

# Distributing the Heat Equation

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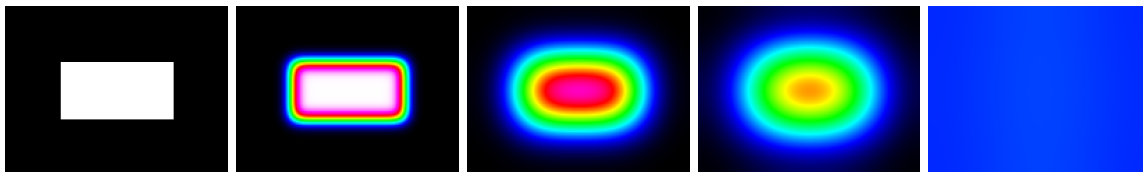
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This homework is due Sunday, December 07, 23h59, Lyon time. Send your archive to both email addresses.

## 1 Heat equation

The heat equation (for information,  $\frac{\partial x}{\partial t} = \nabla^2 x$ ) is a local rule allowing one to compute the evolution of temperature of a system over time. In this homework, we will implement *average cellular automata* that behave similarly:



The first picture corresponds to a plate with a rectangular distribution of temperature, the following ones show how the temperature evolves over time, to finally converge to a uniform distribution.

## 2 Cellular automata

A cellular automaton is a quadruplet  $\mathcal{A} = (d, Q, r, \delta)$  where

- $d \in \mathbb{N}$  is the dimension,
- $Q$  is a set, the states,
- $r \in \mathbb{N}$  is the radius,
- $\delta : Q^{\llbracket -r, r \rrbracket^d} \rightarrow Q$  is the local rule<sup>1</sup>.

The cellular automaton is defined on a grid of cells of  $\mathbb{Z}^d$ . Each cell has a state in  $Q$ . The local function  $\delta$  is the rule to apply to get the next state of a cell, depending on its neighborhood. The global function  $\delta^\dagger$  computes the next step for all the states of the whole grid, according to the rule  $\delta$ .

To formalize this, a configuration for  $\mathcal{A}$  is an element  $X \in Q^{\mathbb{Z}^d}$  and  $\delta$  lifts to a global function on the set of configurations:  $\delta^\dagger : Q^{\mathbb{Z}^d} \rightarrow Q^{\mathbb{Z}^d}$ , such that  $\delta^\dagger$  is invariant under translation each in all the  $d$  directions and coincides with  $\delta$  at the origin (i.e.  $\delta^\dagger(X)_{0,0,\dots,0} = \delta(X|_{\llbracket -r, r \rrbracket^d})$ ).

We focus on the sequence  $(X^t)_{t \in \mathbb{N}}$  where  $X^t$  is the state of the grid at time  $t$ :  $X^{t+1} = \delta^\dagger(X^t)$ . The sequence depends on its initial state  $X^0$ .

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<sup>1</sup>When  $a$  and  $b$  are integers,  $\llbracket a, b \rrbracket$  represents the set  $\{a, a+1, \dots, b\}$ .

That being said, we will consider in this homework 2-dimensional periodic grids of period  $N$  in each direction, which can be thought as finite grids  $\mathcal{G} = \llbracket 0, N-1 \rrbracket^2$ , and the radius of the automata will be 1, meaning that for every cell coordinates  $(i, j) \in \mathcal{G}$  we will consider as its neighborhood the set of cells of coordinates  $(i-1, j-1)$ ,  $(i, j-1)$ ,  $(i+1, j-1)$ ,  $(i, j)$ ,  $(i, j+1)$ ,  $(i+1, j)$ ,  $(i+1, j+1)$  and we handle the edges by considering  $\mathcal{G}$  as a torus. This means that, given the values  $X^t = (x_{i,j}^t)_{(i,j) \in \mathcal{G}}$  at step  $t$ , the next step  $X^{t+1} = \delta^\dagger(X^t)$  is defined as follows:

$$\boxed{(\delta^\dagger(X^t))_{i,j}} \triangleq \delta \left( \begin{array}{|c|c|c|} \hline x_{i-1,j+1}^t & x_{i,j+1}^t & x_{i+1,j+1}^t \\ \hline x_{i-1,j}^t & x_{i,j}^t & x_{i+1,j}^t \\ \hline x_{i-1,j-1}^t & x_{i,j-1}^t & x_{i+1,j-1}^t \\ \hline \end{array} \right)$$

**Question 1.** How many applications of the function  $\delta$  are necessary to compute  $X^t$  on  $\llbracket 0, N-1 \rrbracket^2$ ?

**Question 2.** How would you implement this 2D cellular automaton on a network with a 2D toric grid topology? Be careful to explain where each cell of data is stored, and where the computation of its next state is performed.

**Question 3.** Write a distributed algorithm that computes  $X^{t+1}$ , given  $X^t$  distributed on a toric 2D grid the way you decided in the previous question. What are the time and communication costs of this algorithm? Can you adapt it to a non-toric grid? What would be the complexity on a ring topology?

### 3 Average automata

**Definition 1.** If  $p \neq 0$ , the  $p$ -average automaton is the cellular automaton where  $Q = \mathbb{R}$  and  $\delta$  is:

$$\delta \left( \begin{array}{|c|c|c|} \hline a & b & c \\ \hline d & e & f \\ \hline g & h & i \\ \hline \end{array} \right) \triangleq (1-p) \cdot e + p \cdot \frac{b+d+f+h}{4} .$$

In other terms, the new value of a cell is the average of the old values of cells inside its immediate neighborhood, weighed by  $p$ , and of the old value of the cell itself, weighed by  $1-p$ .

**Question 4.** In the file `average.c`, implement on a toric grid the algorithm of Question 3 for any  $p$ -average automata. See Section 6 for implementation details.

When  $X$  and  $Y$  are two configurations of the grid  $\mathcal{G}$ , we write  $X + Y$  the state of  $\mathcal{G}$  defined by the point-wise sum of the two states:  $(X + Y)_{i,j} = X_{i,j} + Y_{i,j}$ . Similarly, for every  $k \in \mathbb{R}$  the state  $k \cdot X$  is defined as:  $(k \cdot X)_{i,j} = kX_{i,j}$ . A function  $f$  is linear if  $\forall X, Y, k, f(X + Y) = f(X) + f(Y)$  and  $f(k \cdot X) = k \cdot f(X)$ .

When computing complexity bounds, we assume that basic operations on real numbers (such as sum, product, ...) cost 1 unit of time. For the space complexity, storing one real number takes one unit of memory. Finally, we assume that sending one real number from one processor to another takes  $c$  units of time (as usual, independent communications can be performed in parallel).

**Question 5.** In the case of a  $p$ -average automaton, prove that  $\delta^\dagger$  is linear. Use that property to derive an algorithm that, given  $X^0$ , computes  $X^t$  in time  $O(\log t)$  for a fixed  $N$ . What is the time and space complexity, in terms of both  $t$  and  $N$ ? Compare to the complexity in the general case.

**Question 6.** Describe a distributed variant of the above algorithm on a  $p \times p$  processors toric grid. What are the new time, space, and communication costs?

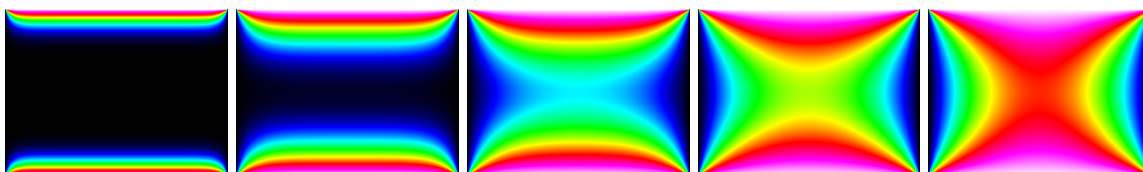
**Question 7** (Sparse initial conditions). Let  $Z$  be the state of the grid such that  $Z_{i,j}$  is 1 when  $i = j = 0$  and 0 otherwise, and let assume that  $Z^t$  is *already computed* and distributed on a  $p \times p$  toric grid. Given an arbitrary *sparse* state  $X^0$  of the grid (i.e.,  $|X^0|$ , the number of non-zero cells in  $X^0$ , is small), how can you compute  $X^t$  on the  $p \times p$  toric grid? What are, the time/space/communication complexities in terms of  $N$  and  $|X^0|$ ?

**Question 8.** In the file `sparse.c`, implement Question 7 on a toric grid: first, given  $t$  and the dimensions of  $Z$ , precompute  $Z^t$  using Question 4. Then, provide the user with an interface that lets her update  $X^0$  by entering  $(i, j, x_{i,j}^0)$  one by one, starting from  $X^0 = 0$  and keep  $X^t$  updated at each new entry.

**Question 9.** Give some fixed points of  $\delta^\dagger$  in  $\mathbb{R}^{\mathbb{Z}^d}$  and in  $\mathbb{R}^{[0, N-1]^d}$  (note that the latter is a torus).

## 4 Thermal reservoirs

A thermal reservoir is a thermodynamic system with constant, unalterable temperature, influencing in turn the temperature of the environment. The pictures below describe the evolution of a plate with warm thermal reservoirs on the horizontal edges and cold thermal reservoirs on the vertical edges.



We suppose now  $0 < p \leq 1$ . We augment  $Q$  with special states:  $Q = \mathbb{R} \uplus \mathcal{C}$  where  $\mathcal{C}$  a set of special states called *constants* written as  $C_k$  where  $k$  is a real number. Now the notion of average automaton is refined, so that a cell in state  $C_k$  stays in the same state forever, and is considered of temperature  $k$  by its neighbors.

Formally, we define the temperature  $\theta(x)$  of a state as  $\theta(x) = k$  when  $x = C_k$  and  $\theta(x) = x$  otherwise. The local rule becomes the following function:

$$\delta \left( \begin{array}{|c|c|c|} \hline a & b & c \\ \hline d & e & f \\ \hline g & h & i \\ \hline \end{array} \right) \triangleq \begin{cases} C_k & \text{if } e = C_k, \\ (1-p) \cdot \theta(e) + p \cdot \frac{\theta(b) + \theta(d) + \theta(f) + \theta(h)}{4} & \text{otherwise.} \end{cases}$$

**Question 10.** Give an example of a fixed point with one constant, and another with two different constants. Give the limit of  $(X^t)$ , if it exists, given that  $X^0$  has at most one constant.

**Question 11.** For a  $p$ -average automaton with constants, is  $\delta^\dagger$  linear?

**Question 12** (Bonus). Prove that the sequence  $(X^t)$  converges when  $X^0$  has at least one constant.

**Question 13.** In the file `constants.c`, adapt Question 4 to the setting of Section 4.

## 5 Graphical implementation

**Question 14.** Use the display of the first processor to provide the user with a simple graphic interface, featuring a  $[0, 1]$ -valued heat map:

- for Question 8: where the interface is a black, cold map and the user can click to set some  $X_{i,j}^0$  to 1.
- for Question 13: given a map of  $C_0$  and  $C_1$  constants, compute and display the fixed point in a distributed setting.

You can use Douglas Thain's simple X11 graphics library.  
<http://www3.nd.edu/~dthain/courses/cse20211/fall2013/gfx/>

## 6 Implementation details

Use the C programming language. Using any other language including C++ is likely to halve your mark.

Your programs must compile (with `mpicc`) and run (with `mpirun`) on the machines of the ENS (`s1su0-01`, `s1su0-02` etc.). Provide a `name.tar.gz` archive in which you have a folder `name` where `name` is your name. Provide a makefile, such that running `make` at the root of `name` will compile everything and create all executable binaries at the root of `name`. Use `double` to represent real numbers.

**Input** Input data is given via standard input. Note that you can use standard input with `./myprogram` and then type things manually, or with `./myprogram < file` to use the file `file` as standard input. The format is the following:

- width of the grid on first line of standard input
- height on second line
- $p$  on third line
- $t$  the number of iterations on the fourth
- then, the initial grid, described as a sparse matrix on each line with its coordinates:
  - `0 i j x` is **input data** for a value  $x \in [0, 1]$  with coordinates  $(i, j)$
  - `1 i j k` is **input data** of a constant  $k \in [0, 1]$  with coordinates  $(i, j)$
  - `2 i j 0` is a **request** to give the value at position  $(i, j)$  after  $t$  iterations.

**Output** Answer to each of the `2 i j 0` requests by printing the temperature of the corresponding cell. Note that:

- in the sparse case, requests and input data can be interleaved (and constants will be ignored).
- in the other cases, the first request triggers the computation (subsequent input data will be ignored).