Simuler les feux de forêt

Comment utiliser l'informatique pour réduire l'impact des feux de forêts en transformant le moins possible ces dernières ?

N° SCEI 14423

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Contexte

Les feux de forêt sont de plus en plus fréquents. L'informatique peut se révéler être un atout de taille pour prévoir et anticiper ces derniers.

Figure: Feu de forêt à Malibu[1]

[1] National Geographic Education

Sommaire

Un premier modèle de feux de forêt

Automate cellulaire (2D)

- Une grille
- Un état par case
- Un ensemble de règles de transitions entre les états

[2] Science Direct

Un premier modèle de feux de forêt

Automate cellulaire (2D)

- Une grille
- Un état par case
- Un ensemble de règles de transitions entre les états

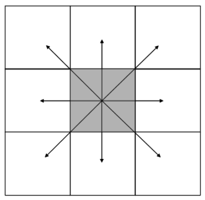

Figure: Voisinage de Moore [2]

[2] Science Direct

Un premier modèle de feux de forêt

Types de cases :

- Arbres
- Champs
- Feu
- Case brulée *
- Eau *

* Ne peuvent pas/plus bruler

p_b	Voisin direct	Voisin diagonal
Arbres	$\frac{1}{8}$	$\frac{1}{16}$
Champs	$\frac{1}{8}$	$\frac{1}{16}$

Figure: Changement d'états

Un premier modèle de feux de forêt

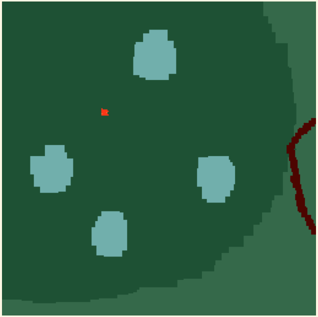

Figure: À $t = 0$

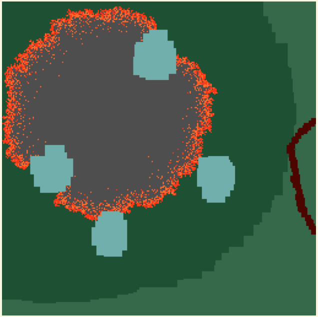

Figure: À $t = 200$

Vers le modèle d'Alexandridis

> ***Idée***
> Il serait intéressant de prendre en compte des données du milieu : vent, densité de végétation

Modèle d'Alexandridis pour les feux de forêt

Nouveau type de case :

- Arbres denses

Règles de transition

Pour tout $(i, j, t) \in \mathbb{N}^3$, on a :

- Si $etat(i, j, t) = feu$, alors $etat(i, j, t+1) = brule$
- Si $etat(i, j, t) = feu$, alors $etat(i \pm 1, j \pm 1, t+1) = brule$ avec une probabilité p_b
- Si $etat(i, j, t) = brule$, alors $etat(i, j, t+1) = brule$

Modèle d'Alexandridis pour les feux de forêt

Probabilité d'inflammage p_b

On a $p_b = p_h(1 + p_{veg})(1 + p_{den})p_{vent}$ avec $p_h = 0.27$ une constante

Probabilité liée au vent p_{vent}

On a $p_{vent} = exp(0.045 \times v) \times exp(v \times 0.131 \times (cos(\theta) - 1))$ avec θ l'angle entre la propagation du feu et la direction du vent et v la vitesse du vent (en m/s)

	p_{veg}	p_{den}
Arbres	0.3	0.3
Arbres denses	0.3	0
Champs	-0.1	0

Figure: Probabilités p_{veg} et p_{den} selon le type de végétation

Comparaison du premier modèle et de celui d’Alexandridis à $t = 200$.

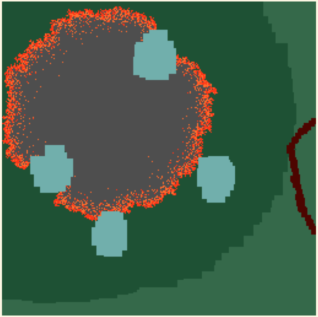

Figure: Modèle 1

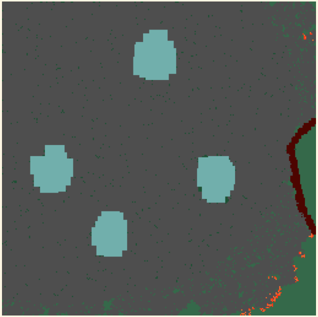

Figure: Modèle 2

Modèle d’Alexandridis pour les feux de forêt

Comparaison selon la densité de végétation avec 15 m/s de vent vers l’est.

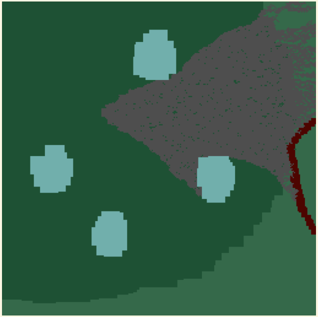

Figure: Végétation normale

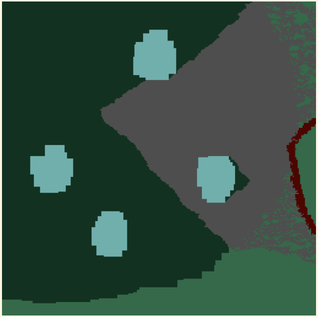

Figure: Végétation dense

Transformations envisageables

Objectif

Mieux protéger la forêt contre les incendies en la modifiant le moins possible.

Figure: Chemin forestier - Forêt du Rouvray [3]

[3] ONF

Transformations envisageables

Nouveau type de case :

- Chemins/Tranchées avec $p_{veg} = -0.55$ et $p_{den} = 0$

Probabilité d'inflammage p_b

On a $p_b = p_h(1 + p_{veg})(1 + p_{den})p_{vent}$ avec $p_h = 0.27$ une constante

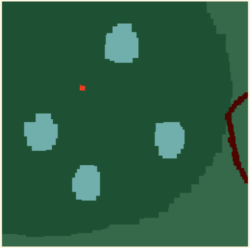

Figure: Exemple de chemins

Transformations envisageables

Comparaison entre une forêt avec une tranchée et une sans (moyennée sur 100 générations)

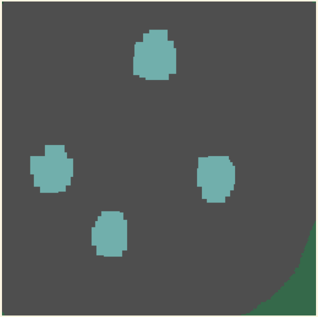

Figure: Sans tranchées

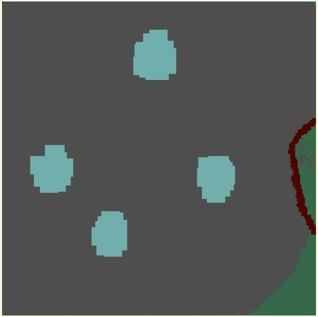

Figure: Avec tranchées

Transformations envisageables

Comparaison entre une forêt avec une tranchée et 15 ou 30 m/s de vent (moyennée sur 100 générations)

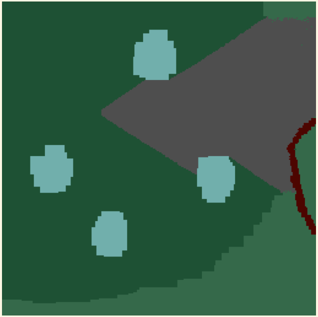

Figure: 15 m/s de vent

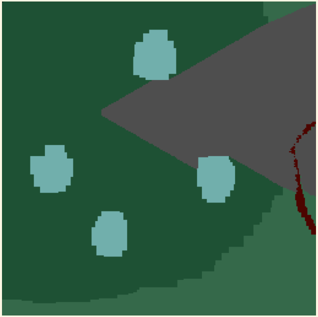

Figure: 30 m/s de vent

Comparaison entre deux tranchées de largeurs différentes
(moyennée sur 100 générations)

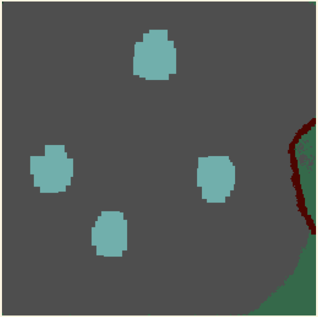

Figure: Tranchée de 8m

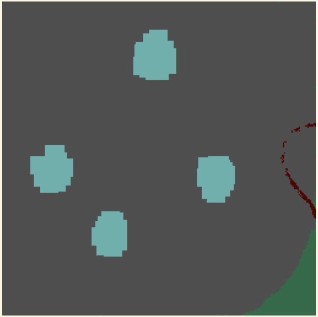

Figure: Tranchée de 4m

Conclusion

Possibilité de prendre en compte pour améliorer les simulations :

- Humidité
- Altitude/pentes
- Température

D’autres transformations sont envisageables :

- Lacs/Cours d’eau
- Réduction de la densité de végétation

Navigateur

```c
#include <time.h>
#include "grid.c"

/**
 * Main function of the program
 * <p>
 * The program can be launched with the following arguments:
 * <ul>
 * <li>--model [model]: The model of the grid (0-2)</li>
 * <li>--count [count]: The number of grids to simulate</li>
 * <li>--iterations [iterations]: The max number of iterations</li>
 * <li>--enable_graphics [0/1]: Whether graphics are disabled</li>
 * <li>--tick [ms]: The number of milliseconds between each tick</li>
 * <li>--export_csv: Export grids in csv format</li>
 * <li>--export_png: Export grids in png format</li>
 * <li>--wind_direction [direction]: The wind direction (0 to 360)</li>
 * <li>--wind_speed [speed]: The wind speed</li>
 * <li>--generate_mean: Generate the mean of the grids (useful only if you export the
 ↪  grids)</li>
 * <li>--help: Display the help message</li>
 * </ul>
 * </p>
 * @param argc The number of arguments
 * @param argv The arguments
 * @return The exit code
 */
int main(int argc, char * argv[]) {
  // Command arguments management
```

main.c (2/10)

```c
int model = 0;
int count = 1;
int iterations = -1;
int tick_ms = 10;
bool enable_graphics = true;
bool export_csv = false;
bool export_png = false;
double wind_direction = 0;
double wind_speed = 0;
bool generate_mean = false;

if (argc > 1) {
  for (int i = 1; i < argc; i++) {
    if (strcmp(argv[i], "--model") == 0) {
      if (i + 1 < argc) {
        model = atoi(argv[i + 1]);
      }
    } else if (strcmp(argv[i], "--count") == 0) {
      if (i + 1 < argc) {
        count = atoi(argv[i + 1]);
      }
    } else if (strcmp(argv[i], "--iterations") == 0) {
      if (i + 1 < argc) {
        iterations = atoi(argv[i + 1]);
      }
    } else if (strcmp(argv[i], "--tick") == 0) {
      if (i + 1 < argc) {
        tick_ms = atoi(argv[i + 1]);
      }
```

main.c (3/10)

```
} else if (strcmp(argv[i], "--enable_graphics") == 0) {
  if (i + 1 < argc) {
    enable_graphics = atoi(argv[i + 1]);
  }
} else if (strcmp(argv[i], "--help") == 0) {
  printf("Usage: %s --model [model] --count [count] --iterations [iterations]
  ↪  --enable_graphics [0/1] --tick [ms] --export_png --export_csv
  ↪  --wind_direction [direction] --wind_speed [speed] --generate_mean
  ↪  --help\n\nArguments:\n--model [model]: The model of the grid
  ↪  (0-2)\n--count [count]: The number of grids to simulate\n--iterations
  ↪  [iterations]: The max number of iterations\n--enable_graphics [0/1]:
  ↪  Whether graphics are disabled\n--tick [ms]: The number of milliseconds
  ↪  between each tick\n--help: Display this help message\n--export_csv:
  ↪  Export grids in csv format\n--export_png: Export grids in png
  ↪  format\n--wind_direction [direction]: The wind direction (0 to
  ↪  360)\n--wind_speed [speed]: The wind speed\n--generate_mean: Generate the
  ↪  mean of the grids (useful only if you export the grids)\n--help: Display
  ↪  the help message\n",
       argv[0]);
  return 0;
} else if (strcmp(argv[i], "--export_csv") == 0) {
  export_csv = true;
} else if (strcmp(argv[i], "--export_png") == 0) {
  export_png = true;
} else if (strcmp(argv[i], "--wind_direction") == 0) {
  if (i + 1 < argc) {
    wind_direction = atof(argv[i + 1]);
  }
} else if (strcmp(argv[i], "--wind_speed") == 0) {
```

```
      if (i + 1 < argc) {
        wind_speed = atof(argv[i + 1]);
      }
    } else if (strcmp(argv[i], "--generate_mean") == 0) {
      generate_mean = true;
    }
  }
}

printf("Launching simulation\nModel %d\nCount %d\nIterations %d\nGraphics %d\n",
↪  model, count, iterations,
     enable_graphics);

srandom(time(NULL));

if (tick_ms < 2) {
  printf("Invalid tick, setting to 2\n");
  tick_ms = 2;
}

if (count <= 0) {
  printf("Invalid count, setting to 1\n");
  count = 1;
}

int remaining = count;
Grid * grids = malloc(count * sizeof(*grids));

// Choose the number of grids to display per line and per column
```

main.c (5/10)

```c
int max_x;
int max_y;
if (count == 1) {
  max_x = 1;
  max_y = 1;
} else if (count <= 2) {
  max_x = 2;
  max_y = 1;
} else if (count <= 6) {
  max_x = 3;
  max_y = 2;
} else if (count <= 18) {
  max_x = 6;
  max_y = 3;
} else if (count <= 36) {
  max_x = 9;
  max_y = 4;
} else {
  max_x = 14;
  max_y = 7;
}

remove("grids.csv");
remove("grids_png");

// Create the window and the grids
Window window;
if (enable_graphics) {
  window = create_window(max_x, max_y);
```

main.c (6/10)

```
} else {
  window = (Window) {
      .window = NULL,
      .surface = NULL
  };
}

for (int i = 0; i < count; i++) {
  grids[i] = create_grid(model, window, i % max_x, i / max_x, export_csv,
  ↪  export_png);
  grids[i].wind_direction = wind_direction;
  grids[i].wind_speed = wind_speed;
}

// Main loop to update the grids and tick until all grids have ended
do {
  SDL_Event event;
  while (SDL_PollEvent(&event)) {
    // Used to close the window if the user clicks on the close button
    if (event.type == SDL_QUIT) {
      for (int i = 0; i < count; i++) {
        destroy_grid(grids[i]);
      }

      free(grids);
      return 0;
    }
  }
```

```c
    // Update the grids
    for (int i = 0; i < count; i++) {
      if (!grids[i].ended) {
        tick(&grids[i]);

        grids[i].ended = is_ended(grids[i]);
        // If the grid has ended, we decrease the number of remaining grids
        if (grids[i].ended) {
          remaining--;
        }
      }
    }

    wait(tick_ms);
  } while (remaining > 0 && --iterations != -1);

  wait(2500);

  // DO SOMETHING WITH GRIDS IF NEEDED
  if (generate_mean) {
    int *** data = malloc(GRID_SIZE * sizeof(*data));
    for (int i = 0; i < GRID_SIZE; i++) {
      data[i] = (int **) malloc(GRID_SIZE * sizeof(*data[i]));
      for (int j = 0; j < GRID_SIZE; j++) {
        data[i][j] = malloc(TILE_TYPE_SIZE * sizeof(*data[i][j]));
      }
    }

    for (int i = 0; i < count; i++) {
```

```
    for (int x = 0; x < GRID_SIZE; x++) {
      for (int y = 0; y < GRID_SIZE; y++) {
        data[x][y][grids[i].data[x][y].current_type]++;
      }
    }
  }

  Tile ** tiles = malloc(GRID_SIZE * sizeof(*tiles));

  for (int x = 0; x < GRID_SIZE; x++) {
    tiles[x] = malloc(GRID_SIZE * sizeof(*tiles[x]));
    for (int y = 0; y < GRID_SIZE; y++) {
      tiles[x][y] = (Tile) {
          .default_type = TILE_TYPE_SIZE,
          .current_type = TILE_TYPE_SIZE,
          .state = 0
      };

      int max = 0;
      int max_type = 0;
      for (int i = 0; i < TILE_TYPE_SIZE; i++) {
        if (data[x][y][i] > max) {
          max = data[x][y][i];
          max_type = i;
        }
      }

      tiles[x][y].current_type = max_type;
    }
```

```
    }

    Grid grid = (Grid) {
        .data = tiles,
        .window = window,
        .model = model,
        .ended = true,
        .coord_x = -1,
        .coord_y = -1,
        .export_png = export_png,
        .export_csv = export_csv,
        .wind_direction = wind_direction,
        .wind_speed = wind_speed
    };

    destroy_grid(grid);

    for (int i = 0; i < GRID_SIZE; i++) {
      for (int j = 0; j < GRID_SIZE; j++) {
        free(data[i][j]);
      }
      free(data[i]);
    }
    free(data);
  }

  // Free the memory and close the window
  for (int i = 0; i < count; i++) {
    destroy_grid(grids[i]);
```

main.c (10/10)

```c
  }

  if (enable_graphics) {
    destroy_window(window);
  }
  free(grids);

  return 0;
}
```

misc.c (1/3)

```c
#include <stdio.h>
#include <stdint.h>
#include <stdlib.h>

/**
 * Get the maximum of two integers
 *
 * @param a The first integer
 * @param b The second integer
 * @return The maximum of the two integers
 */
int max(int a, int b) {
  return a > b ? a : b;
}

/**
 * Get the minimum of two integers
 *
 * @param a The first integer
 * @param b The second integer
 * @return The minimum of the two integers
 */
int min(int a, int b) {
  return a < b ? a : b;
}

/**
 * Read a file and return its content as a string
```

```
 *
 * @param file The file to read
 * @return The content of the file
 */
char * readfile(FILE * file) {
  // Check if the file is null or if the seek failed
  if (file == NULL || fseek(file, 0, SEEK_END)) {
    return NULL;
  }

  long length = ftell(file);
  rewind(file);
  // Check if the length is invalid
  if (length == -1 || (unsigned long) length >= SIZE_MAX) {
    return NULL;
  }

  // Convert from long to size_t
  size_t ulength = (size_t) length;
  char * buffer = malloc(ulength + 1);
  // Check if the buffer is null or if the read failed
  if (buffer == NULL || fread(buffer, 1, ulength, file) != ulength) {
    free(buffer);
    return NULL;
  }
  // Finish the string
  buffer[ulength] = '\0';

  return buffer;
```

misc.c (3/3)

```c
}

/**
 * Get a random number between 0 and max (excluded)
 *
 * @param max The maximum value
 * @return The random number
 */
int get_random(int max) {
  return (int) (random() % max);
}
```

grid.c (1/21)

```c
#include "draw.c"
#include <cjson/cJSON.h>
#include <unistd.h>
#include <png.h>
#include <sys/stat.h>

/**
 * Model 0 constants
 *
 * The following probabilities are 1 / [number]
 */
/**
 * The probability for a tree tile to burn
 */
const int M0_PROBA_TREE_BURN = 8;
/**
 * The probability for a grass tile to burn
 */
const int M0_PROBA_GRASS_BURN = 8;
/**
 * The probability for a tile to change state between fire and burnt
 */
const int M0_PROBA_STATE_CHANGE = 16;

/**
 * Model 1 constants
 *
 * The following probabilities are 1 / [number]
```

```
 */
/**
 * The probability for a tree tile to burn (in direct neighbors)
 */
const int M1_C_PROBA_TREE_BURN = 8;
/**
 * The probability for a grass tile to burn (in direct neighbors)
 */
const int M1_C_PROBA_GRASS_BURN = 8;
/**
 * The probability for a tree tile to burn (in diagonal neighbors)
 */
const int M1_D_PROBA_TREE_BURN = 16;
/**
 * The probability for a grass tile to burn (in diagonal neighbors)
 */
const int M1_D_PROBA_GRASS_BURN = 16;
/**
 * The probability for a tile to change state between fire and burnt
 */
const int M1_PROBA_STATE_CHANGE = 16;

void write_to_file(Grid grid);

/**
 * Create a grid
 *
 * @param model The model of the grid
 * @param window The window to draw the grid
```

```c
 * @param coord_x The x coordinate of the grid
 * @param coord_y The y coordinate of the grid
 * @return The created grid
 */
Grid create_grid(int model, Window window, int coord_x, int coord_y, bool
↪  export_csv, bool export_png) {
  // Create the grid
  Grid grid = {
      .data = (Tile **) malloc(GRID_SIZE * sizeof(*grid.data)),
      .window = window,
      .model = model,
      .ended = false,
      .coord_x = coord_x,
      .coord_y = coord_y,
      .export_csv = export_csv,
      .export_png = export_png
  };

  // Initialize the grid
  for (int i = 0; i < GRID_SIZE; i++) {
    grid.data[i] = (Tile *) malloc(GRID_SIZE * sizeof(*grid.data[i]));
  }

  // Load the grid from a json file if it exists, otherwise create a random grid
  if (access("grid.json", F_OK) == 0) {
    // The json file exists, we load the grid from it
    cJSON * grid_json = cJSON_Parse(readfile(fopen("grid.json", "r")));
    cJSON * grid_json_object = cJSON_GetObjectItem(grid_json, "grid");
```

```
    for (int i = 0; i < GRID_SIZE; i++) {
      cJSON * row = cJSON_GetArrayItem(grid_json_object, i);
      for (int j = 0; j < GRID_SIZE; j++) {
        // Get the value of the tile and set it to the grid
        int value = cJSON_GetArrayItem(row, j)->valueint;

        grid.data[i][j].current_type = value;
        grid.data[i][j].default_type = value;
        grid.data[i][j].state = 0;
      }
    }
  } else {
    // The json file does not exist, we create a random grid
    for (int i = 0; i < GRID_SIZE; i++) {
      for (int j = 0; j < GRID_SIZE; j++) {
        // Get a random value between 0 and 3 and set it to the grid
        int value = get_random(4);

        grid.data[i][j].current_type = value;
        grid.data[i][j].default_type = value;
        grid.data[i][j].state = 0;
      }
    }
  }

  return grid;
}

/**
```

grid.c (5/21)

```c
 * Copy a grid
 *
 * @param data The grid to copy
 * @return The copied grid
 */
Tile ** copy_grid(Tile ** data) {
  // Malloc the copy of the grid
  Tile ** copy = (Tile **) malloc(GRID_SIZE * sizeof(*copy));

  // Fill the copy with the data of the grid
  for (int i = 0; i < GRID_SIZE; i++) {
    copy[i] = (Tile *) malloc(GRID_SIZE * sizeof(*copy[i]));
    memcpy(copy[i], data[i], GRID_SIZE * sizeof(*copy[i]));
  }

  return copy;
}

/**
 * Get the tile at a point
 *
 * @param grid The grid
 * @param point The point
 * @return The tile at the point
 */
Tile get_tile(Grid grid, Point point) {
  return grid.data[point.x][point.y];
}
```

grid.c (6/21)

```c
/**
 * Get the direct neighbors of a point
 *
 * @param grid The grid
 * @param point The point
 * @return The neighbors of the point
 */
Point * get_direct_neighbors(Grid * grid, Point point) {
  Point * neighbors = (Point *) malloc(4 * sizeof(*neighbors));

  neighbors[0] = (Point) {point.x - 1, point.y};
  neighbors[1] = (Point) {point.x + 1, point.y};
  neighbors[2] = (Point) {point.x, point.y - 1};
  neighbors[3] = (Point) {point.x, point.y + 1};

  return neighbors;
}

/**
 * Get the diagonal neighbors of a point
 *
 * @param grid The grid
 * @param point The point
 * @return The neighbors of the point
 */
Point * get_diagonal_neighbors(Grid * grid, Point point) {
  Point * neighbors = (Point *) malloc(4 * sizeof(*neighbors));

  neighbors[0] = (Point) {point.x - 1, point.y - 1};
```

```c
  neighbors[1] = (Point) {point.x + 1, point.y - 1};
  neighbors[2] = (Point) {point.x - 1, point.y + 1};
  neighbors[3] = (Point) {point.x + 1, point.y + 1};

  return neighbors;
}

/**
 * Check if a point is valid (ie inside the grid)
 *
 * @param point The point to check
 * @return True if the point is valid, false otherwise
 */
bool is_valid(Point point) {
  return point.x >= 0 && point.x < GRID_SIZE && point.y >= 0 && point.y < GRID_SIZE;
}

/**
 * Check if the grid is ended
 *
 * @param grid The grid to check
 * @return True if the grid is ended, false otherwise
 */
bool is_ended(Grid grid) {
  if (grid.model == 0 || grid.model == 1 || grid.model == 2) {
    bool is_fire = false;

    // Check if there is no more fire, if there is no more fire, the grid is ended
    for (int i = 0; i < GRID_SIZE; i++) {
```

```
      for (int j = 0; j < GRID_SIZE; j++) {
        if (grid.data[i][j].current_type == FIRE) {
          is_fire = true;
          break;
        }
      }
    }

    return !is_fire;
  } else {
    // Unknown model
    return true;
  }
}

/**
 * Check a probability : if the tile is of the given type and the probability is
 ↪  valid
 *
 * @param grid The grid
 * @param point The point to check
 * @param type The type to check
 * @param proba The probability
 * @return True if the probability is valid, false otherwise
 */
bool check_probability(Grid * grid, Point point, TileType type, int proba) {
  return get_tile(*grid, point).current_type == type && get_random(proba) == 0;
}
```

grid.c (9/21)

```c
/**
 * Apply the rules to a cell (model 0 and 1)
 *
 * @param grid The grid
 * @param copy The copy of the grid
 * @param point The point to apply the rules to
 * @param neighbors The neighbors of the point
 * @param tree_burn The probability for a tree tile to burn
 * @param grass_burn The probability for a grass tile to burn
 * @param state_change The probability for a tile to change state between fire and
 ↪  burnt
 */
void apply_to_cell(Grid * grid, Tile ** copy, Point point, Point * neighbors, int
↪  tree_burn, int grass_burn,
           int state_change) {
  // First step, change the state of the neighbors based on the probability
  for (int k = 0; k < 4; k++) {
    if (is_valid(neighbors[k])) {
      if (check_probability(grid, neighbors[k], TREE, tree_burn) ||
        check_probability(grid, neighbors[k], GRASS, grass_burn)) {
        Tile * tile_copy = &copy[neighbors[k].x][neighbors[k].y];

        tile_copy->current_type = FIRE;
        tile_copy->state = 0;
      }
    }
  }

  // Second step, change the state of the point based on the probability to a new
  ↪  state or to burnt
```

```c
  Tile point_tile = get_tile(*grid, point);
  if (check_probability(grid, point, FIRE, state_change)) {
    Tile * tile_copy = &copy[point.x][point.y];

    // If the tile is newly on fire, we increment the state of the tile, otherwise we
    ↪  set it to burnt
    if (point_tile.state == 0) {
      tile_copy->state++;
    } else {
      tile_copy->current_type = BURNT;
      tile_copy->state = 0;
    }
  }

  free(neighbors);
}

/**
 * Get the burn probability (used for Alexandridis model)
 *
 * @return The burn probability
 */
double get_burn_probability(Tile tile, Point point, Point parent, Grid * grid) {
  double p_v;
  switch (tile.current_type) {
    case TREE:
    case DENSE_TREE:
      p_v = 0.3;
      break;
```

```
    case GRASS:
      p_v = -0.1;
      break;
    case TRENCH:
      p_v = -0.50;
      break;
    default:
      p_v = -1;
      break;
  }

  int dx = point.x - parent.x;
  int dy = point.y - parent.y;
  double theta = 0;

  switch (dx) {
    case 0: {
      if (dy == 0) {
        theta = 0; // Should not happen
      } else if (dy == 1) {
        theta = 90;
      } else {
        theta = 270;
      }
      break;
    }
    case 1: {
      if (dy == 0) {
        theta = 0;
```

```
    } else if (dy == 1) {
      theta = 45;
    } else {
      theta = 315;
    }
    break;
  }
  case -1: {
    if (dy == 0) {
      theta = 180;
    } else if (dy == 1) {
      theta = 135;
    } else {
      theta = 225;
    }
    break;
  }
}

theta = (grid->wind_direction - theta) * M_PI / 180;

double p_d = 0; // TODO : Implement density
if (tile.current_type == DENSE_TREE) {
  p_d = 0.3;
}

double p_h = 0.34; // TODO : Compute value, best value is 0.58 according to the
↪  paper
double p_w =
```

```c
      exp(0.045 * grid->wind_speed) * exp(grid->wind_speed * 0.131 * (cos(theta) -
      ↪  1)); // TODO : Implement wind
  double p_s = exp(0.078 * 0 /* TODO : Add angle for slope */);

  return p_h * (1 + p_v) * (1 + p_d) * p_w * p_s;
}

/**
 * Update the grid
 *
 * @param grid The grid to update
 */
void tick(Grid * grid) {
  Tile ** copy = copy_grid(grid->data);

  // Update the grid based on the model
  if (grid->model == 0) {
    // MODEL 0 -> 4 neighbors
    for (int i = 0; i < GRID_SIZE; i++) {
      for (int j = 0; j < GRID_SIZE; j++) {
        Point point = (Point) {i, j};

        // If the tile is not on fire, we continue
        if (get_tile(*grid, point).current_type != FIRE) {
          continue;
        }

        // Apply the rules to the cell
        apply_to_cell(grid, copy, point, get_direct_neighbors(grid, point),
        ↪  M0_PROBA_TREE_BURN,
```

```
                M0_PROBA_GRASS_BURN,
                M0_PROBA_STATE_CHANGE);
      }
    }

    free(grid->data);

    grid->data = copy;

    draw_grid(grid->window, *grid);
  } else if (grid->model == 1) {
    // MODEL 1 -> 8 neighbors (same as model 0 but with diagonal neighbors)
    for (int i = 0; i < GRID_SIZE; i++) {
      for (int j = 0; j < GRID_SIZE; j++) {
        Point point = (Point) {i, j};

        // If the tile is not on fire, we continue
        if (get_tile(*grid, point).current_type != FIRE) {
          continue;
        }

        // Apply the rules to the cell
        apply_to_cell(grid, copy, point, get_direct_neighbors(grid, point),
        ↪  M1_C_PROBA_TREE_BURN,
                M1_C_PROBA_GRASS_BURN,
                M1_PROBA_STATE_CHANGE);
        apply_to_cell(grid, copy, point, get_diagonal_neighbors(grid, point),
        ↪  M1_D_PROBA_TREE_BURN,
                M1_D_PROBA_GRASS_BURN,
```

```
              M1_PROBA_STATE_CHANGE);
      }
    }

    free(grid->data);

    grid->data = copy;

    draw_grid(grid->window, *grid);
  } else if (grid->model == 2) { // Alexandridis
    for (int i = 0; i < GRID_SIZE; i++) {
      for (int j = 0; j < GRID_SIZE; j++) {
        Point point = (Point) {i, j};

        // If the tile is not on fire, we continue to the next tile
        Tile tile = get_tile(*grid, point);
        if (tile.current_type != FIRE) {
          continue;
        }

        Tile * copy_tile = &copy[point.x][point.y];

        if (tile.state == 0) {
          Point * direct_neighbors = get_direct_neighbors(grid, point);
          Point * diagonal_neighbors = get_diagonal_neighbors(grid, point);

          for (int k = 0; k < 4; k++) {
            Point direct_point = direct_neighbors[k];
            if (is_valid(direct_point)) {
```

grid.c (16/21)

```
      Tile direct_tile = get_tile(*grid, direct_point);
      double p_burn = get_burn_probability(direct_tile, direct_point, point,
      ↪  grid);

      if (get_random(1000000) < p_burn * 1000000) {
        Tile * copy_direct_tile = &copy[direct_point.x][direct_point.y];

        copy_direct_tile->current_type = FIRE;
        copy_direct_tile->state = 0;
      }
    }

    Point diagonal_point = diagonal_neighbors[k];
    if (is_valid(diagonal_point)) {
      Tile diagonal_tile = get_tile(*grid, diagonal_point);
      double p_burn = get_burn_probability(diagonal_tile, diagonal_point,
      ↪  point, grid);

      if (get_random(1000000) < p_burn * 1000000) {
        Tile * copy_diagonal_tile =
        ↪  &copy[diagonal_point.x][diagonal_point.y];

        copy_diagonal_tile->current_type = FIRE;
        copy_diagonal_tile->state = 0;
      }
    }
  }

  free(direct_neighbors);
```

```c
          free(diagonal_neighbors);

          copy_tile->state = 1;
        } else {
          copy_tile->current_type = BURNT;
          copy_tile->state = 0;
        }
      }
    }

    free(grid->data);

    grid->data = copy;

    draw_grid(grid->window, *grid);
  } else {
    // Unknown model :(
    free(copy);
  }
}

/**
 * Write to png file
 *
 * @param grid The grid to write
 */
void write_png(Grid grid) {
  struct stat st = {0};
  if (stat("grids_png", &st) == -1) {
```

grid.c (18/21)

```
  mkdir("grids_png", 0700);
}

char * file_name = malloc(100 * sizeof(*file_name));
sprintf(file_name, "grids_png/grid-%d-%d.png", grid.coord_x, grid.coord_y);

FILE * fp = fopen(file_name, "wb");
if (!fp) {
  fprintf(stderr, "Failed to open file %s for writing\n", file_name);
  return;
}

png_structp png = png_create_write_struct(PNG_LIBPNG_VER_STRING, NULL, NULL, NULL);
if (!png) {
  fprintf(stderr, "Failed to create png write struct\n");
  fclose(fp);
  return;
}

png_infop info = png_create_info_struct(png);
if (!info) {
  fprintf(stderr, "Failed to create png info struct\n");
  png_destroy_write_struct(&png, NULL);
  fclose(fp);
  return;
}

if (setjmp(png_jmpbuf(png))) { // To handle errors
  printf("Error during png creation\n");
```

grid.c (19/21)

```c
    png_destroy_write_struct(&png, &info);
    fclose(fp);
    return;
  }

  png_init_io(png, fp);

  // Write the header (8-bit color depth, RGB format)
  png_set_IHDR(png, info, 512, 512, 8, PNG_COLOR_TYPE_RGB,
         PNG_INTERLACE_NONE, PNG_COMPRESSION_TYPE_DEFAULT, PNG_FILTER_TYPE_DEFAULT);
  png_write_info(png, info);

  png_bytep row = (png_bytep) malloc(3 * 512 * sizeof(png_byte));

  Tile tile;
  Color color;
  for (int y = 0; y < 512; y++) {
    for (int x = 0; x < 512; x++) {
      tile = grid.data[x / TILE_SIZE][y / TILE_SIZE];
      color = get_color(tile.current_type, tile.state);
      row[x * 3 + 0] = color.r; // Red
      row[x * 3 + 1] = color.g;   // Green
      row[x * 3 + 2] = color.b;   // Blue
    }
    png_write_row(png, row);
  }

  // Finish writing the file
  png_write_end(png, NULL);
```

```
  // Free resources
  fclose(fp);
  png_destroy_write_struct(&png, &info);
  free(row);

  free(file_name);
}

/**
 * Write to a csv file
 *
 * @param grid The grid to write
 */
void write_csv(Grid grid) {
  FILE * fp = fopen("grids.csv", "a");

  fprintf(fp, "NEW GRID\n"); // Grid Separator

  for (int x = 0; x < GRID_SIZE; x++) {
    for (int y = 0; y < GRID_SIZE; ++y) {
      fprintf(fp, "%d-%d-%d,", grid.data[x][y].current_type,
      ↪  grid.data[x][y].default_type, grid.data[x][y].state);
    }

    fprintf(fp, "\n");
  }

  fclose(fp);
```

grid.c (21/21)

```c
}

/**
 * Destroy a grid
 *
 * @param grid The grid to destroy
 */
void destroy_grid(Grid grid) {
  if (grid.export_png) {
    write_png(grid);
  }

  if (grid.export_csv) {
    write_csv(grid);
  }

  // Free the data of the grid
  for (int i = 0; i < GRID_SIZE; i++) {
    free(grid.data[i]);
  }

  free(grid.data);
}
```

typings.c (1/7)

```c
#include <SDL2/SDL.h>
#include <stdbool.h>

/**
 * Represents the size of the grid
 */
const int GRID_SIZE = 256;
/**
 * Represents the size of a tile
 */
int TILE_SIZE = 2;

/**
 * Represents a window
 */
typedef struct {
  /**
   * The SDL window
   */
  SDL_Window * window;
  /**
   * The SDL surface
   */
  SDL_Surface * surface;
} Window;

/**
 * Represents a color
```

typings.c (2/7)

```c
 */
typedef struct {
  /**
   * The red component of the color (0-255)
   */
  int r;
  /**
   * The green component of the color (0-255)
   */
  int g;
  /**
   * The blue component of the color (0-255)
   */
  int b;
} Color;

/**
 * Represents a point
 */
typedef struct {
  /**
   * The x coordinate of the point
   */
  int x;
  /**
   * The y coordinate of the point
   */
  int y;
} Point;
```

typings.c (3/7)

```c
/**
 * Represents a tile type
 */
typedef enum {
  /**
   * A tree tile
   */
  TREE,
  /**
   * A dense tree tile
   */
  DENSE_TREE,
  /**
   * A water tile
   */
  WATER,
  /**
   * A grass tile
   */
  GRASS,
  /**
   * A fire tile
   */
  FIRE,
  /**
   * A burnt tile
   */
  BURNT,
```

typings.c (4/7)

```c
  /**
   * A trench tile
   */
  TRENCH,
  /**
   * Just to have a size for the enum
   */
  TILE_TYPE_SIZE
} TileType;

/**
 * Represents a tile
 */
typedef struct {
  /**
   * The default type of the tile
   */
  TileType default_type;
  /**
   * The current type of the tile
   */
  TileType current_type;
  /**
   * The state of the tile (for example, the state of a fire)
   */
  int state;
} Tile;

/**
```

typings.c (5/7)

```c
 * Represents a grid
 */
typedef struct {
  /**
   * The data of the grid
   */
  Tile ** data;
  /**
   * The window of the grid
   */
  Window window;
  /**
   * The model of the grid
   */
  int model;
  /**
   * Whether the grid has ended
   */
  bool ended;
  /**
   * The x coordinate of the grid
   */
  int coord_x;
  /**
   * The y coordinate of the grid
   */
  int coord_y;
  /**
   * Whether to save the content into a png file
```

```
     */
    bool export_png;
    /**
     * Whether to save the content into a csv file
     */
    bool export_csv;
    /**
     * Wind direction
     */
    double wind_direction;
    /**
     * Wind speed
     */
    double wind_speed;
} Grid;

/**
 * Get a color according to a tile type and a state
 *
 * @param type The type of the tile
 * @param state The state of the tile
 * @return The color of the tile
 */
Color get_color(TileType type, int state) {
  switch (type) {
    case TREE:
      return (Color) {30, 81, 52};
    case DENSE_TREE:
      return (Color) {18, 49, 33};
```

```
    case WATER:
      return (Color) {113, 175, 172};
    case GRASS:
      return (Color) {53, 105, 74};
    case FIRE:
      switch (state) {
        case 0:
          return (Color) {253, 54, 23};
        case 1:
          return (Color) {255, 108, 46};
        default:
          return (Color) {253, 54, 23};
      }
    case BURNT:
      return (Color) {78, 78, 78};
    case TRENCH:
      return (Color) {77, 5, 0};
  }

  return (Color) {0, 0, 0};
}
```

draw.c (1/6)

```c
#include <stdbool.h>
#include <unistd.h>
#include "typings.c"
#include "misc.c"

/**
 * Draw a pixel on the window
 *
 * @param window The window to draw on
 * @param point The point to draw
 * @param color The color of the pixel
 * @param update Whether to update the window (ie to display the pixel)
 */
void draw_pixel(Window window, Point point, Color color, bool update) {
  // If the point is outside the window, do nothing
  if (point.x < 0 || point.x >= window.surface->w || point.y < 0 || point.y >=
  ↪  window.surface->h) {
    return;
  }

  // Get the pixel at the point and set its color
  Uint32 * pixel = (Uint32 *) window.surface->pixels + point.y *
  ↪  window.surface->pitch / 4 + point.x;
  *pixel = SDL_MapRGB(window.surface->format, color.r, color.g, color.b);

  // If we want to update the window, we update it
  if (update) {
    SDL_UpdateWindowSurface(window.window);
```

draw.c (2/6)

```c
  }
}

/**
 * Draw a square on the window
 *
 * @param window The window to draw on
 * @param point The top-left corner of the square
 * @param size The size of the square
 * @param color The color of the square
 * @param update Whether to update the window (ie to display the square)
 */
void draw_square(Window window, Point point, int size, Color color, bool update) {
  // Draw a square of pixels
  for (int i = 0; i < size; i++) {
    for (int j = 0; j < size; j++) {
      // Draw the pixel
      draw_pixel(window, (Point) {point.x + i, point.y + j}, color, false);
    }
  }

  // If we want to update the window, we update it
  if (update) {
    SDL_UpdateWindowSurface(window.window);
  }
}

/**
 * Draw the grid on the window
```

```c
 *
 * @param window The window to draw on
 * @param grid The grid to draw
 */
void draw_grid(Window window, Grid grid) {
  // Graphics not enabled
  if (!window.window) {
    return;
  }

  // Draw the grid using the constants defined in typings.c, and translate the grid
  ↪  to the right position
  for (int i = 0; i < GRID_SIZE; i++) {
    for (int j = 0; j < GRID_SIZE; j++) {
      Tile tile = grid.data[i][j];

      // Draw the tile as a square
      draw_square(window, (Point) {TILE_SIZE * (i + (GRID_SIZE + 1) * grid.coord_x),
                         TILE_SIZE * (j + (GRID_SIZE + 1) * grid.coord_y)}, TILE_SIZE,
            get_color(tile.current_type, tile.state), false);
    }
  }

  // Update the window to display the grid
  SDL_UpdateWindowSurface(window.window);
}

/**
 * Create a window
```

draw.c (4/6)

```c
 *
 * @param max_x The maximum number of grids on the x axis
 * @param max_y The maximum number of grids on the y axis
 * @return The window
 */
Window create_window(int max_x, int max_y) {
  // The window and the surface of the window
  Window window = {
      .window = NULL,
      .surface = NULL
  };

  // Define the size of the tiles based on the number of grids (to ensure that the
  ↪  window is not too big)
  TILE_SIZE = TILE_SIZE - (1.5) * min(max_y - 1, 4);

  if (SDL_Init(SDL_INIT_VIDEO) < 0) {
    // SDL initialization failed
    printf("SDL could not initialize! SDL_Error: %s\n", SDL_GetError());
    exit(1);
  } else {
    // Create the window
    window.window = SDL_CreateWindow(
        "TIPE",
        SDL_WINDOWPOS_UNDEFINED,
        SDL_WINDOWPOS_UNDEFINED,
        (max_x * (GRID_SIZE + 1) - 1) * TILE_SIZE,
        (max_y * (GRID_SIZE + 1) - 1) * TILE_SIZE,
        SDL_WINDOW_SHOWN
```

```
    );

    if (window.window == NULL) {
      // Window creation failed
      printf("Window could not be created! SDL_Error: %s\n", SDL_GetError());
      exit(1);
    } else {
      window.surface = SDL_GetWindowSurface(window.window);
    }
  }

  return window;
}

/**
 * Wait for a certain amount of time
 *
 * @param ms The number of milliseconds to wait
 */
void wait(int ms) {
  usleep(ms * 1000);
}

/**
 * Destroy a window
 *
 * @param window The window to destroy
 */
void destroy_window(Window window) {
```

draw.c (6/6)

```
  // Destroy the window and quit SDL
  SDL_DestroyWindow(window.window);
  SDL_Quit();
}
```