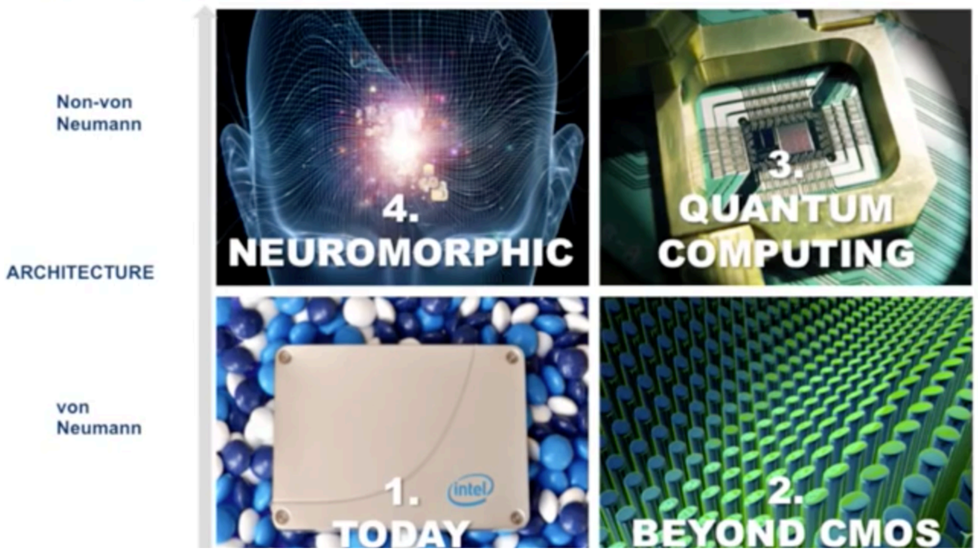
- The dark side:
  - Power wall
  - Costs
  - Hardware limits

Its slowing down !

- *Any good news?*

Beyond Moore…

- A lot of different ideas thought up over the years have been put on a shelf because we could always rely on getting smaller and faster transistors.
- Now it's time to go back through the library of things that we've thought of.
  - Computing models and architectures
  - Materials
  - Etc
- ***What about robots?***



Institute of Systems and Robotics University of Coimbra

- ***The** Institute Systems and Robotics,* ***has activities in the areas of:***
  - ***robotics vision,***
  - ***autonomous systems,***
  - ***multi-sensor fusion and integration,***
  - ***tele-operation,***
  - ***sensor development,***
  - ***soft-control and motors and drives.***

INSTITUTO DE SISTEMAS E ROBÓTICA
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Robots?

ARTIFICIAL PERCEPTION TEAM
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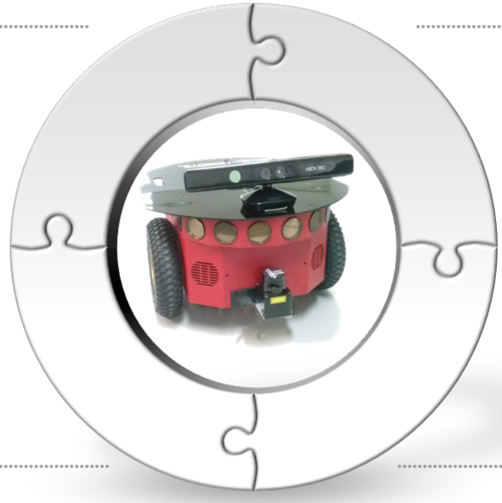
Multisensory Perception

Fundamentals

Computation and Models

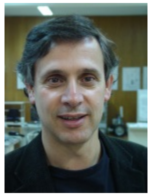


Cooperative Behaviour

Applications

Human-Machine Interaction

BAMBI
Bottom-up Approaches to Machines dedicated to Bayesian Inference



Jorge Miranda Dias (jorge@isr.uc.pt), Dr. Habil., Ph.D.
Local PI.

Computer Vision; Multi-Sensor Fusion; Bayesian Perception; Autonomous Robotic Systems.

Jorge Lobo (jlobo@isr.uc.pt), Ph.D.
Senior researcher (PI deputy).

Visuoinertial Sensor Fusion; Bayesian Perception; Reconfigurable Hardware; Autonomous Robotic Systems.

João Filipe Ferreira (jfilipe@isr.uc.pt), Ph.D.
Senior researcher.

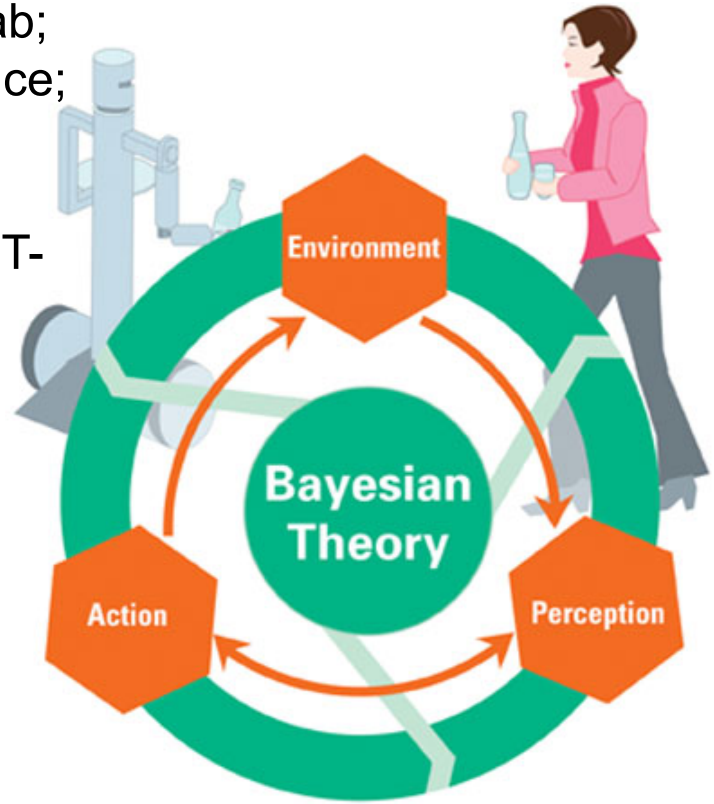
Bioinspired Perception; Human-Robot Interaction; Probabilistic Modelling; Autonomous Systems.

BACS - Bayesian Approach to Cognitive Systems

- **BACS** - EU FP6-IST-027140
  - Coordinator: Roland Siegwart, ETH Zurich.
  - Partners: ETH Zurich Autonomous Systems Lab; INRIA, e-Motion; CNRS-LPPA-Collége de France; CNRS-LSCP-Institut des Sciences Cognitives; CNRS-Grenoble; MPS, Inst. for Biological Cybernetics; HUG, Neurology Department; FCT-UC, DEEC; BlueBotics; Probayes SAS; EDF, R&D; Aeroscout; EPFL.
  - http://www.bacs.ethz.ch/
  - Jan. 2006 - Feb. 2010

BACS

BAYESIAN APPROACH TO COGNITIVE SYSTEMS



Robots?

ARTIFICIAL PERCEPTION TEAM
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- **Bayesian modeling:**

helping robot to deal with uncertainty and incompleteness

A roboticist

Robot

Incompleteness

Uncertainty

Decision

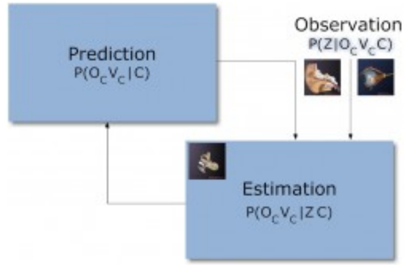
Preliminary Knowledge
(Programming)
+
Experimental Data (Learning)
=
Probabilistic Representation

Perception (Inference)
+
Action (Decision)
=
Probabilistic Action-Perception Loop

Robots?

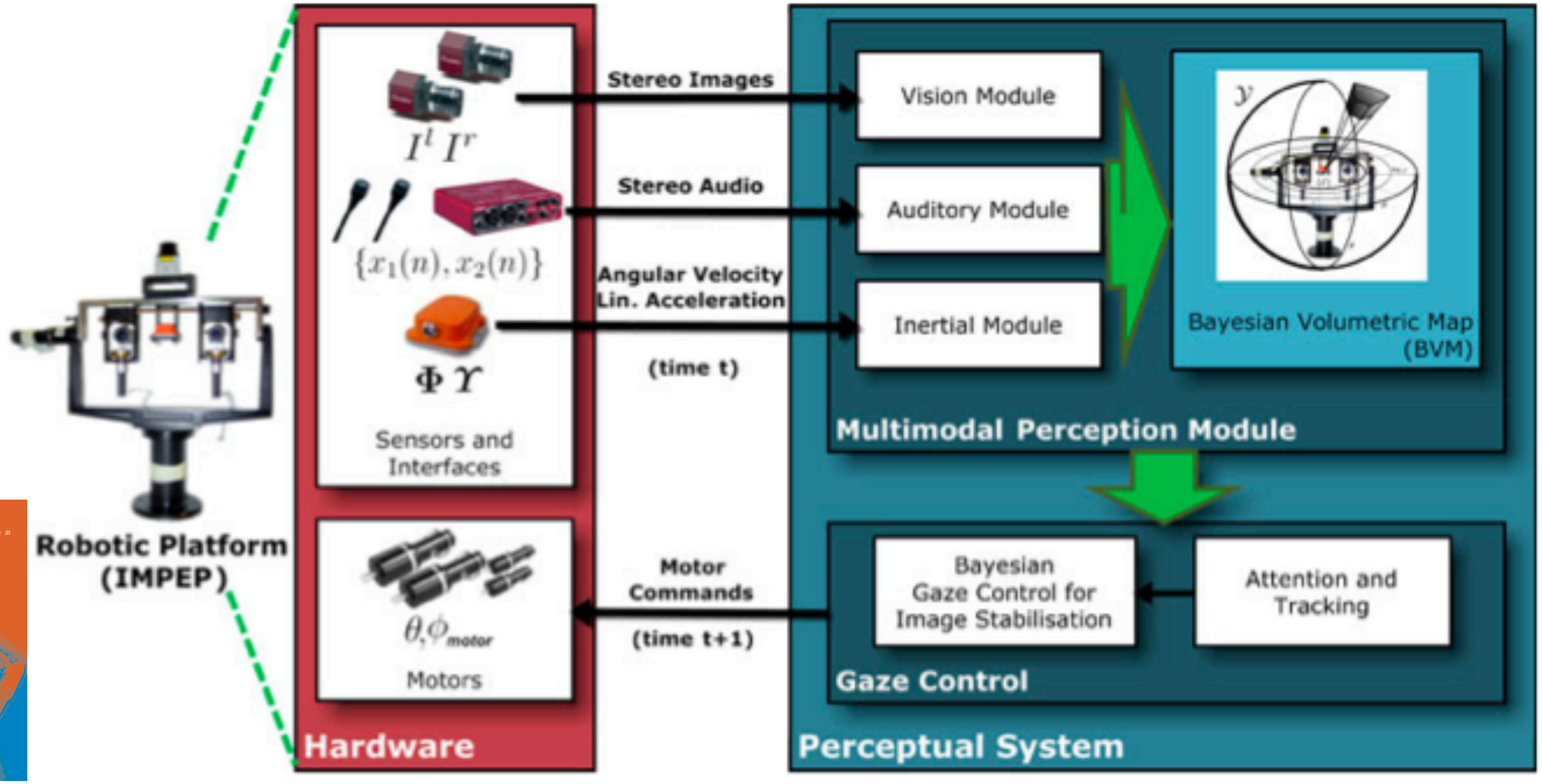
From Bioinspired to Biomimetic
The Bayesian Approach

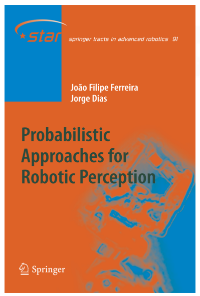
BACS



Robots?

AP4ISR Bayesian Know-How





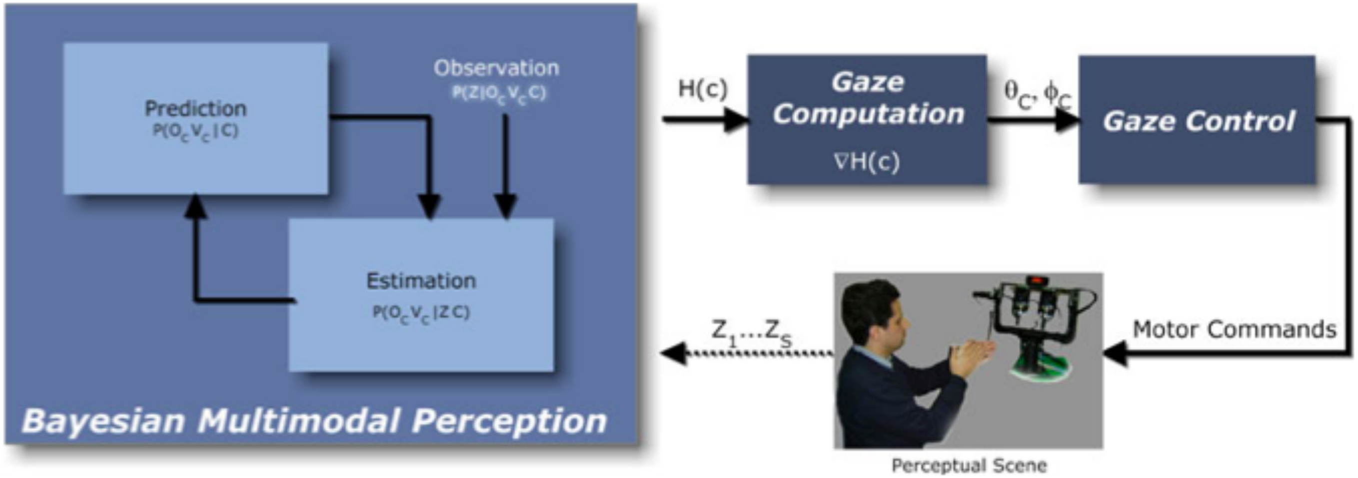
Bayesian real-time perception algorithms on GPU

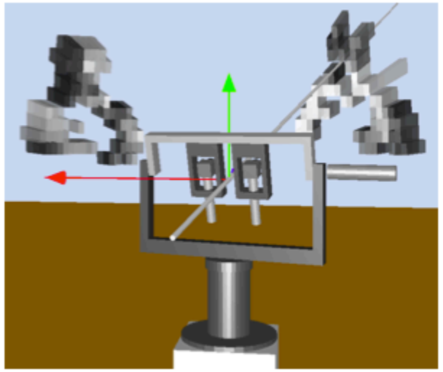
Real-time implementation of Bayesian models for multimodal perception using CUDA

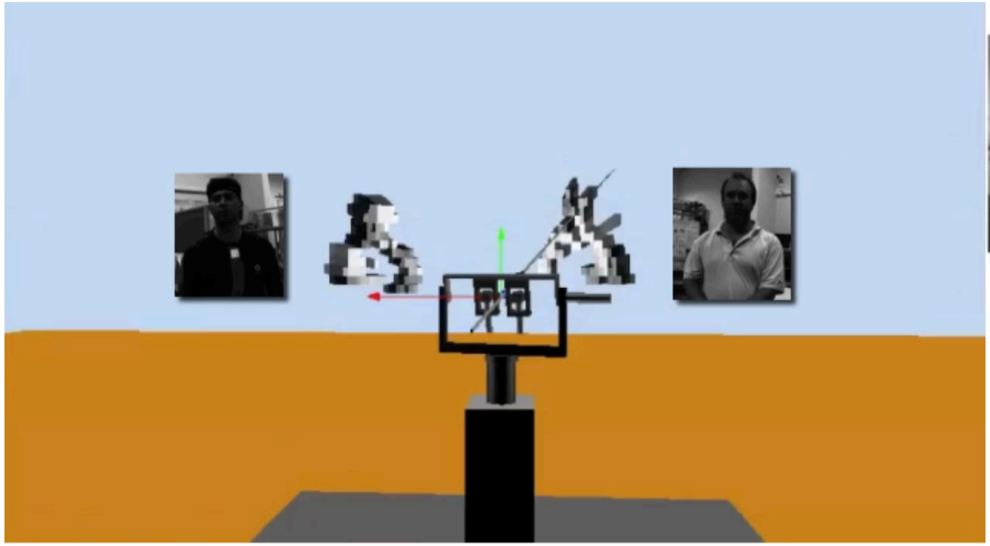
João Filipe Ferreira, Jorge Lobo and Jorge Dias

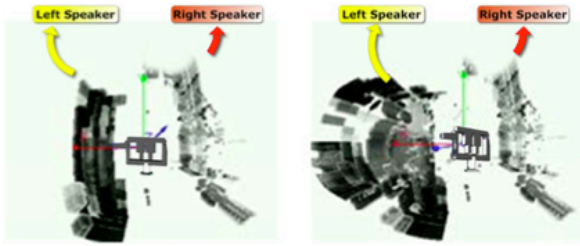
Robots?

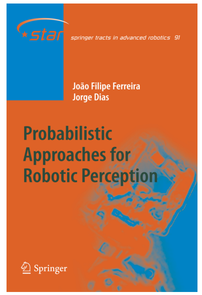
AP4ISR Bayesian Know-How











Robots need computation power…

- Need to perceive the environment, infer, decide and act efficiently enough to survive

- To deal with uncertainty in the data and incompleteness of the models, computations are done with probability distributions, overloading current architectures

- Look at nature and biology

- Revisit correctness contract between hardware and software

IROS UCBI and IJAR special issue

IEEE/RSJ International Conference on Intelligent Robots and Systems

iROS Hamburg 2015

IROS 2015 workshop on

Unconventional computing for Bayesian inference

BAMBI

Bottom-up Approaches to Machines dedicated to Bayesian Inference

Main Menu
- Welcome
- Abstract
- Organisers
- List of speakers
- Schedule
- Submissions
- Important dates

Workshop on

Unconventional computing for Bayesian inference

:: Followup and News

November 2015: the call for contributions for the **International Journal of Approximate Reasoning (IJAR) special issue on Unconventional computing for Bayesian inference** is now open, accepting submissions until May 1, 2016. UCBI special issue of IJAR .

October 2015:
The workshop was a success, we had a packed room and nice interchange of ideas throughout the day.

BAMBI

Bottom-up Approaches to Machines dedicated to Bayesian Inference

- We propose a theory and a hardware implementation of probabilistic computation inspired by biochemical cell signaling.

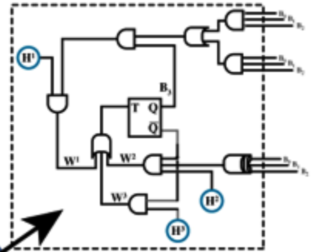
- Following a global vision of a future probabilistic computer we will advance toward this long term goal following three axes: **algebra, biology,** and **hardware**.

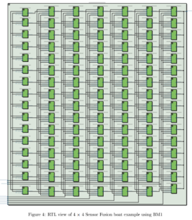
- EU collaborative FET Project,
  www.bambi-fet.eu
  FP7-ICT-2013-C, project number 618024

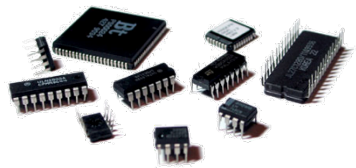
BAMBI
Bottom-up Approaches to Machines dedicated to Bayesian Inference

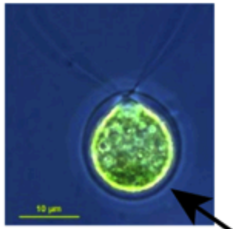
BAMBI project

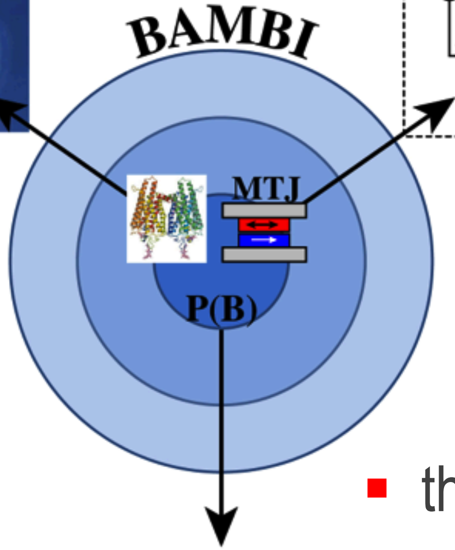
- hardware implementation

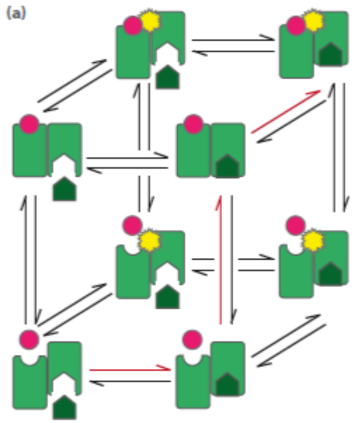




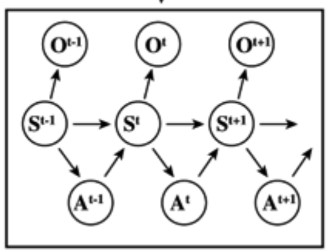








- probabilistic inference in biology



- theory of probabilistic computation

Program
- Description
  - Specification
    - **variables:**
      - D_1, D_2 : observed variables
      - M : variable of interest
    - **decomposition**
      - $P(M \wedge D1 \wedge D2) = P(D_1 \mid M)P(D_2 \mid M)P(M)$
    - **parametric forms:**
      - $P(M)$: uniform
      - $P(D_1 \mid M)$: histogram
      - $P(D_2 \mid M)$: histogram
  - Identification:
- Question : $P(M) \equiv P(M|\widetilde{P}(D))$

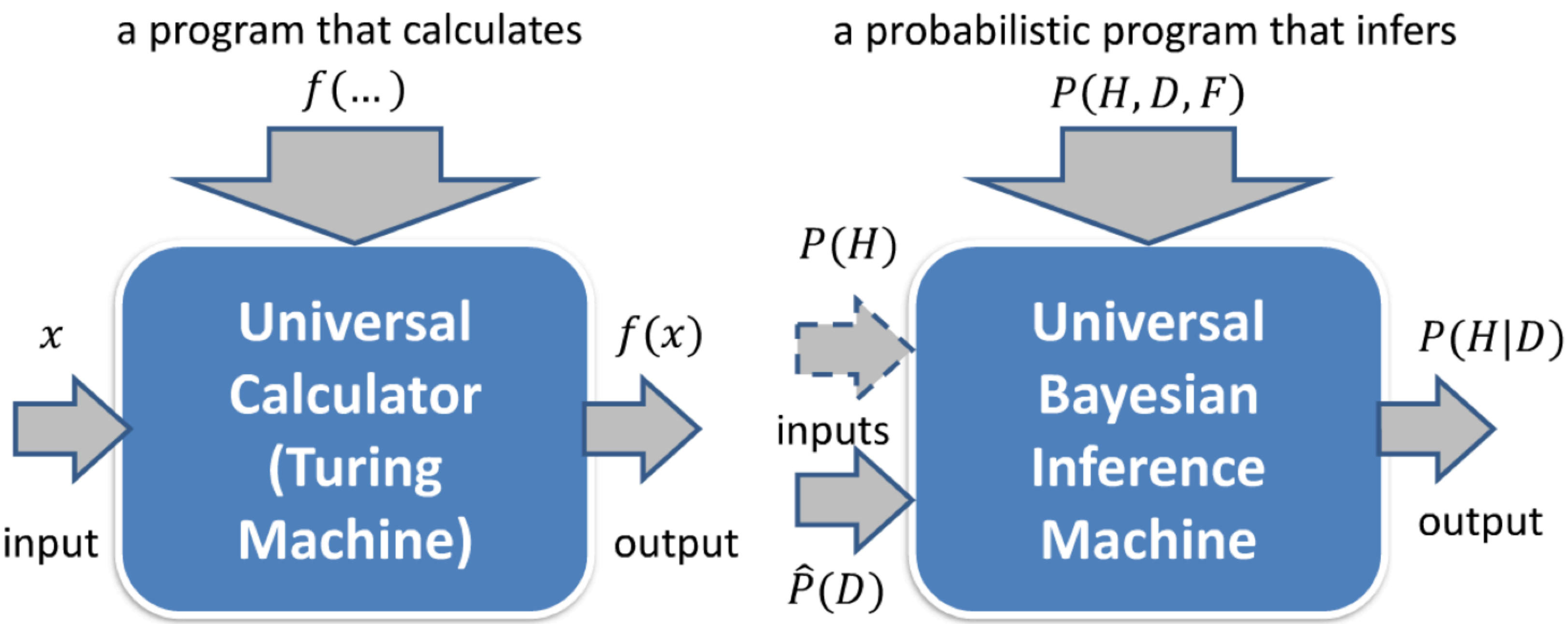
BAMBI
Bottom-up Approaches to Machines dedicated to Bayesian Inference

UPSIDE

DARPA SyNAPSE IBM

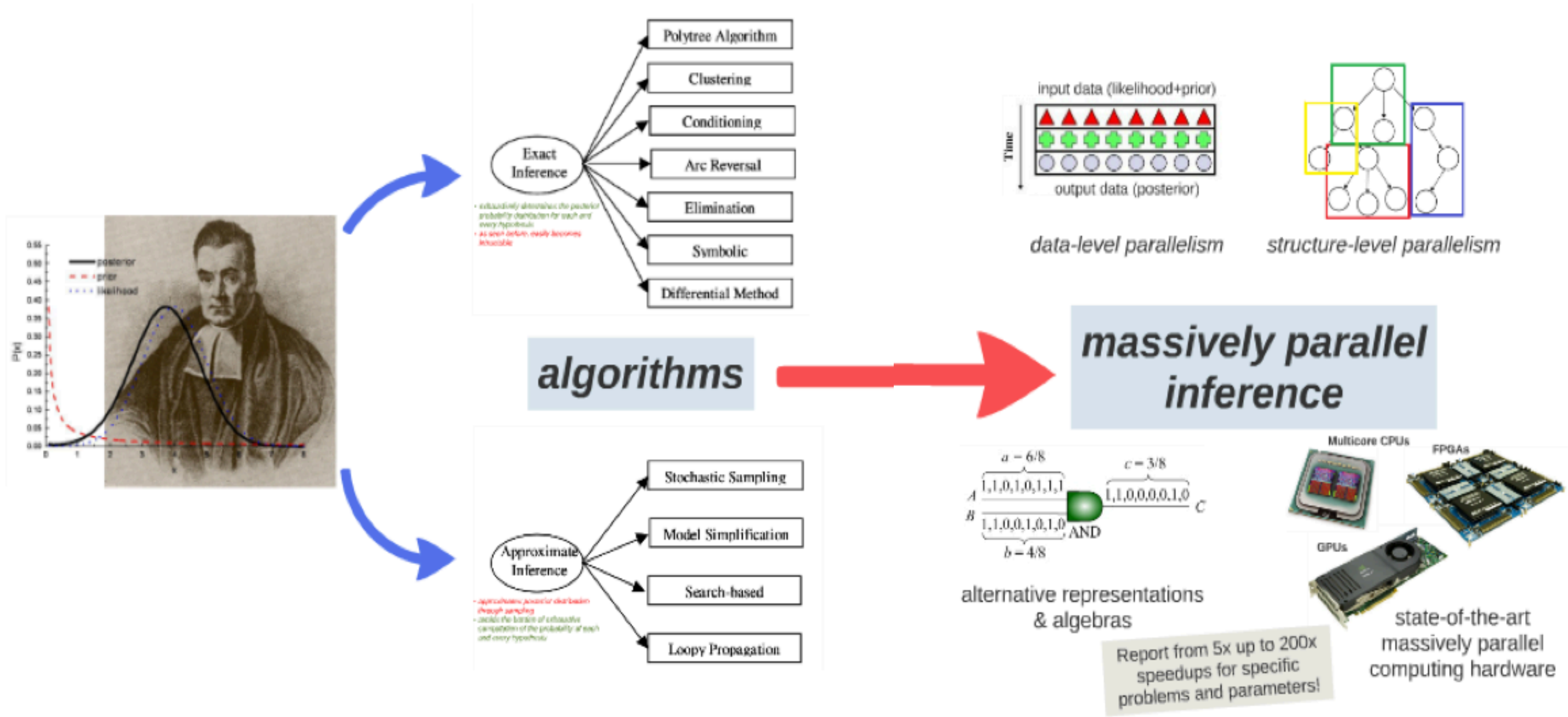
SpinNNaker TrueNorth

where to now?



Beyond von Neumann architectures, towards a "Bayesian computer"?

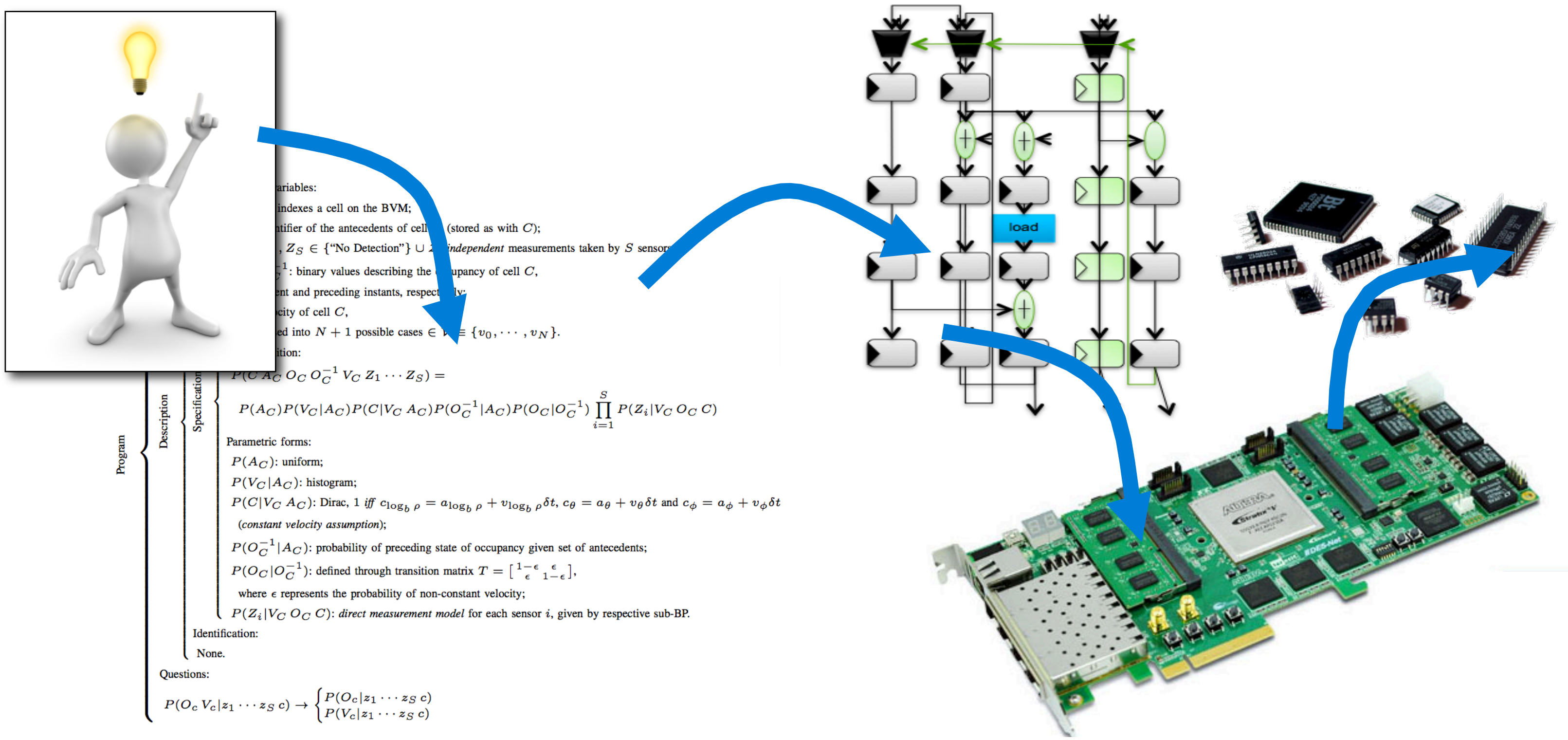
Implementing Bayesian Computing



- Algorithms >> Modelling Languages >> hardware

ISR-UC in BAMBI

Reconfigurable logic will play a key role within the project on the ***emulation hardware implementation*** *and also on testing on hardware the* ***computational architecture*** *to be developed, namely in the composition of* ***basic building blocks for probabilistic computation****.*



Revisiting Stochastic Computing

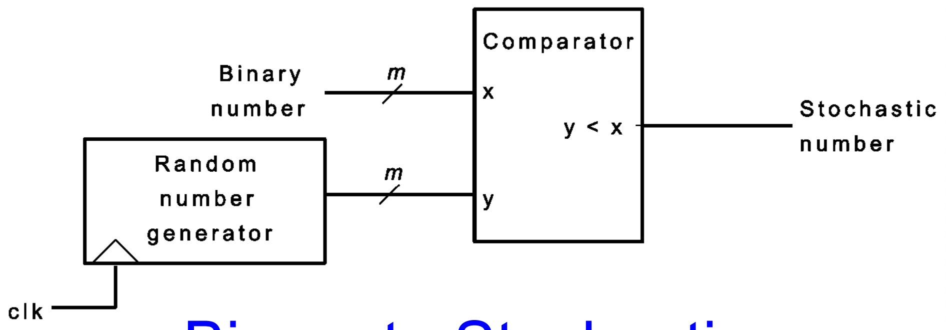
- Stochastic computing was developed to perform precise computations with unreliable hardware

- We want to do approximate computations with little hardware:

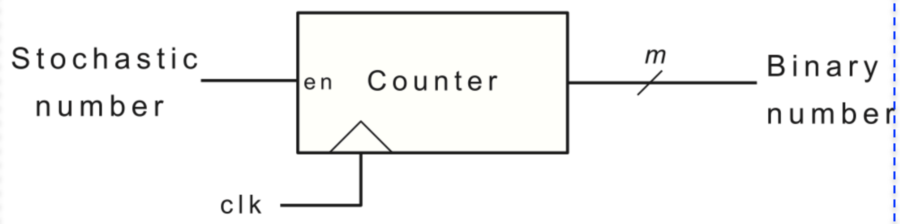
Revisiting stochastic computing methods for parallel probabilistic computations with limited resources

- main limitations:
  - linear increase in precision requires exponential increase in bit-stream,
  - sensitivity to temporal correlations
  - limited dynamic range of the representation.

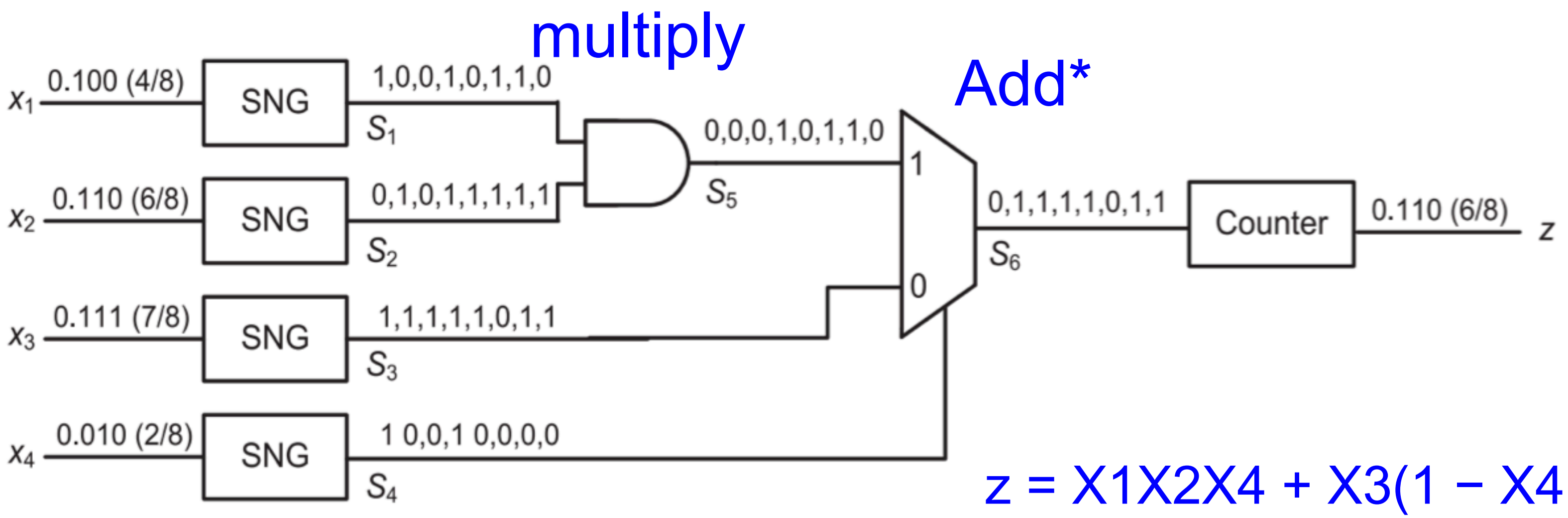
Revisiting Stochastic Computing



Binary to Stochastic



Stochastic to Binary



$z = X1X2X4 + X3(1 - X4)$

Specifying a Bayesian Machine: BM1

$$
\text{Program}\left\{
\begin{array}{l}
\text{Description}\left\{
\begin{array}{l}
\text{Specification}\left\{
\begin{array}{l}
\textbf{variables:}\\
D_1, D_2 : \text{observed variables}\\
M : \text{variable of interest}\\
\textbf{decomposition}\\
P(M \wedge D1 \wedge D2) = P(D_1 \mid M)P(D_2 \mid M)P(M)\\
\textbf{parametric forms:}\\
P(M) : \text{uniform}\\
P(D_1 \mid M) : \text{histogram}\\
P(D_2 \mid M) : \text{histogram}
\end{array}
\right.\\
\text{Identification:}
\end{array}
\right.\\
\text{Question} : P(M) \equiv P(M|\widetilde{P}(D))
\end{array}
\right.
$$

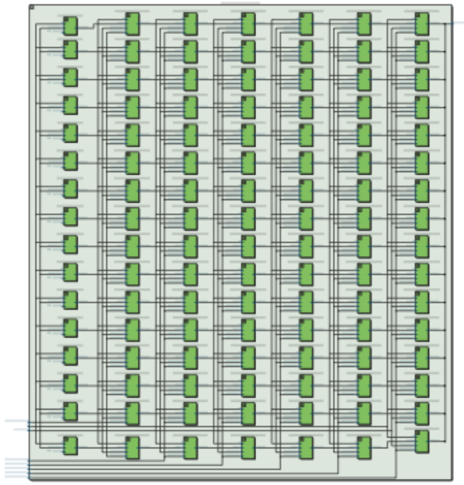
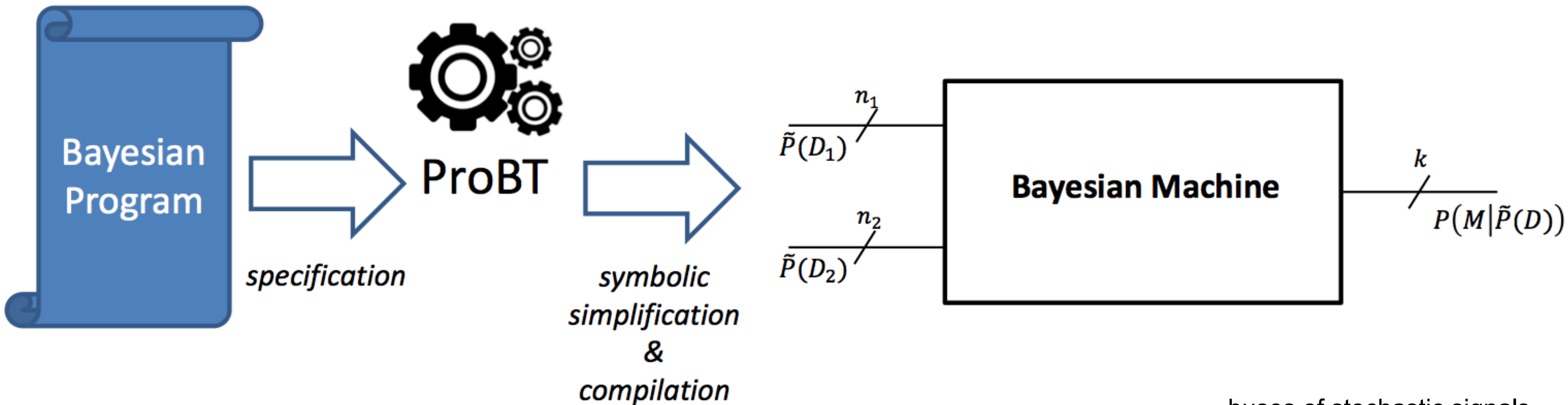


Figure 4: RTL view of 4 × 4 Sensor Fusion boat example using BM1

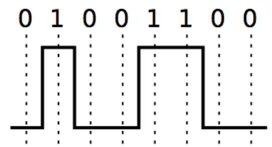


buses of stochastic signals

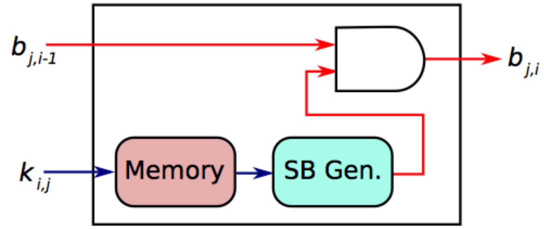
BM1: Bayesian Sensor Fusion
with Fast and Low Power Stochastic Circuits

- Exact inference with approximate computations

$$P([S = s_j] | k_1, \ldots, k_n) = \frac{1}{Z} P([S = s_j]) \prod_{i=1}^{N} P(k_i | [S = s_j])$$

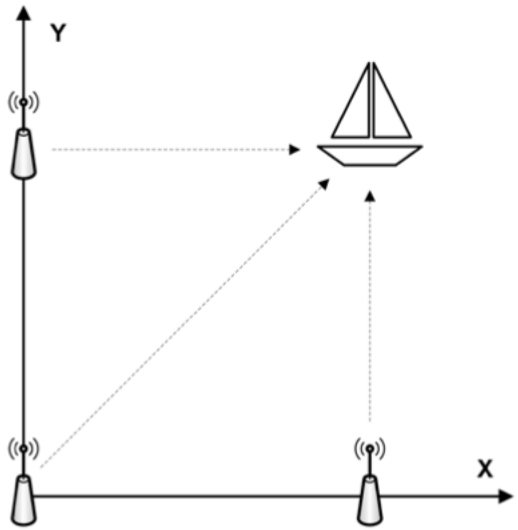


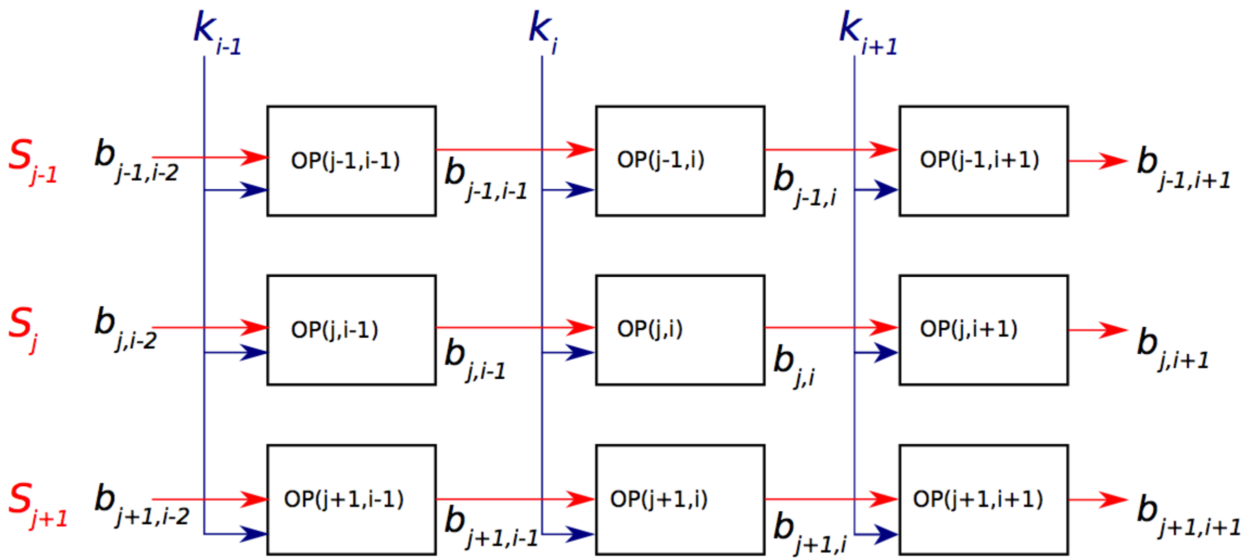
(a) Stochastic bitstream



(b) BM1 element

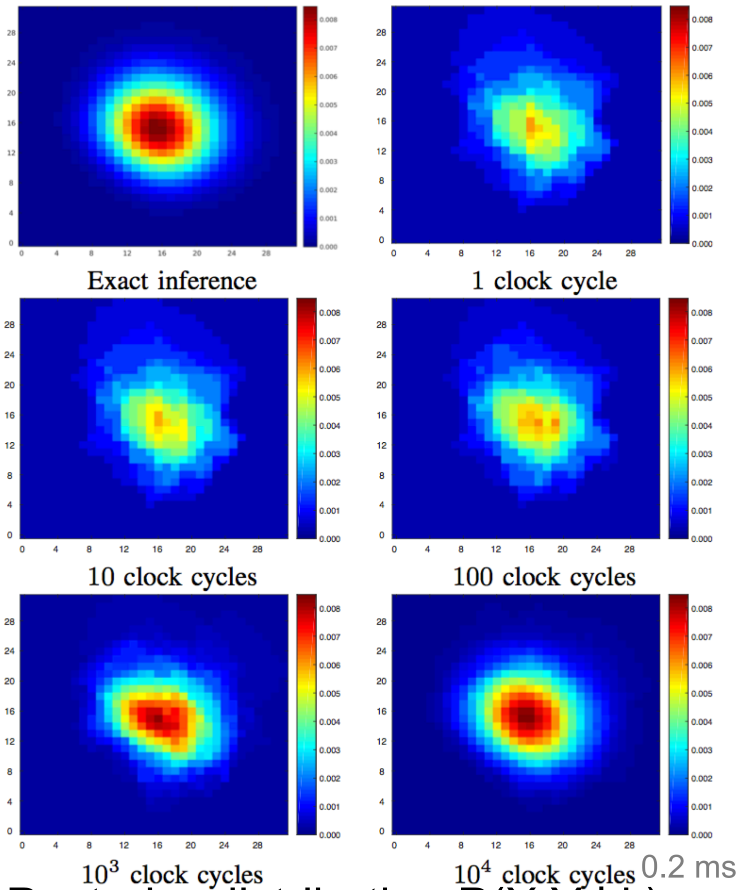
Infer boat coordinates of the boat on grid given distance and bearing sensor readings to three landmarks.





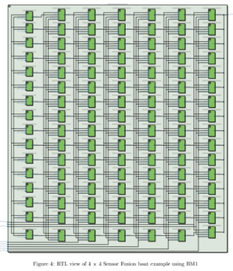
(c) BM1 architecture

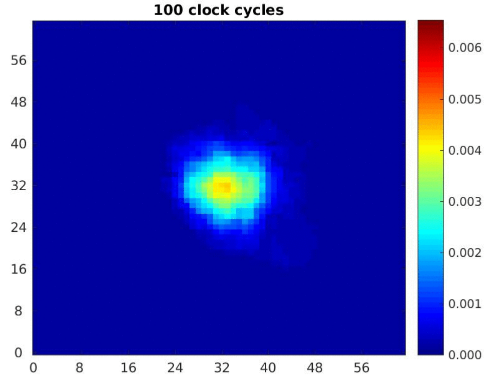
BM1: Bayesian Sensor Fusion

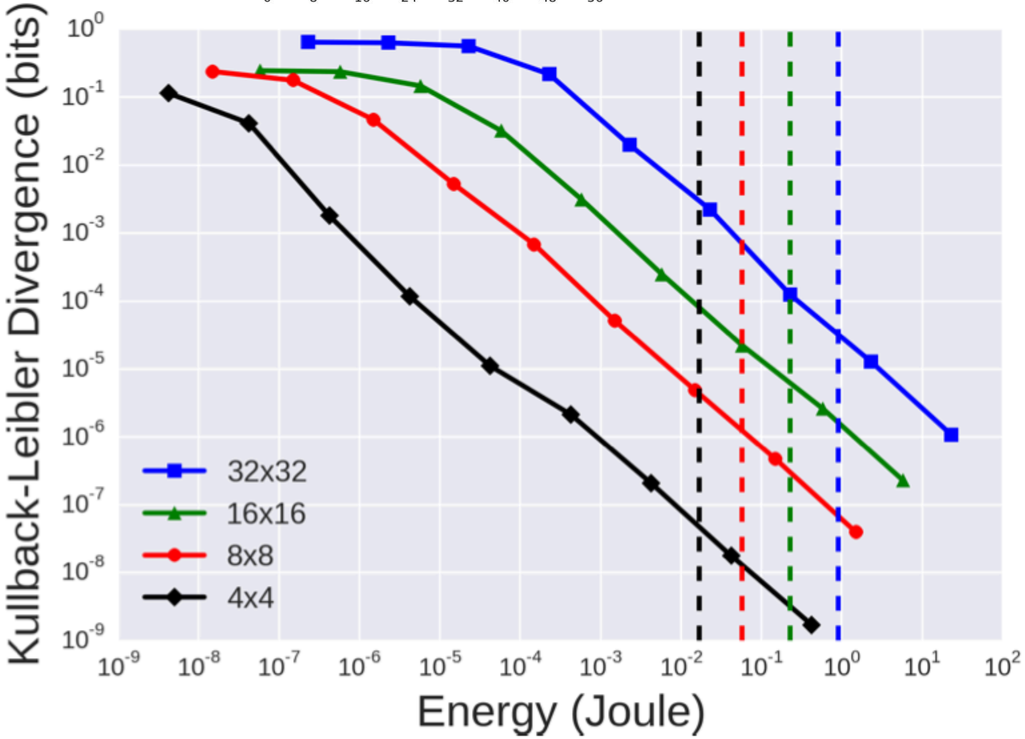


0.2 ms

Posterior distribution P(X,Y | k) with bitstream lengths of 1, 10, 100, 1000, 10000.



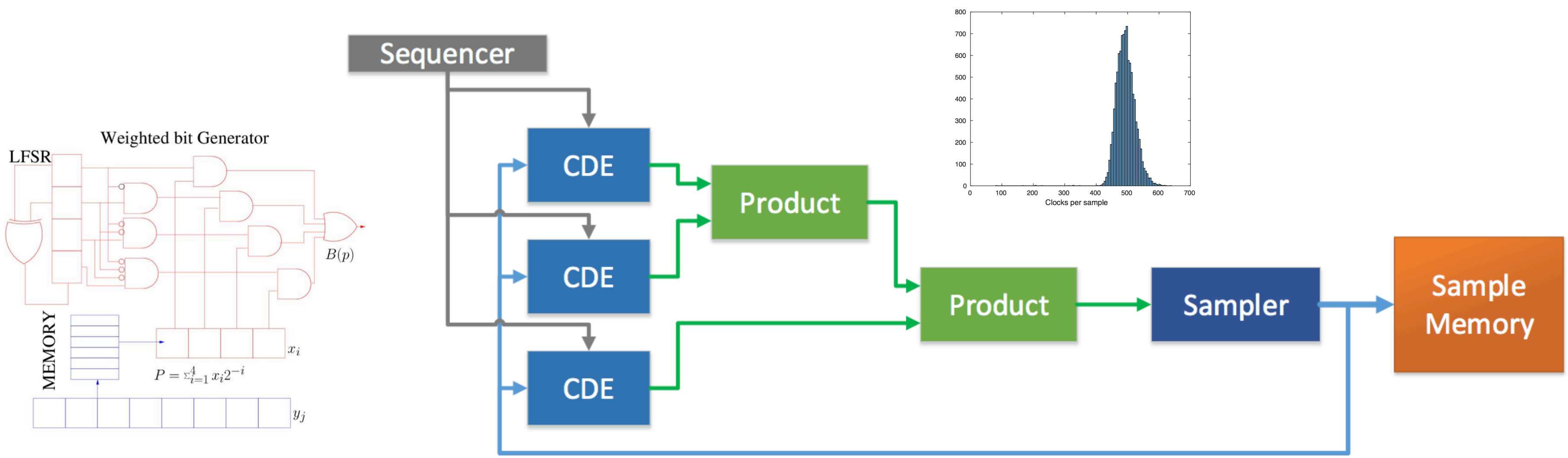




KL divergence for increasing energy use
Vertical lines indicate typical laptop performance

BM2 Approximate Inference

- Gibbs sampling: Computations are performed using stochastic elements and a Gibbs sampler to compute approximate Bayesian inference



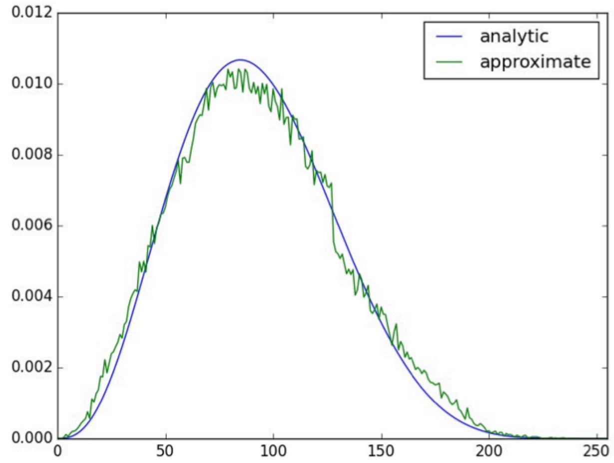
- Gibbs sampling approach adapted to operate at the bit level
- Stochastic signals are sampled

An intractable problem

- To BM2 on intractable inference problems
- inference problem with circular dependences between its variables (as is happens in some image processing applications)
- chose the parametric forms so that we could compute an analytic solution to be used as reference.

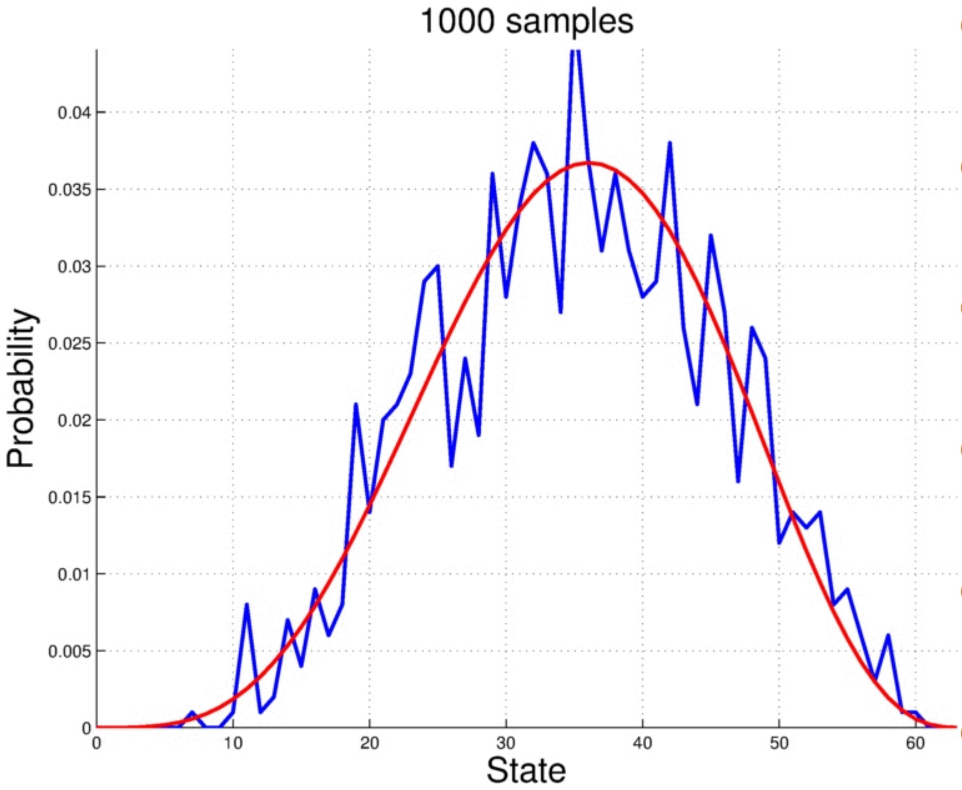
$$P(V_1, ..., V_n, B_1, ..., B_n) = \left(\prod_{i=1}^{n} P(V_i)\right) \prod_{i=1}^{n} P(B_i | V_i V_{1+i\%n})$$

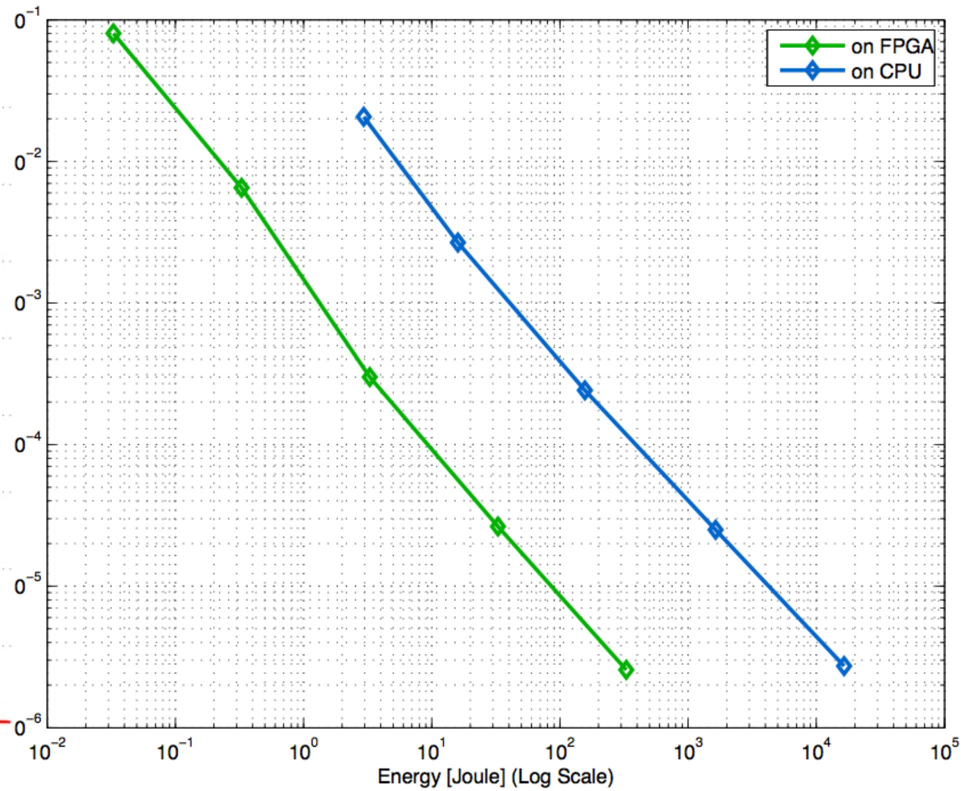
$$P(V_i = k | b_1 = 1, \ldots, b_n = 1) \approx 2^{-m} Beta((k + 0.5)2^{-m}, \alpha, \beta)$$



- 5-bit variables
- 20 searched variables (outputs)
- 64 possible states for each searched variable
- Exact inference requires 2^{100} operations

BM2 solves Intractable Problem

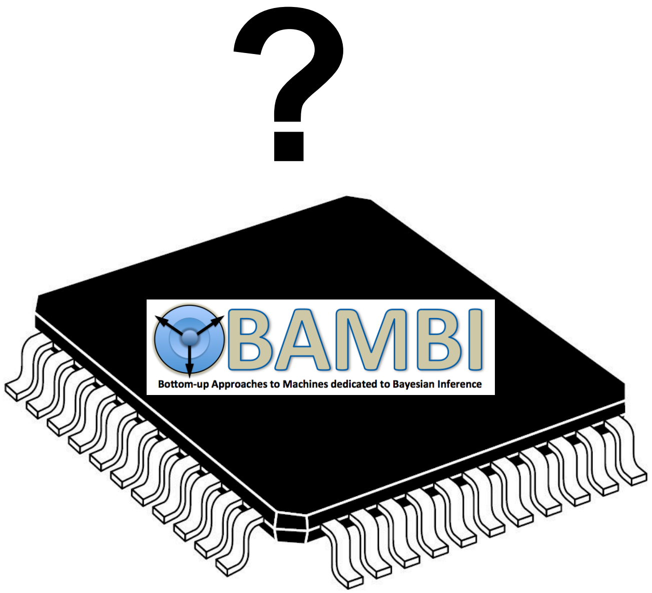


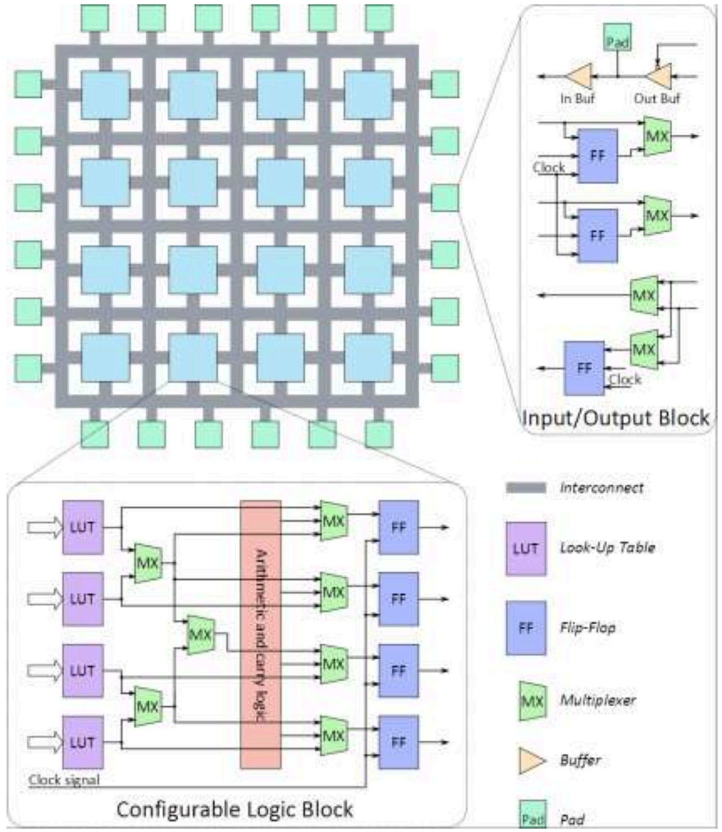


- Example of one pdf output and average KL Divergence of the 5-bit intractable problem as a function of energy consumption

Future perspectives

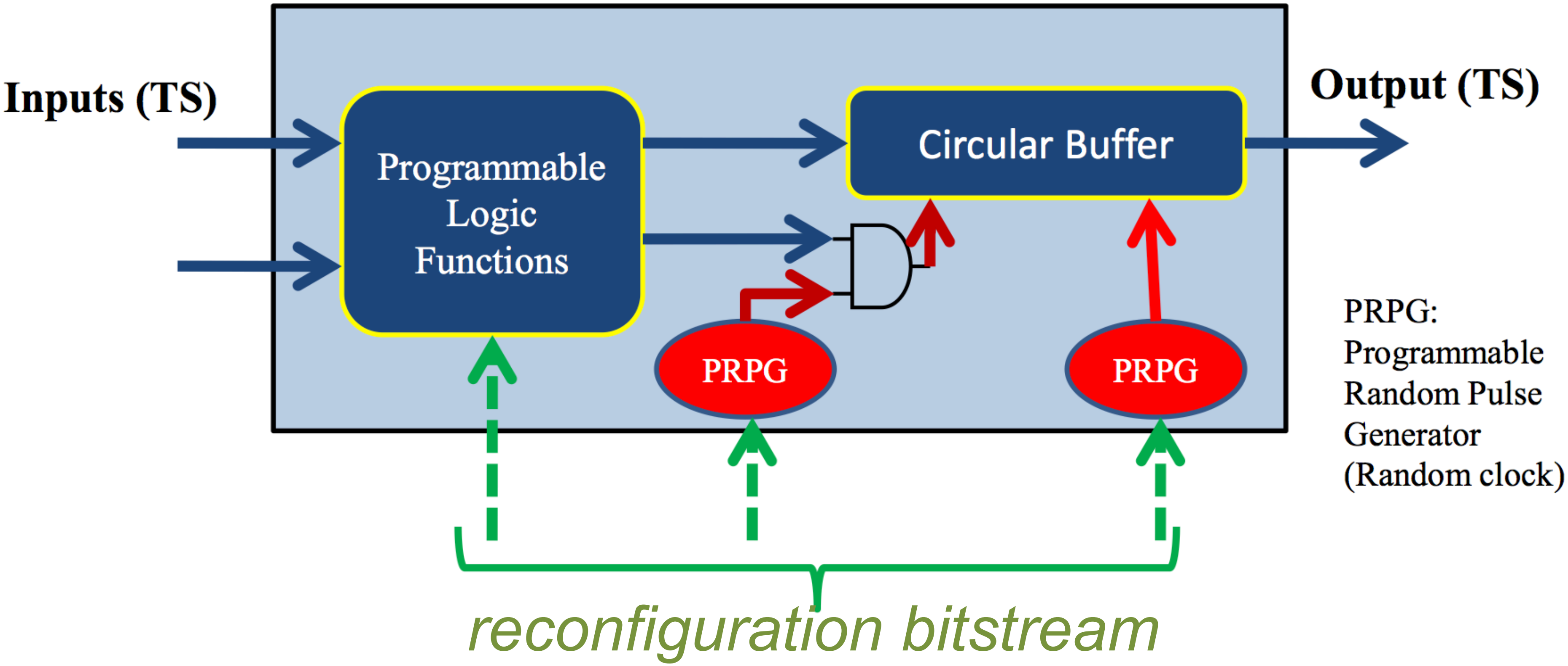
- Possible CLB (configurable logic blocks) of future FPGA?





Future perspectives

- Possible CLB (configurable logic blocks) of future FPGA



Probabilistic Machines for an Uncertain (Robotic) World…

- Moore's Law allowed us to have increasingly smart robots
- Going beyond Moore's law: novel approaches needed to support sustainable computing
- Look at nature and biology
- Revisit correctness contract between hardware and software
- Bayesian probabilistic machines
  - Using stochastic bit streams massively parallel circuits can compute inferences efficiently

BAMBI
Bottom-up Approaches to Machines dedicated to Bayesian Inference

- *Efficient robots dwelling in uncertainty* ***but dealing with it!*** ☺

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