Multi-Angle Bended Heat Pipe Design Using X-Architecture Routing with Dynamic Thermal Weight on Mobile Devices

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Outline

- Introduction
- Thermal simulation on smartphone with heat pipe
- XHPR: X-architecture thermal driven heat pipe routing engine
- Experimental results
- Conclusions

Motivation (1/3)

- The application processor (AP) in high-end smartphones is overheated
  - High performance
  - Die shrink

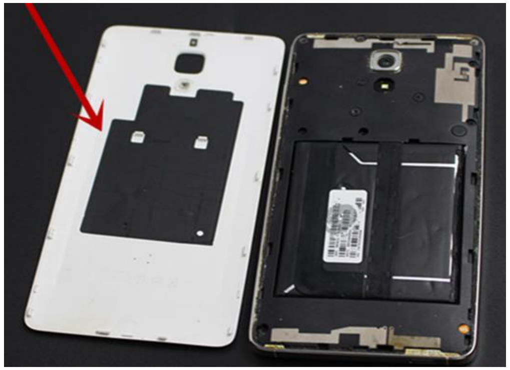
2016 Lumia 950 XL、HTC One M9 [1]

- Why consider thermal issues on smartphones ?
  - Decreasing carrier mobility slows down the device and degrades the performance of die
  - High skin/screen temperature cause the thermal burn

[2]

Motivation (2/3)

- Thermal solutions for smartphones
  - Graphite sheet
  - Metal back cover
  - Heat pipe



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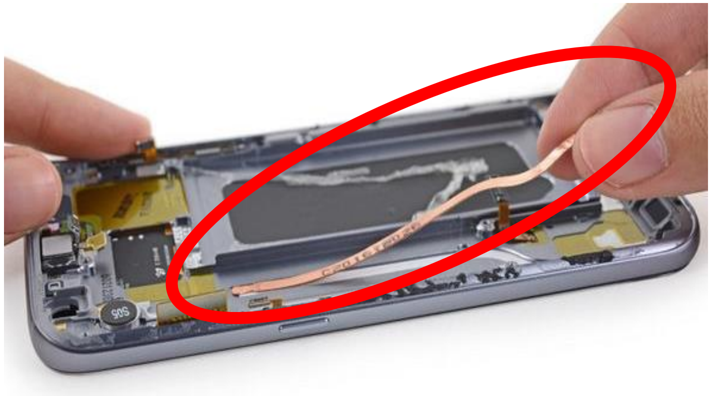


[6]

Motivation (3/3)

- Why heat pipe is suitable for smartphones?
  - High thermal conductivity (1000~100000 W/(m·K)) [7]
  - Light
  - Cheaper (USD$ 1.5) [8]
- The smartphones in industry

There are still few discussions about automatic heat pipe routing design tools

Heat Transfer Equation

- Heat transfer equation for steady state

$$\nabla \cdot \left(\boldsymbol{\kappa}(\mathbf{r}) \nabla T(\mathbf{r}) \right) = p(\mathbf{r})$$

The total heat transferring out of the control volume

Heat generation in the control volume

- Boundary condition

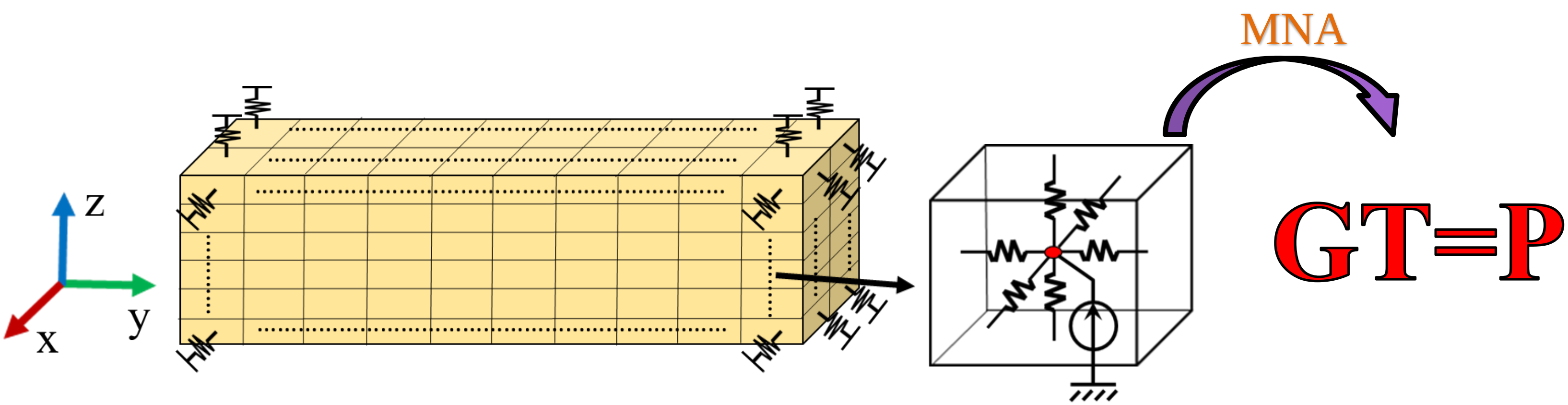
$$\boldsymbol{\kappa}(\mathbf{r}_\mathrm{b}) \frac{\partial T(\mathbf{r}_\mathrm{b})}{\partial \overrightarrow{n_\mathrm{b}}} + h_\mathrm{b} T(\mathbf{r}_\mathrm{b}) = f_\mathrm{b}(\mathbf{r}_\mathrm{b})$$

Heat transfer equation is partial differential equation
It is difficult to be solved

⇨ **Finite difference method**

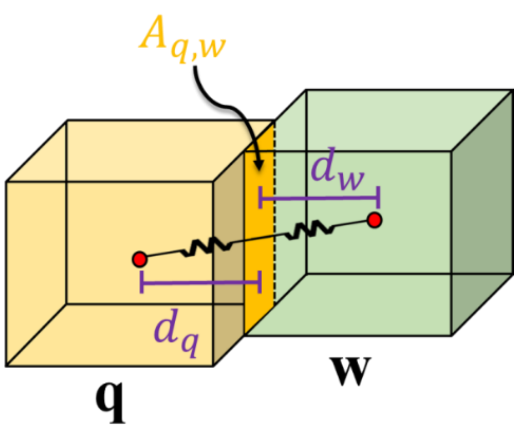
$\mathbf{r}$: Arbitrary position
$\boldsymbol{\kappa}$: Thermal conductivity
T: Temperature
p : Heat generation
$\mathbf{r}_\mathrm{b}$: Arbitrary position in boundary
$\overrightarrow{n_\mathrm{b}}$: Outward normal to boundary
h_b: Heat transfer coefficient on boundary

Compact Thermal Model



- Thermal resistance between two adjacent grids **q** and **w** [12]

$$r(q,w) = \frac{1}{A_{q,w}}\left(\frac{d_q}{k_q} + \frac{d_w}{k_w}\right)$$

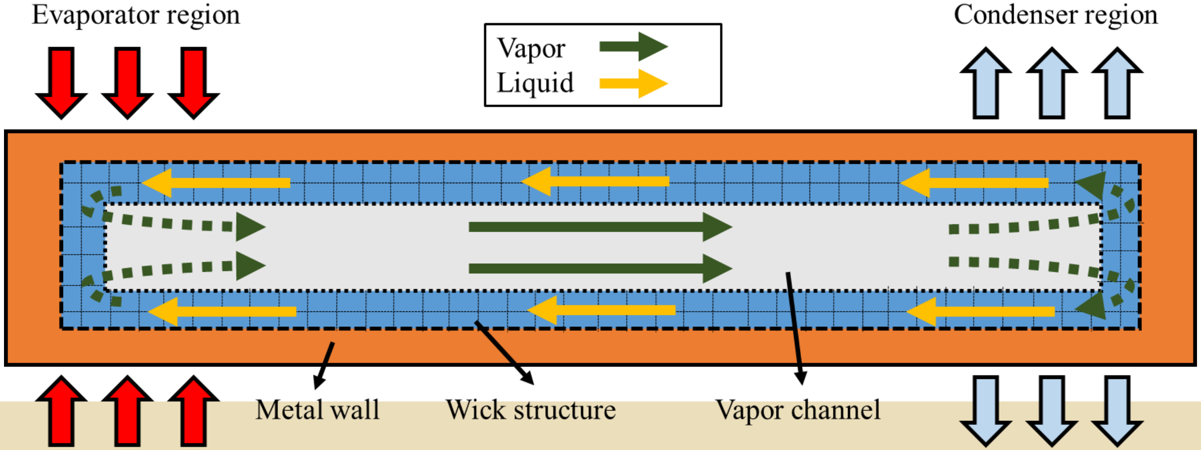


- Boundary thermal resistance

$$r_b = \frac{1}{h_b A_b}$$

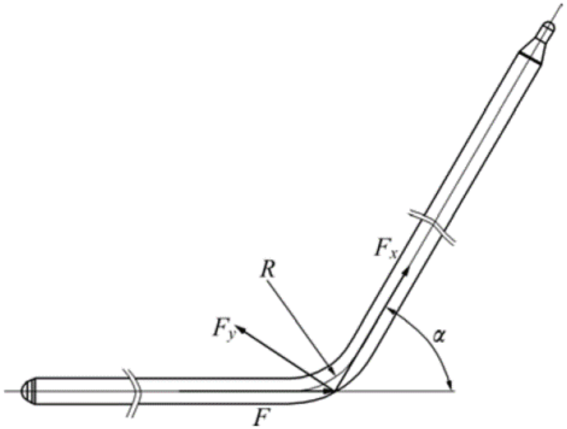
Heat Pipe Cooling Technique (1/2)

- What is heat pipe?
  - A two-phase heat transfer device that has the good ability to transmit heat
- Principle of heat pipe
  - The working fluid evaporates by heat absorption in hot region
  - Vapor travels to the cold region
  - Vapor condenses into fluid by dissipating heat in cold region and flows back through wick structure



Heat Pipe Cooling Technique (2/2)

- Why do we need multiple angle bended heat pipes?
  - Smartphone's structure
  - The thermal resistance increases with increasing the bending angle [13]
    1. Reduction in the vapor core
    2. Disruption in the path of liquid flowing back to the evaporator



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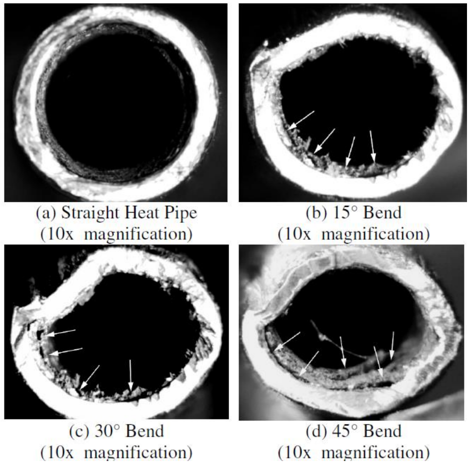
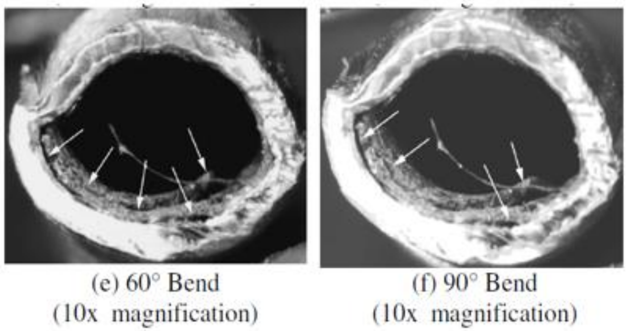


(a) Straight Heat Pipe (10x magnification)
(b) 15° Bend (10x magnification)
(c) 30° Bend (10x magnification)
(d) 45° Bend (10x magnification)

[13]

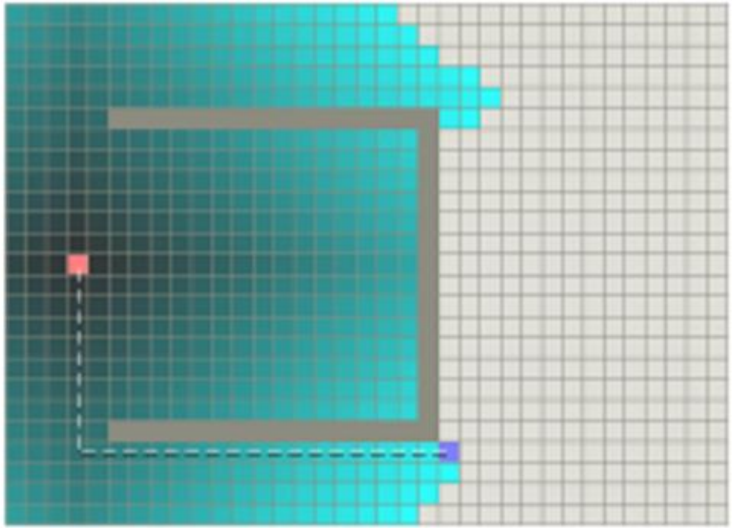


(e) 60° Bend (10x magnification)
(f) 90° Bend (10x magnification)

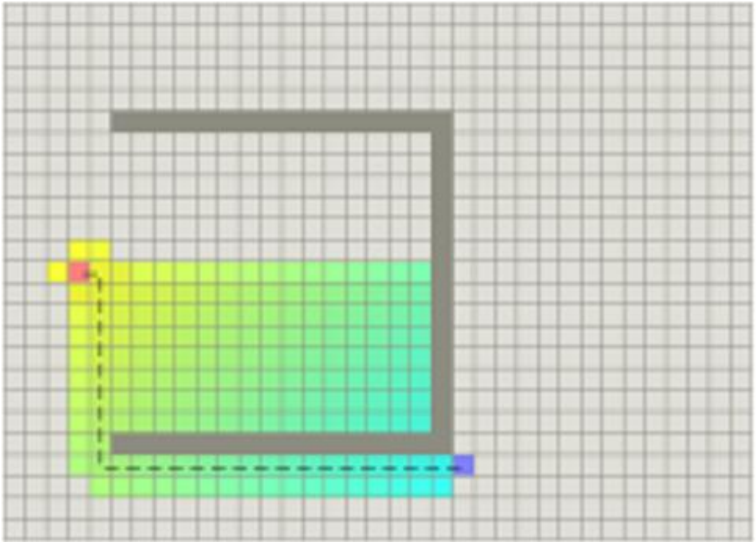
[13]

A* Search Algorithm(1/2)

- An effective pathfinding algorithm that finds the least cost path from source to sink
  - Be extended from the Dijkstra algorithm
  - Apply heuristic estimation to improve searching quality



Dijkstra algorithm
[14]



A* search algorithm
[14]

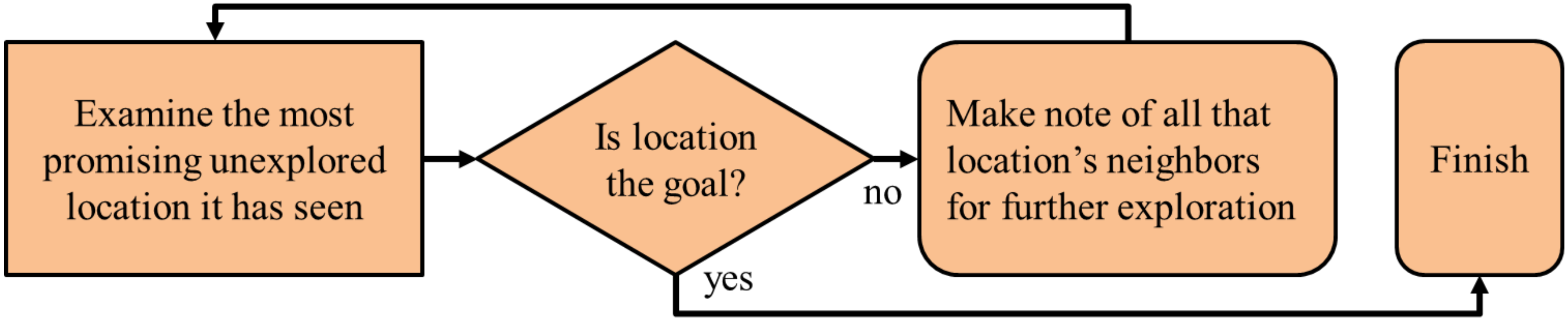
A* Search Algorithm(2/2)

- The mechanism of A* algorithm
  - The evaluation function decides the promising grid

$$f(n) = g(n) + h(n)$$

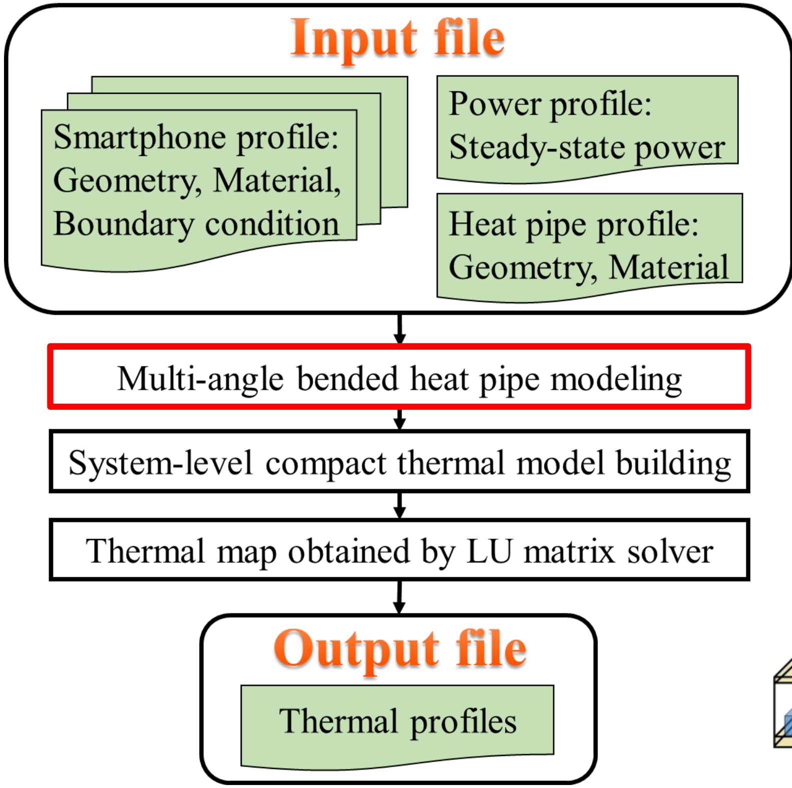
$g(n)$: The exact movement cost (start → n)

$h(n)$: The estimated movement cost (n → destination)

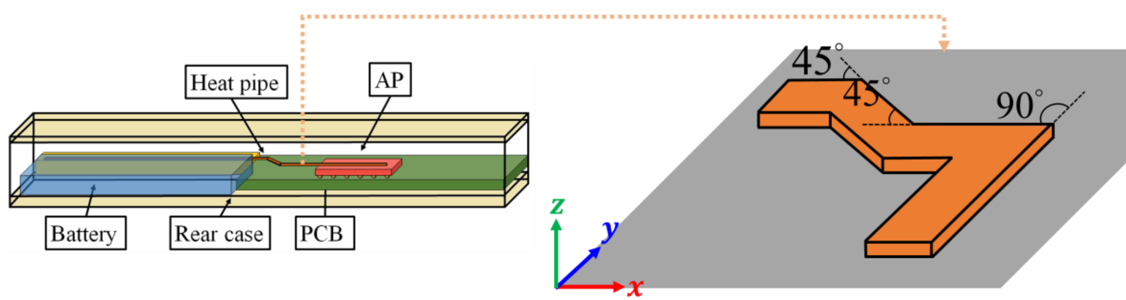


Thermal Simulation on Smartphone with Heat Pipe

Thermal Simulation Flow

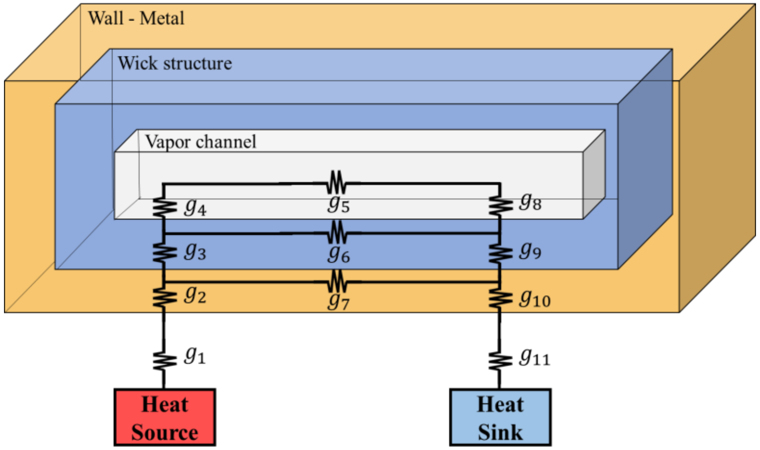


- Multi-angle bended heat pipe modeling
  - Heat pipe effective thermal conductivity
  - Cuboids approximation for bended heat pipe structure



Thermal Simulation on Smartphone with Heat Pipe

Heat Pipe Effective Thermal Conductivity



[15]

$$g_5 = \frac{p_{hp}}{\Delta T} \text{ and } g_5 = \frac{kA_{hp}}{L}$$

$$\rightarrow k = \frac{p_{hp}L}{\Delta T A_{hp}}$$

p_{hp}: The power of AP, ΔT=2.5℃ [15]
L: The length of vapor channel
A_{hp}: The cross-section area of vapor channel
k: Thermal conductivity of straight vapor
n_{45}/n_{90}: The number of 45/90-degree bend

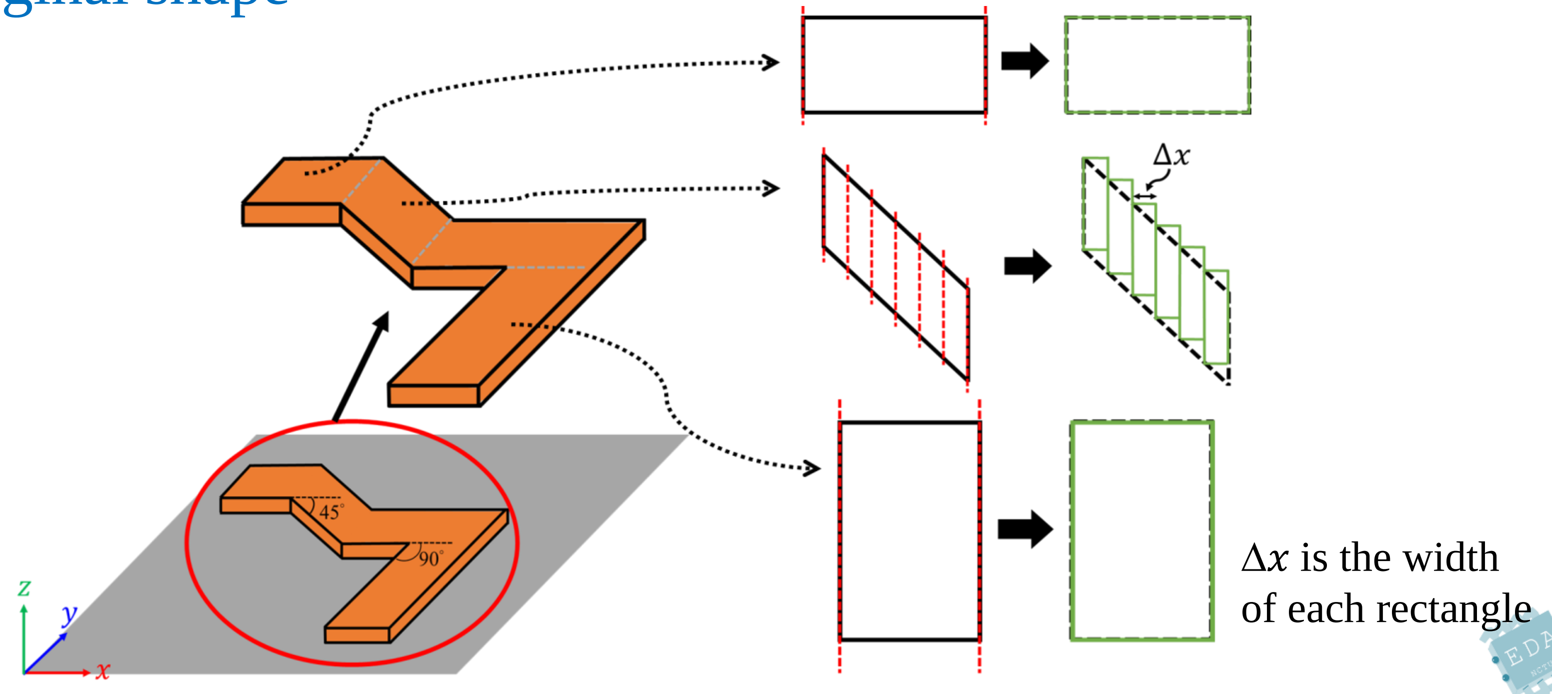
- Degrading rate are 86% and 80% of 45-degree bend and 90-degree bend, respectively [13]

$$k_{vapor,45/90} = \frac{p_{hp}L}{\Delta T A_{hp}} * 0.86^{n_{45}} * 0.8^{n_{90}}$$

Thermal Simulation on Smartphone with Heat Pipe

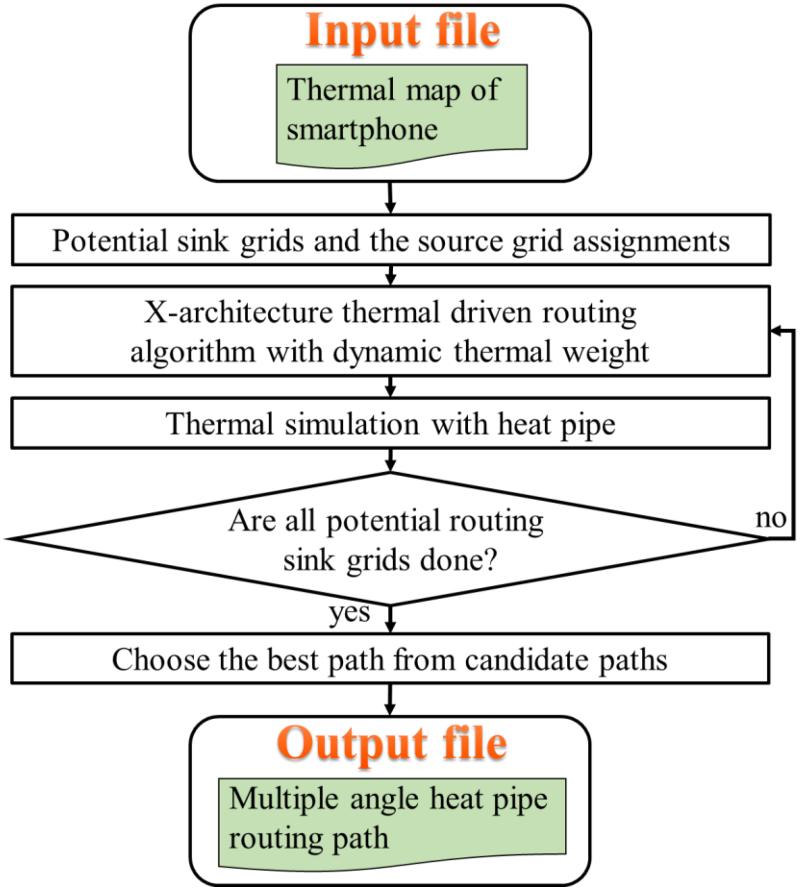
Cuboids Approximation for Bended Heat Pipe Structure

- Integrate the developed compact thermal model of multi-angle bended heat pipe into the compact thermal model of system
  - Chop the heat pipe and use several cuboids to approximate its original shape



XHPR
Design Flow

- Goal
  - Maximize the temperature reduction of AP by designing the 45/90-degree bended heat pipe path
- Overview
  - X-architecture thermal driven routing algorithm
  - Learning based dynamic thermal weight calculator
  - Thermal simulation of heat pipe



Dynamic Thermal Weight Calculator

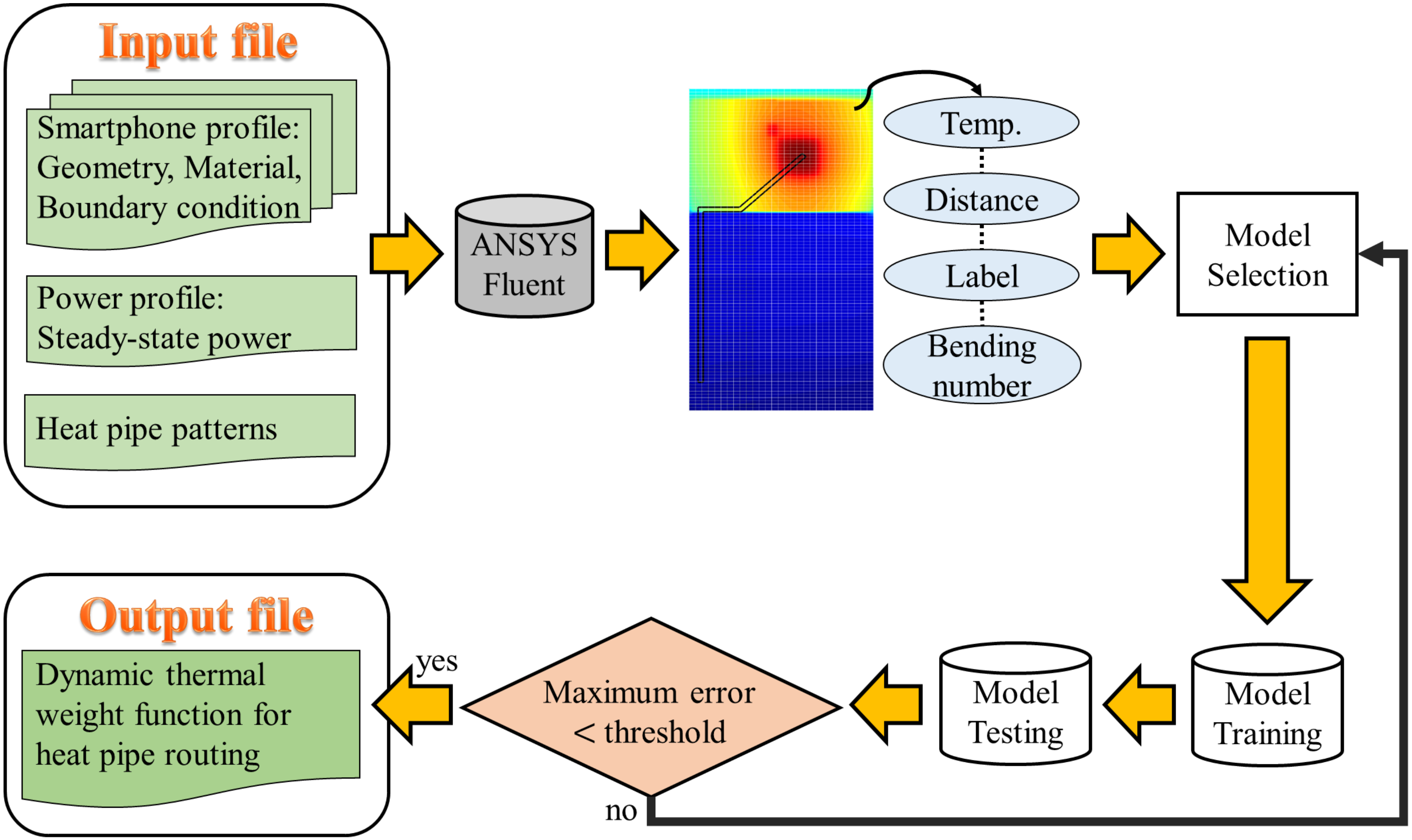
- Why do we need to build dynamic thermal weight function?
  - The phenomenon of two-phase heat transfer with heat pipe is difficult to estimate while routing heat pipe
    1. Bending angle
    2. Bending number
    3. Routing position

- We adopt a supervised machine learning method to build a dynamic thermal weight function

Dynamic Thermal Weight Calculator

Machine Learning Framework

Heat pipe routing patterns with the bending numbers (0 to 3) and two bending angles (45 and 90 degrees)



Dynamic Thermal Weight Calculator

Feature Variable List

- Obtain the thermal distribution of smartphones with heat pipe routing patterns
- Extract the feature variables that would cause some thermal effects from each grid in thermal map as our data
  - The rising temperature of source and sink of heat pipe
  - The distance between the grid and the source grid
  - The label whether the heat pipe passes the grid
  - The bending number of heat pipe in 45 or 90 degrees
  - The rising temperature of grid without employing the heat pipe cooling technique
  - The temperature reduction of each grid

Dynamic Thermal Weight Calculator

Learning Model Building

- $y_p(\mathbf{x}, \mathbf{w}) = \sum_{\substack{k_1+\cdots k_7 \le 6 \\ \forall k_i \in 0 \cup \mathbb{N}}} w_{k_1,\ldots,k_7} \prod_{j=1}^{7} x_j^{k_j}$
  - $y_p(\mathbf{x}, \mathbf{w})$ is our predicted target value
  - $\mathbf{x} = (x_1, x_2, \ldots, x_7)^T$ is the vector of input variables
  - $\mathbf{w} = (w_{0\ldots0}, w_{1\ldots0}, \ldots, w_{0\ldots6})^T$ is the vector of function parameters

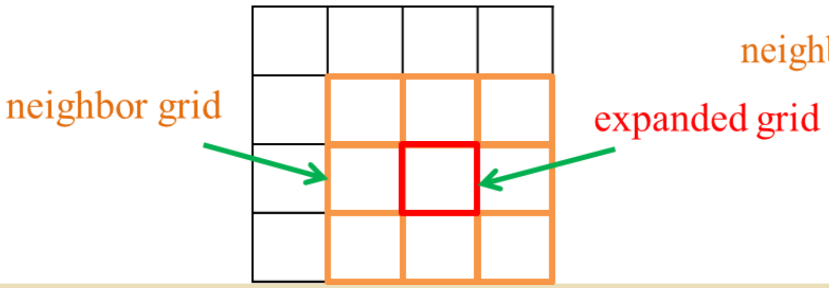
We use six order multivariate polynomial function as our learning model

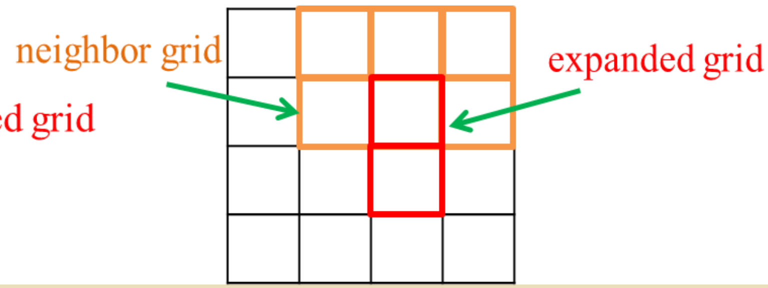
- Gaussian distribution assumption for data
  - $p(t|\mathbf{x}, \mathbf{w}, \beta) = N(t|y_p(\mathbf{x}, \mathbf{w}), \beta^{-1})$
  - t is corresponding target value of $\mathbf{x}$
  - β is the precision of distribution
- Using maximum likelihood function to determine $\mathbf{w}$

X-Architecture Thermal Driven Routing

Routing Algorithm Basic Introduction

- X-architecture thermal driven routing is based on A* algorithm
  - The predicted process improves the result and searching quality
- X-architecture thermal driven routing manipulates the routing grids for finding the path has maximum total accumulated temperature reduction (accumulated heat)
- Definition of terms using in X-architecture thermal driven routing
  - *expanded grid* : The grid chose as promising grid
  - *neighbor grid* : The grid propagated from expanded grid
  - *openList* : A list of grids that has been propagated but not yet expanded
  - *closedList* : A list of grids which has been expanded

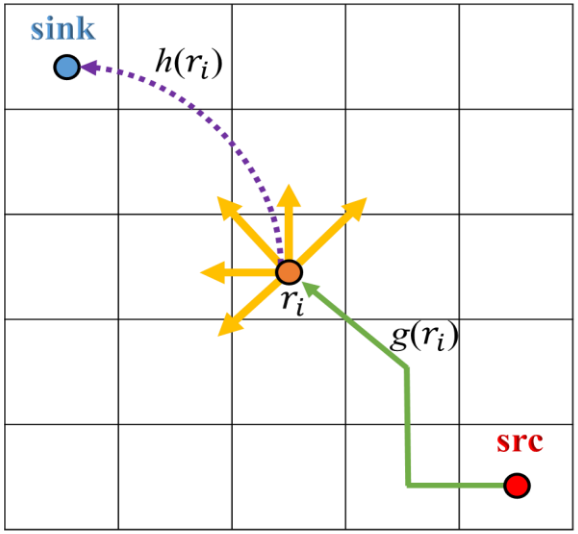




X-Architecture Thermal Driven Routing

Path Scores Definition

- Total accumulated temperature reduction from source to sink through the grid (r_i) is composed of
  - Accumulated temperature reduction from source to r_i
  - Predicted accumulated temperature reduction from r_i to sink
  - $f(r_i) = g(r_i) + h(r_i)$
- Accumulated temperature reduction function
$$g(r_i) = \sum_{j \in src \to r_i} y_p(j.\mathbf{x}, \mathbf{w})$$
- Predicted accumulated temperature reduction function
$$h(r_i) = \sum_{j \in r_i \to sink} y_p(j.\mathbf{x}, \mathbf{w})$$



$y_p(j.\mathbf{x}, \mathbf{w})$: The dynamic thermal weight function
$j.\mathbf{x}$: The feature variable of grid j
$src \to r_i$: The searching path from the source grid to current grid r_i
$r_i \to sink$: The predicted path from the current grid r_i to sink grid

X-Architecture Thermal Driven Routing

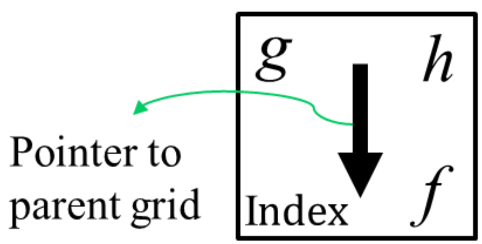
Basic Operation of Routing Algorithm

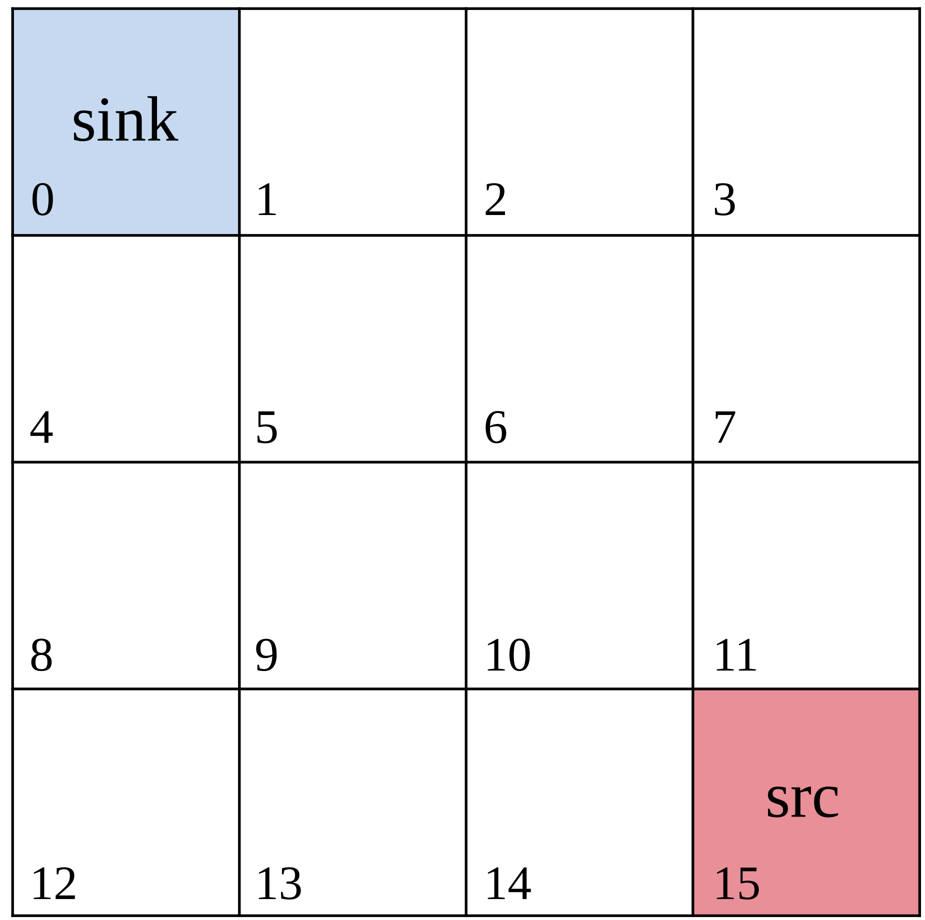
1. Choose the grid which has maximum f scores in *openList* as *expanded grid*
2. Move *expanded grid* from *openList* to *closedList*
3. Find the *neighbor grid* of *expanded grid* and check the condition of it
   - In *closedList*: skip following operations
   - In *openList*: calculate g scores
   - Otherwise: put it into *openList*, and calculate g scores
4. Update the *neighbor grid* if the current expanding is better than before
   - Update g scores
   - Execute the predicted process to get h scores
   - Calculate f scores

X-Architecture Thermal Driven Routing

Routing Process (Part 1)

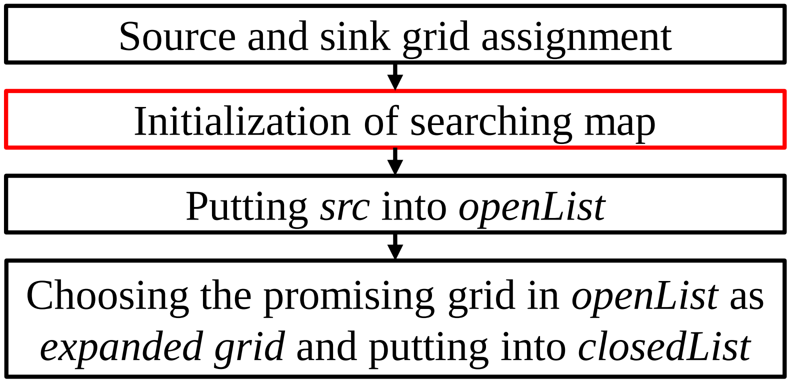
Source and sink grid assignment
↓
Initialization of searching map
↓
Putting *src* into *openList*
↓
Choosing the promising grid in *openList* as *expanded grid* and putting into *closedList*





X-Architecture Thermal Driven Routing

Routing Process (Part 1)

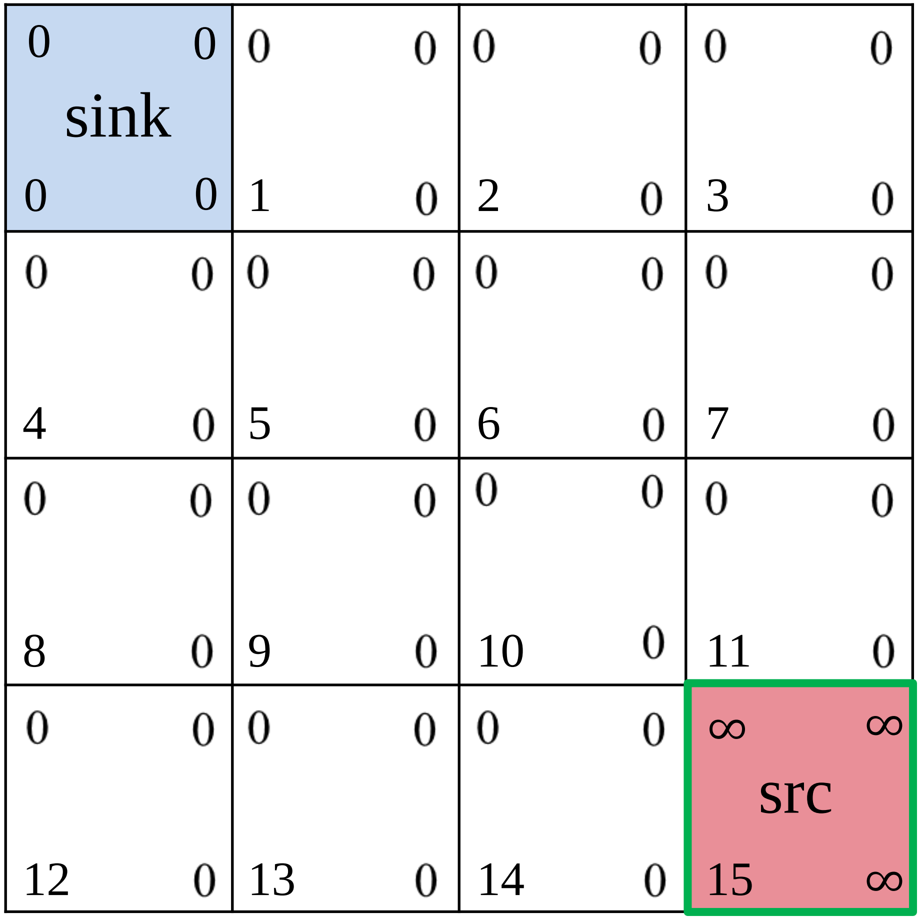


0 0 sink 0 0	0 0 1 0	0 0 2 0	0 0 3 0
0 0 4 0	0 0 5 0	0 0 6 0	0 0 7 0
0 0 8 0	0 0 9 0	0 0 10 0	0 0 11 0
0 0 12 0	0 0 13 0	0 0 14 0	∞ ∞ src 15 ∞

X-Architecture Thermal Driven Routing

Routing Process (Part 1)

1. Source and sink grid assignment
2. Initialization of searching map
3. Putting *src* into *openList*
4. Choosing the promising grid in *openList* as *expanded grid* and putting into *closedList*



X-Architecture Thermal Driven Routing

Routing Process (Part 1)

Source and sink grid assignment

↓

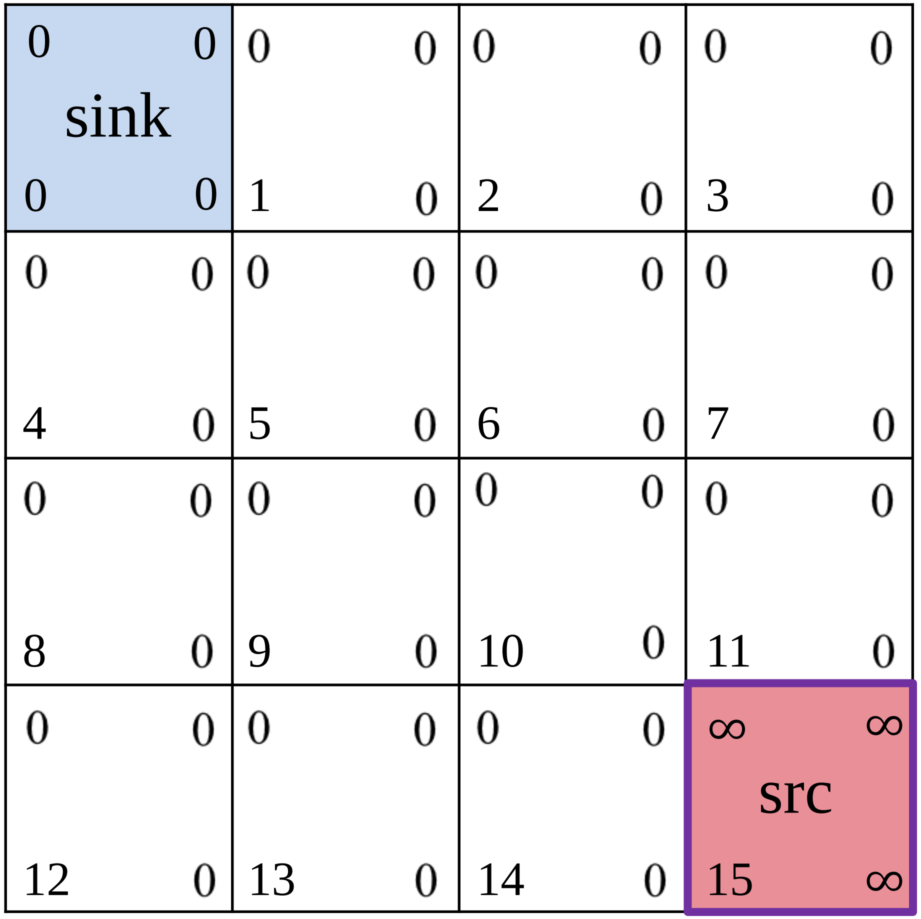
Initialization of searching map

↓

Putting *src* into *openList*

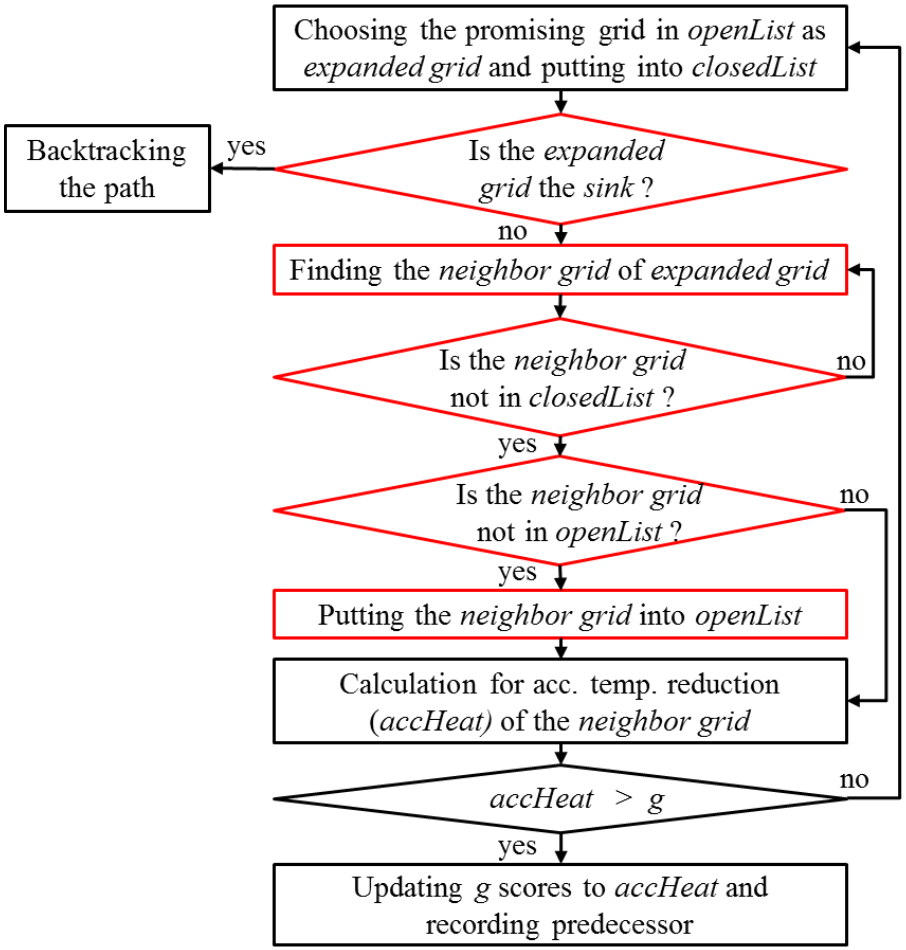
↓

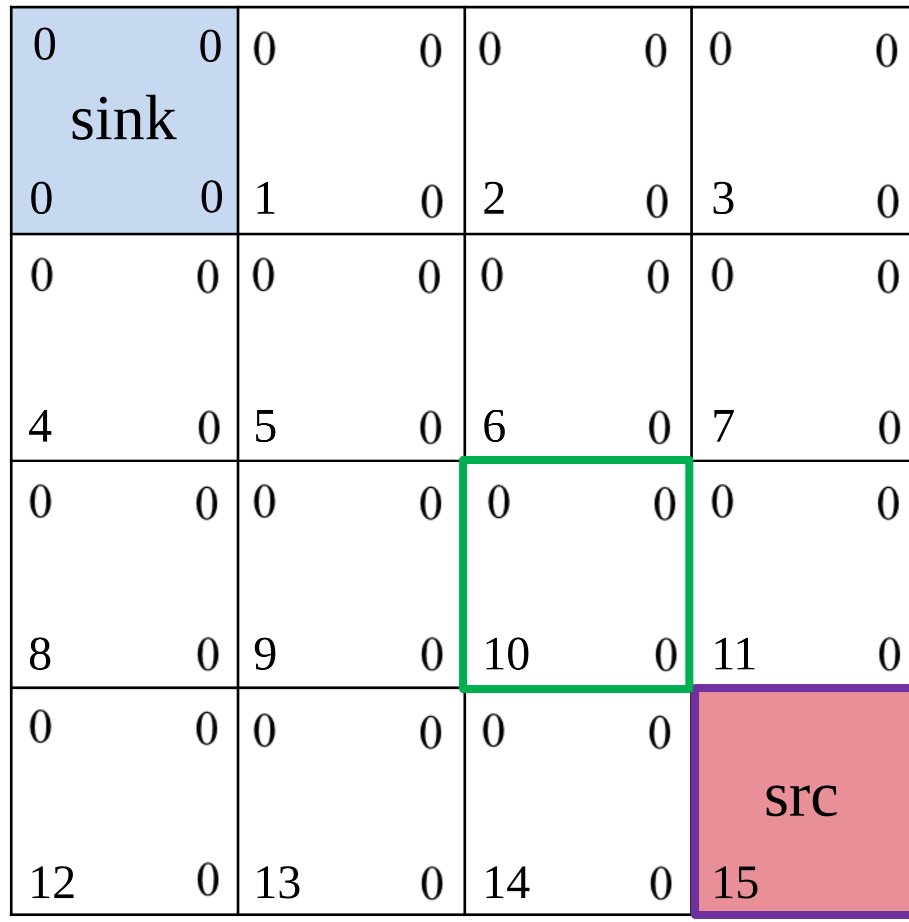
Choosing the promising grid in *openList* as *expanded grid* and putting into *closedList*



X-Architecture Thermal Driven Routing

Routing Process (Part 2)





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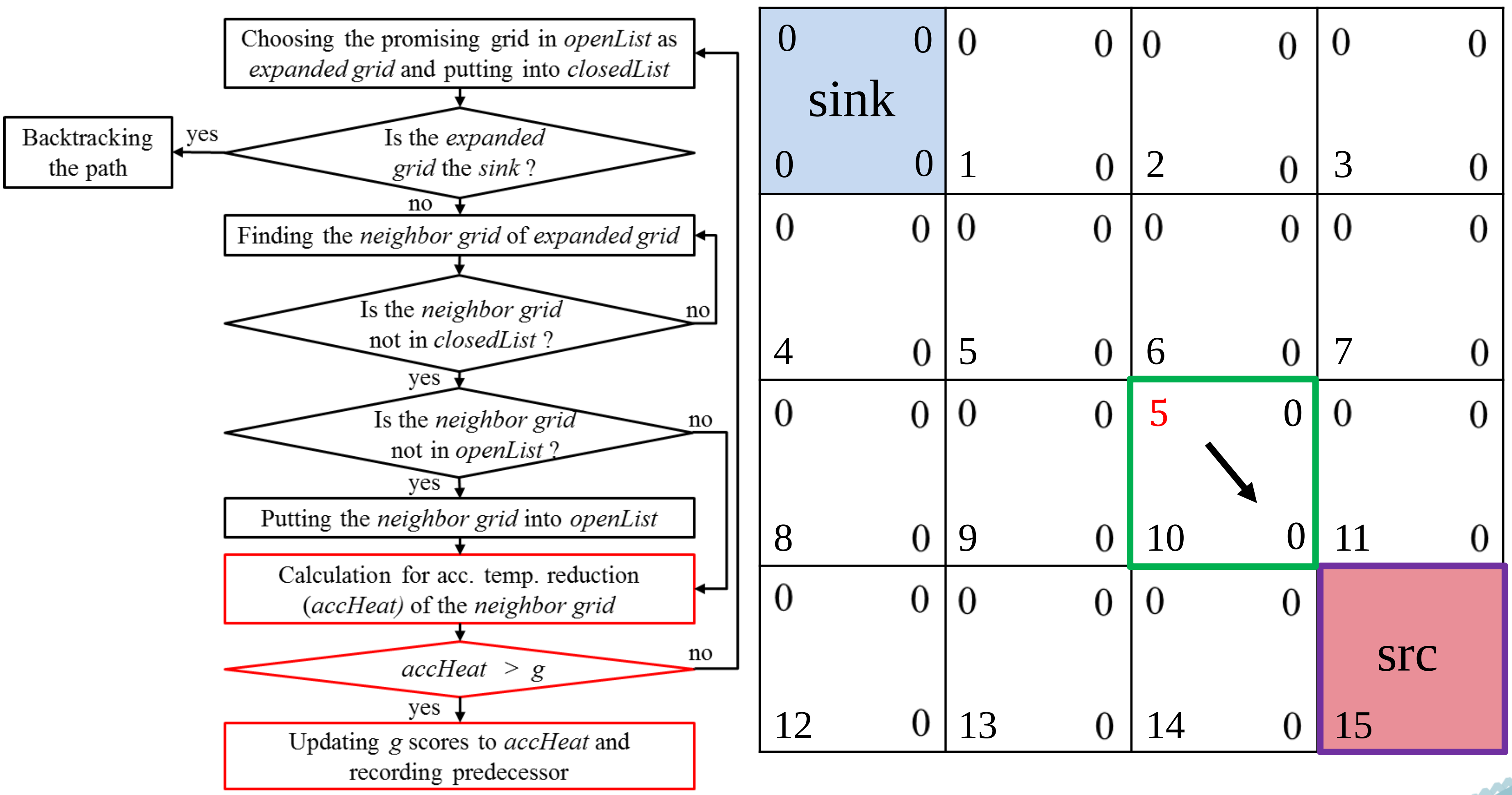
Routing Process (Part 2)



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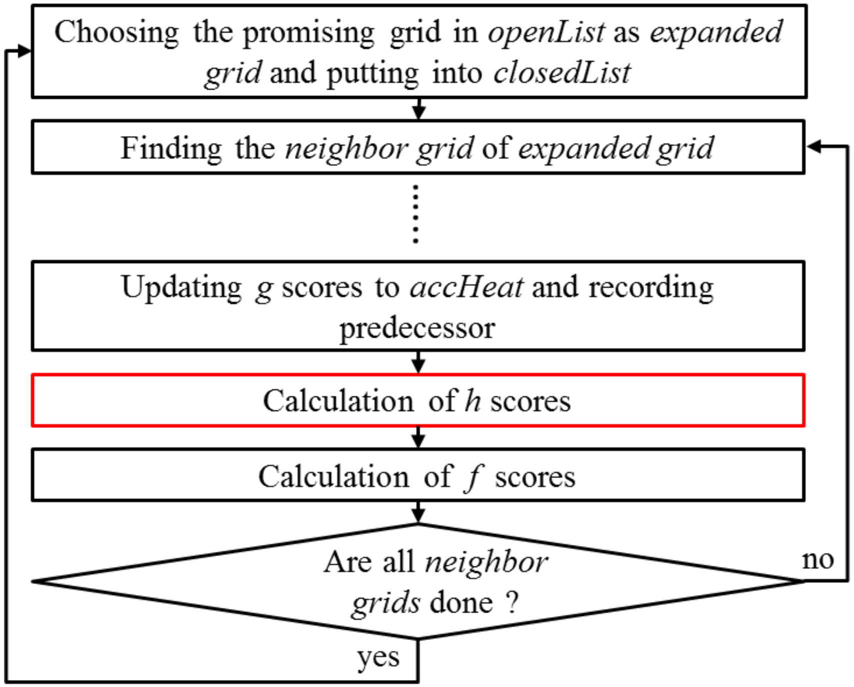
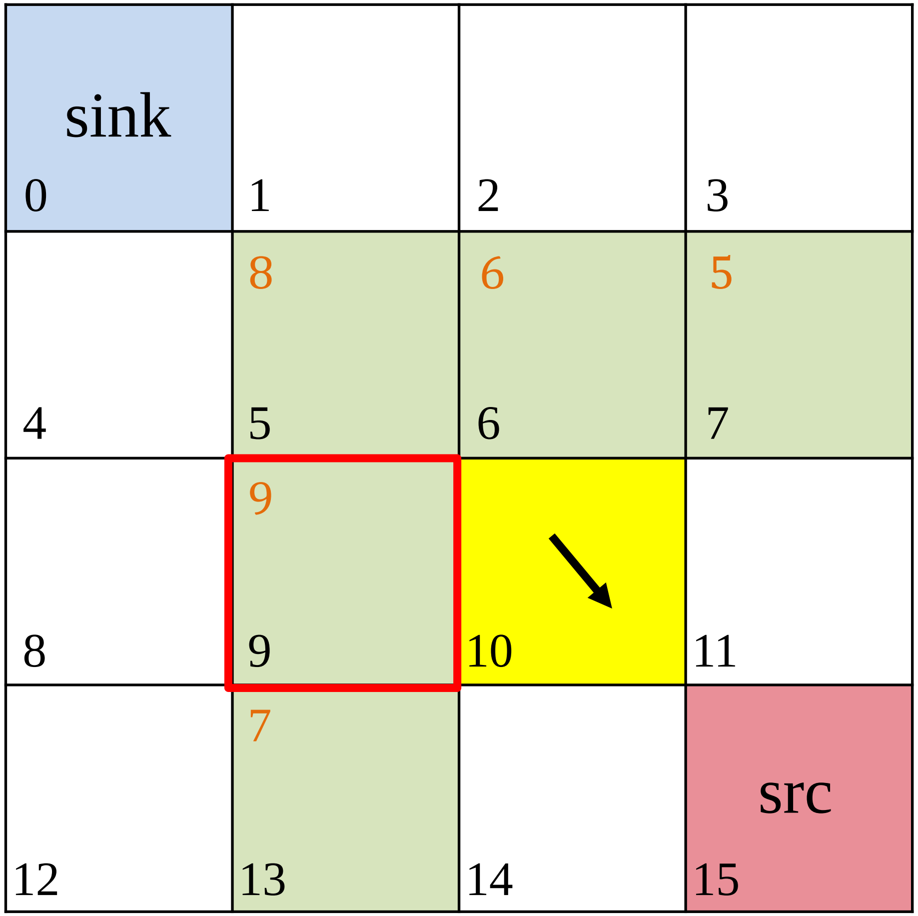
Routing Process (Part 2)





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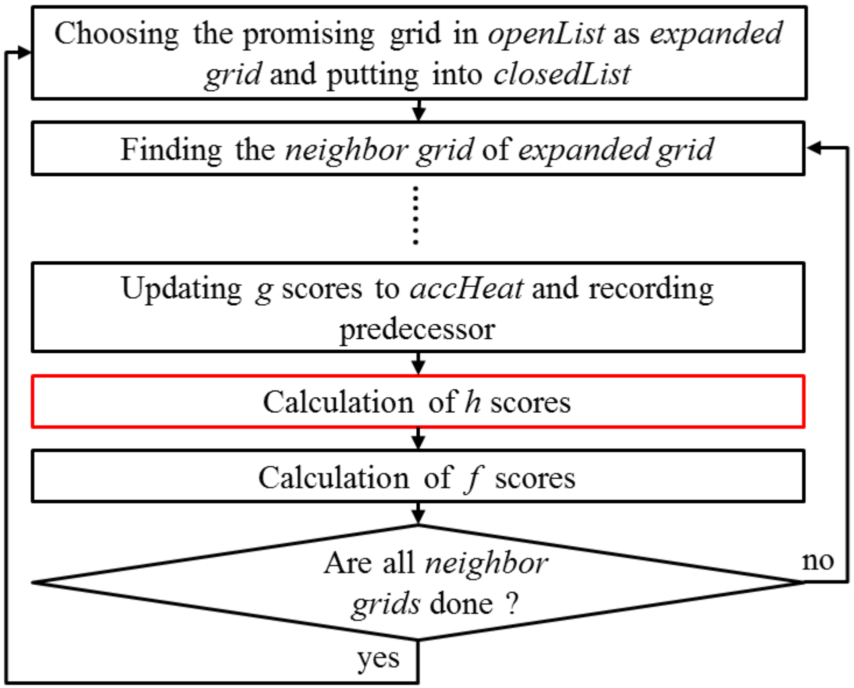
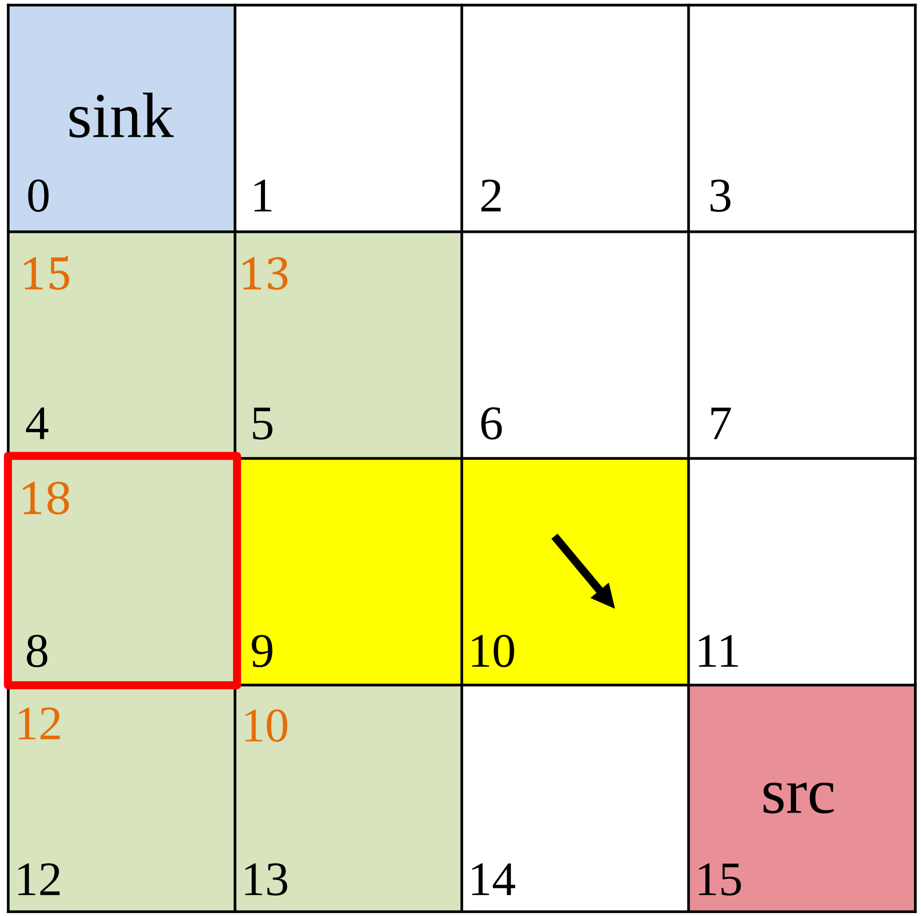
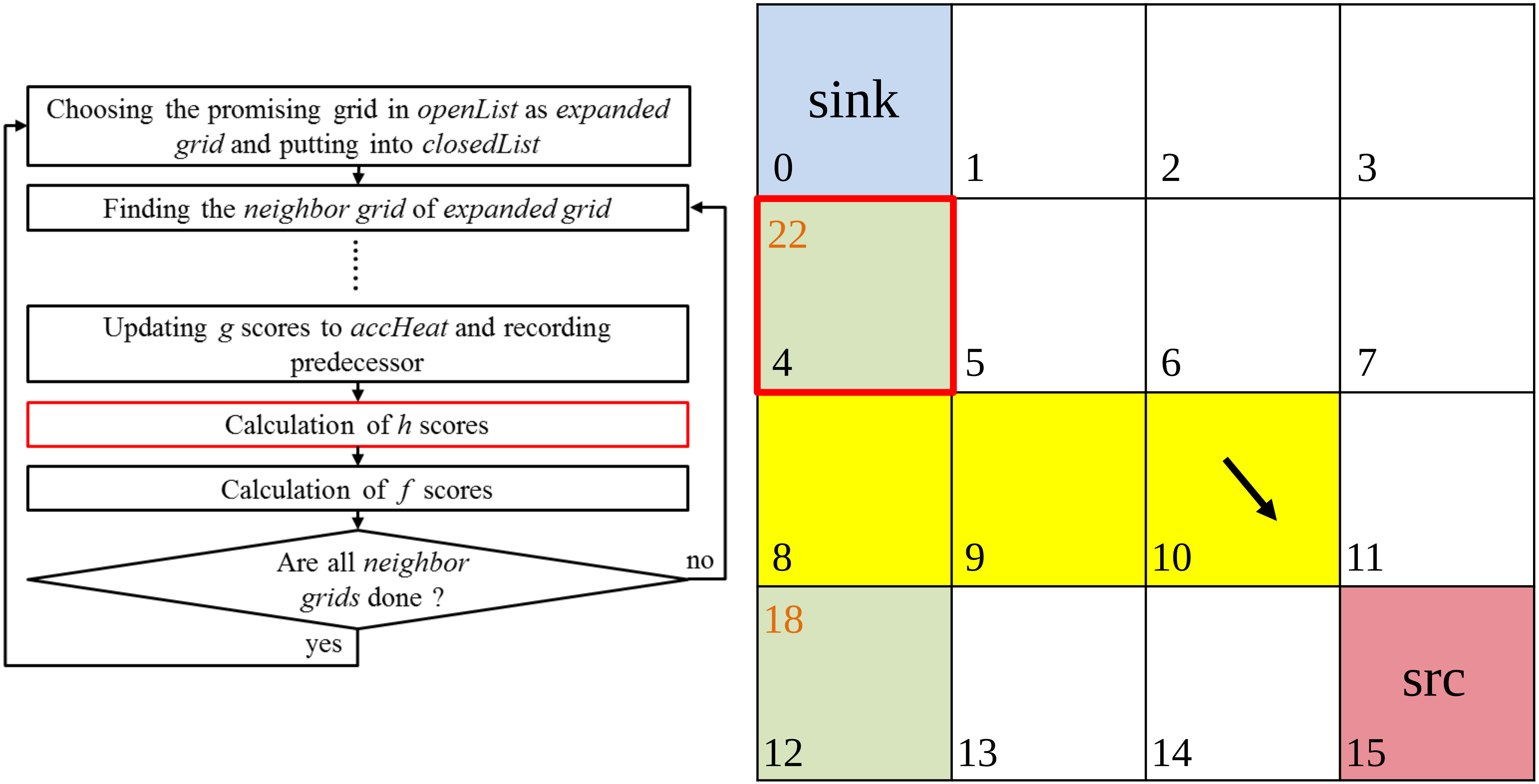
Routing Process (Part 2)





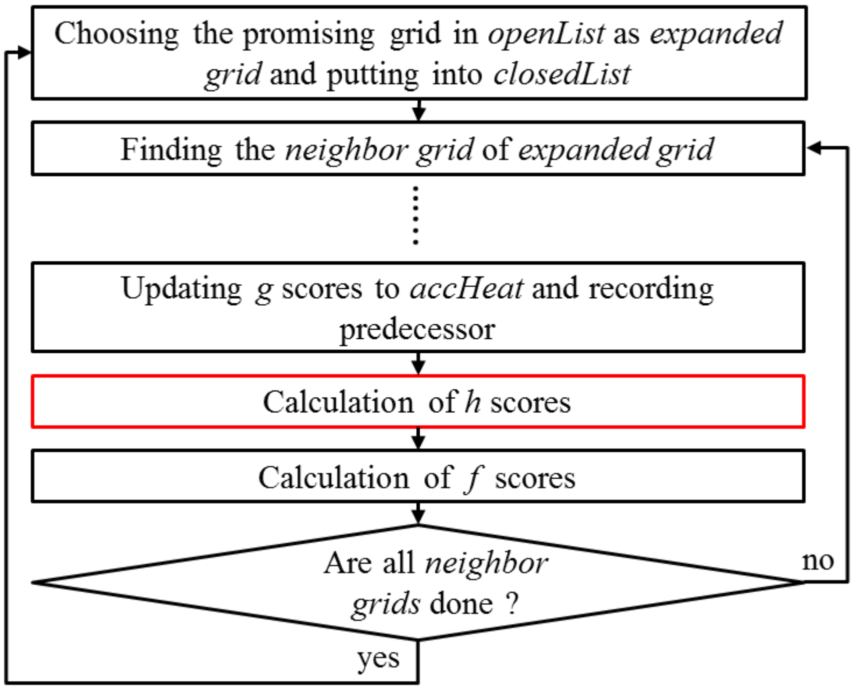
X-Architecture Thermal Driven Routing

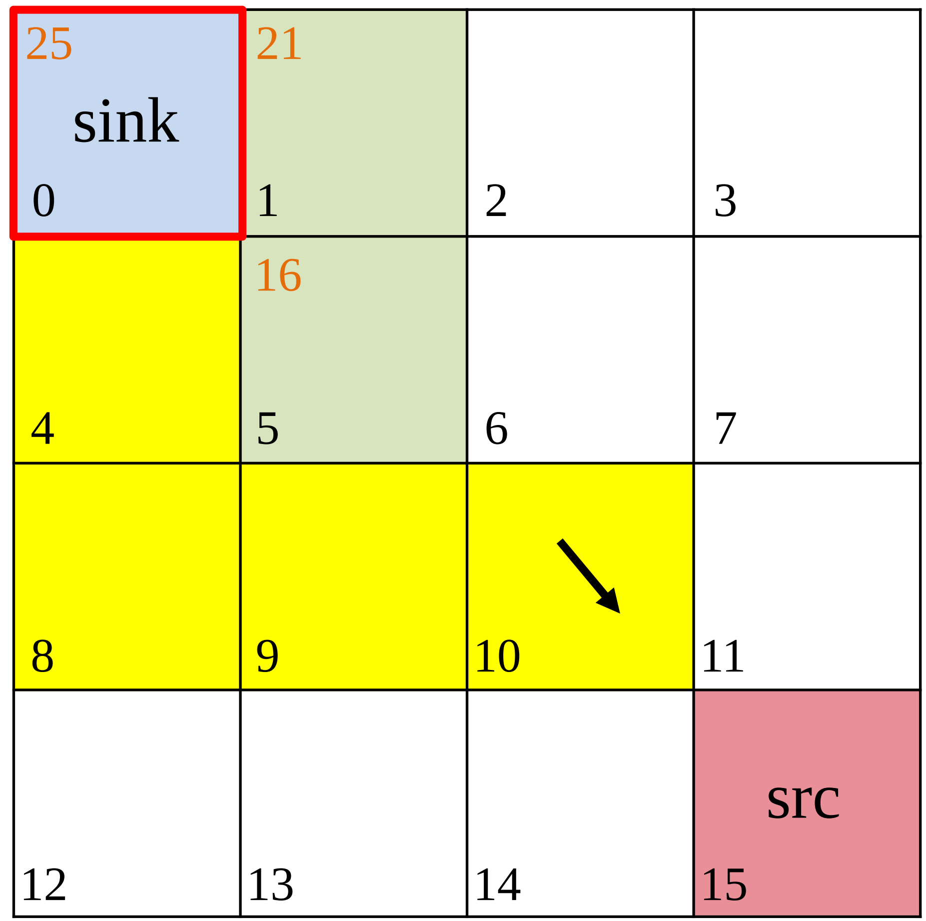
Routing Process (Part 2)



X-Architecture Thermal Driven Routing

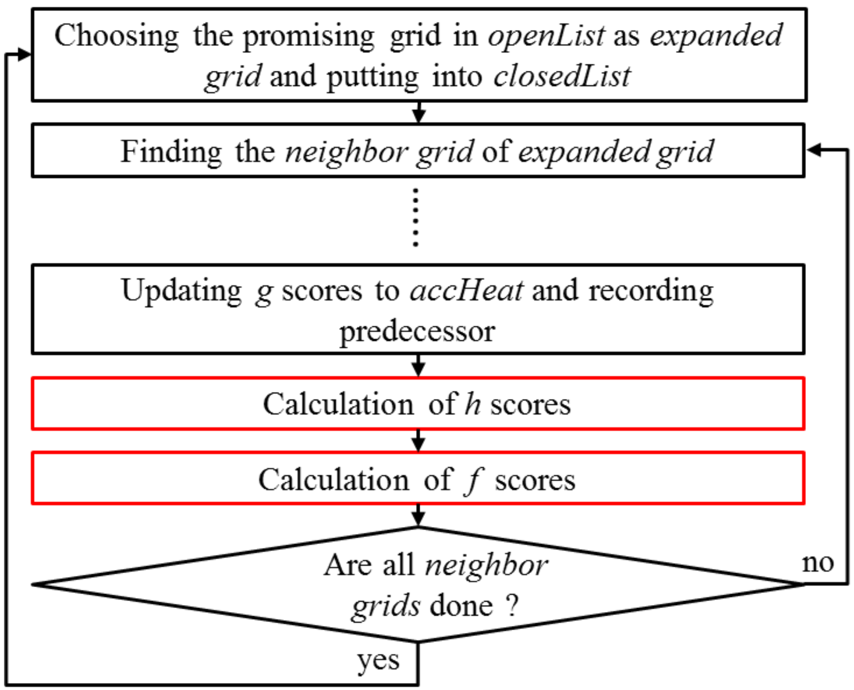
Routing Process (Part 2)

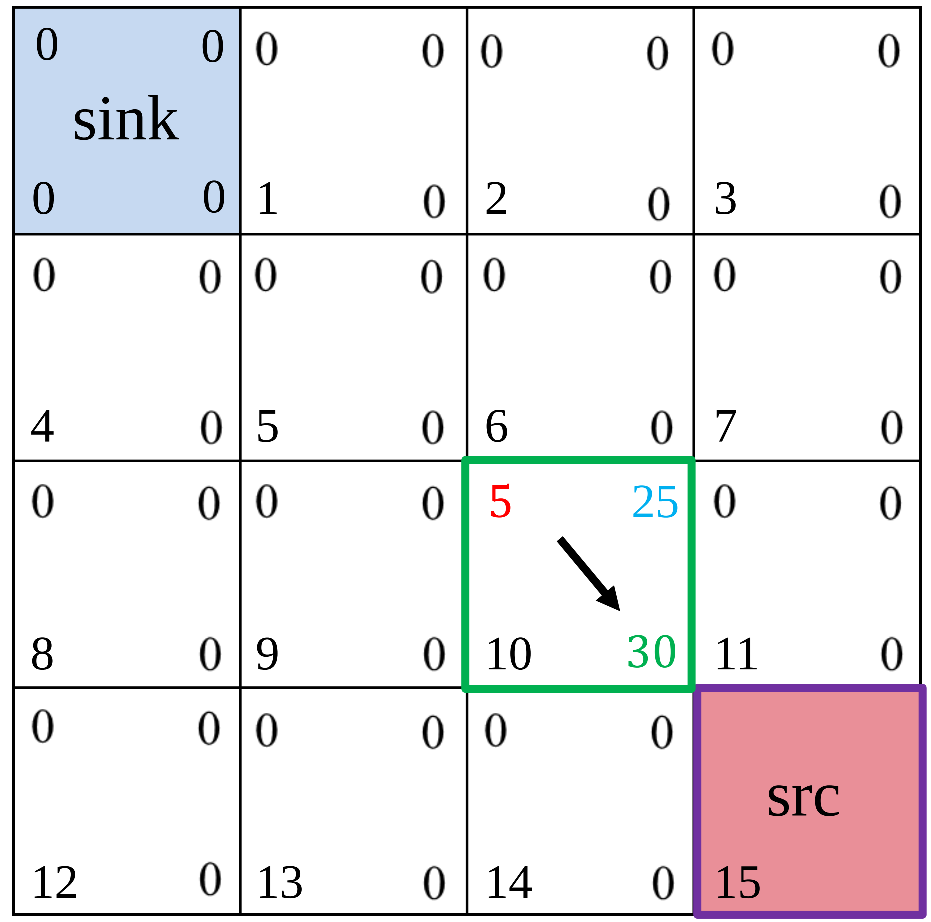




X-Architecture Thermal Driven Routing

Routing Process (Part 2)





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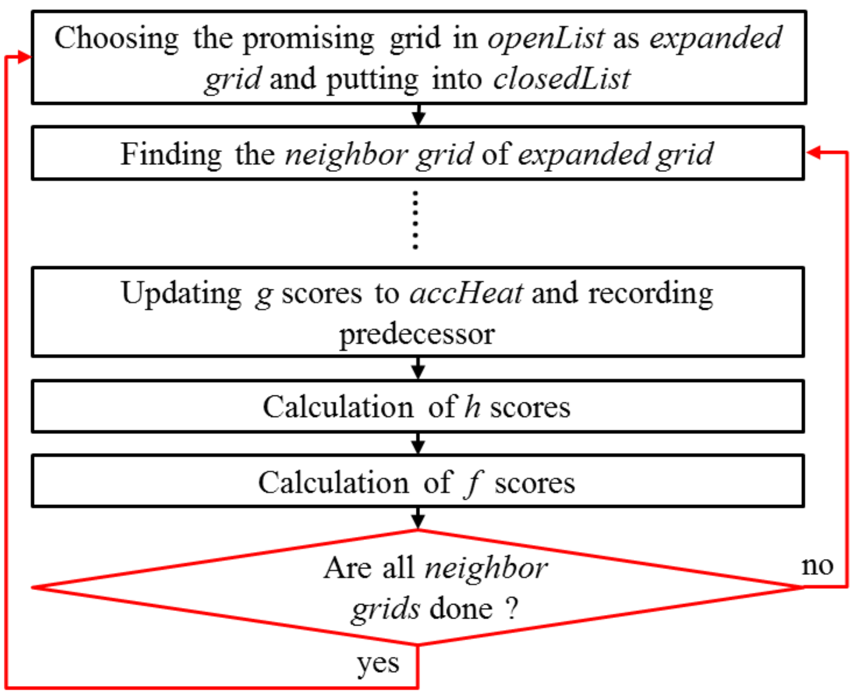
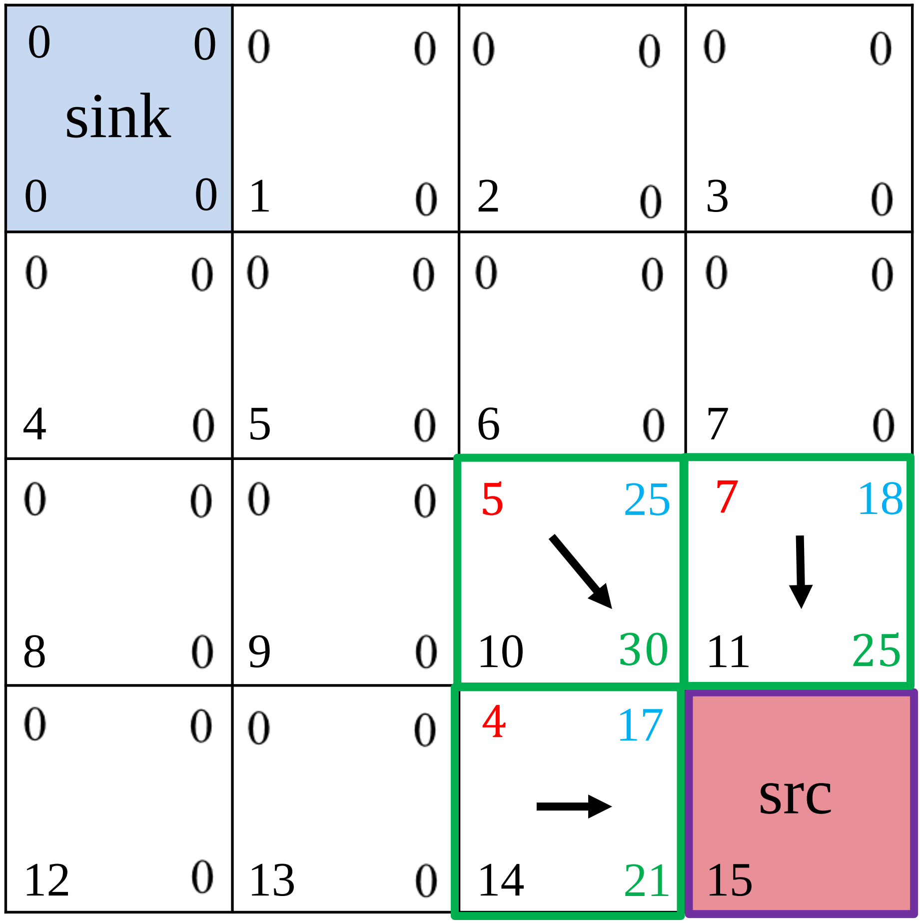
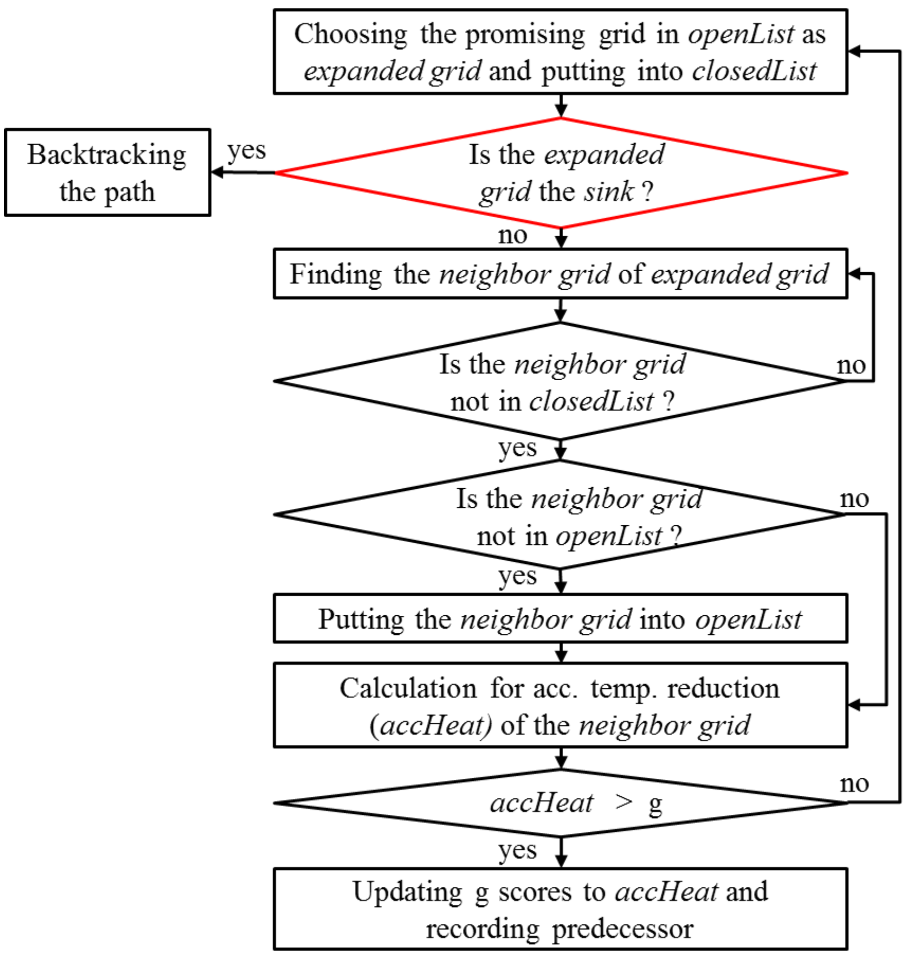
Routing Process (Part 2)

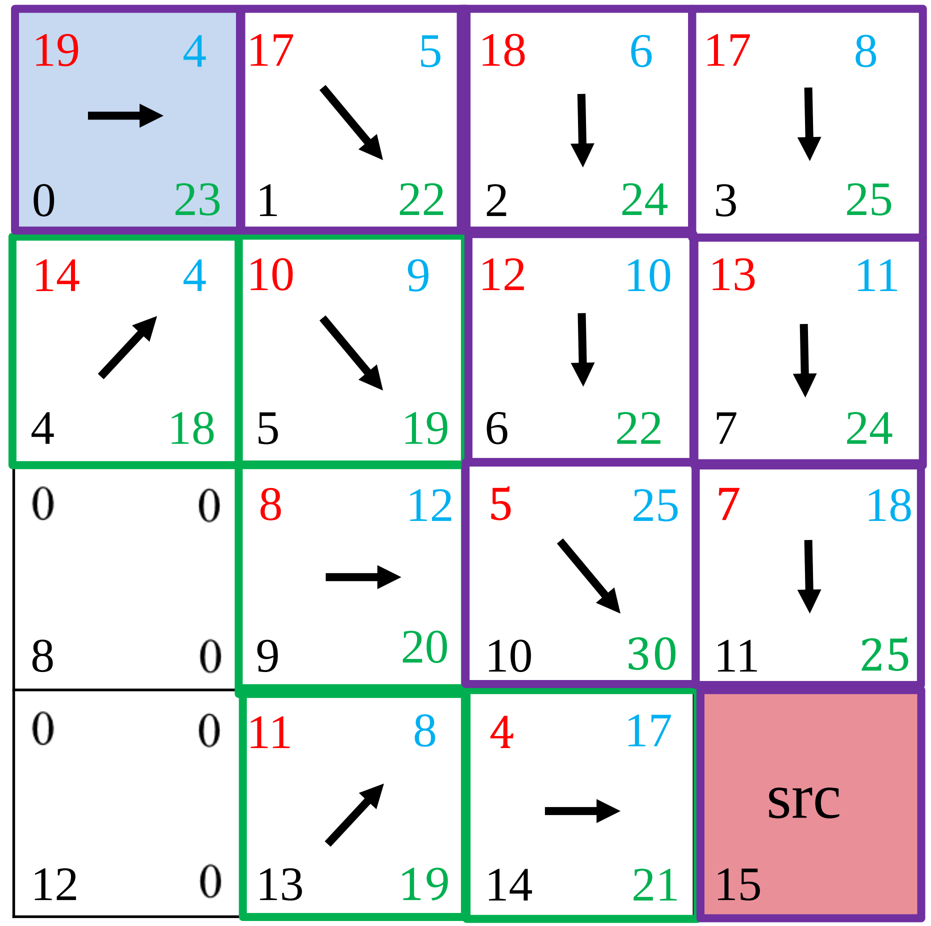




X-Architecture Thermal Driven Routing

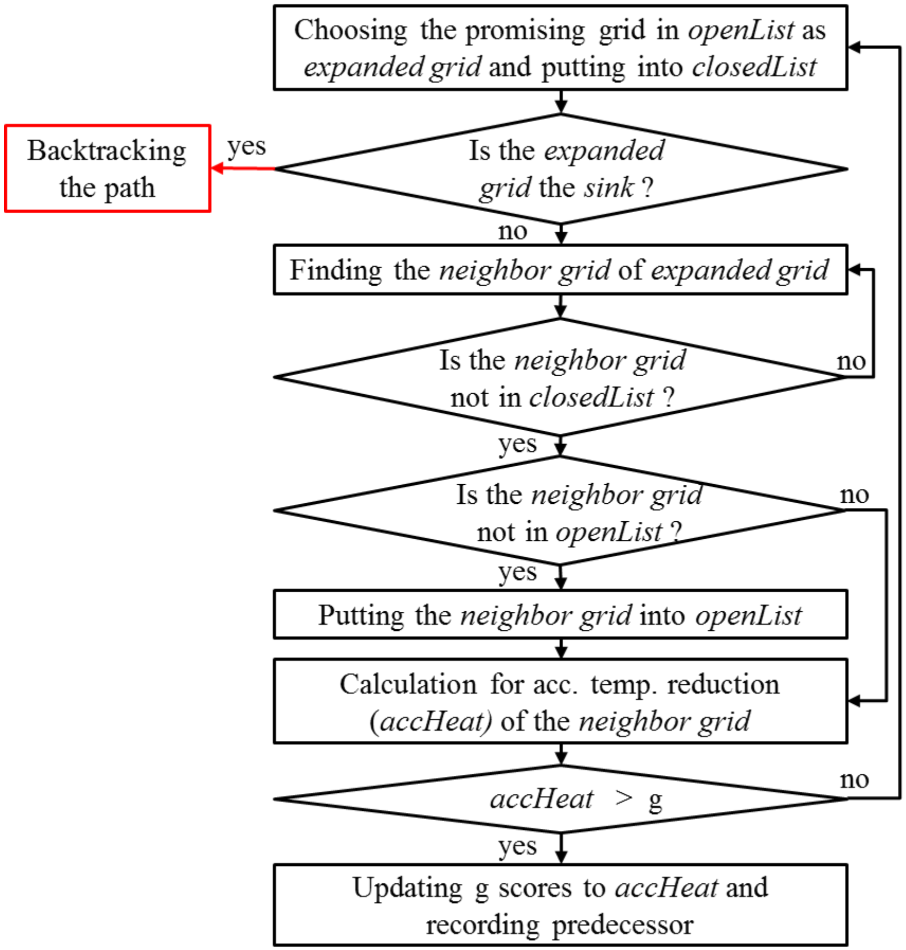
Routing Process (Part 3)

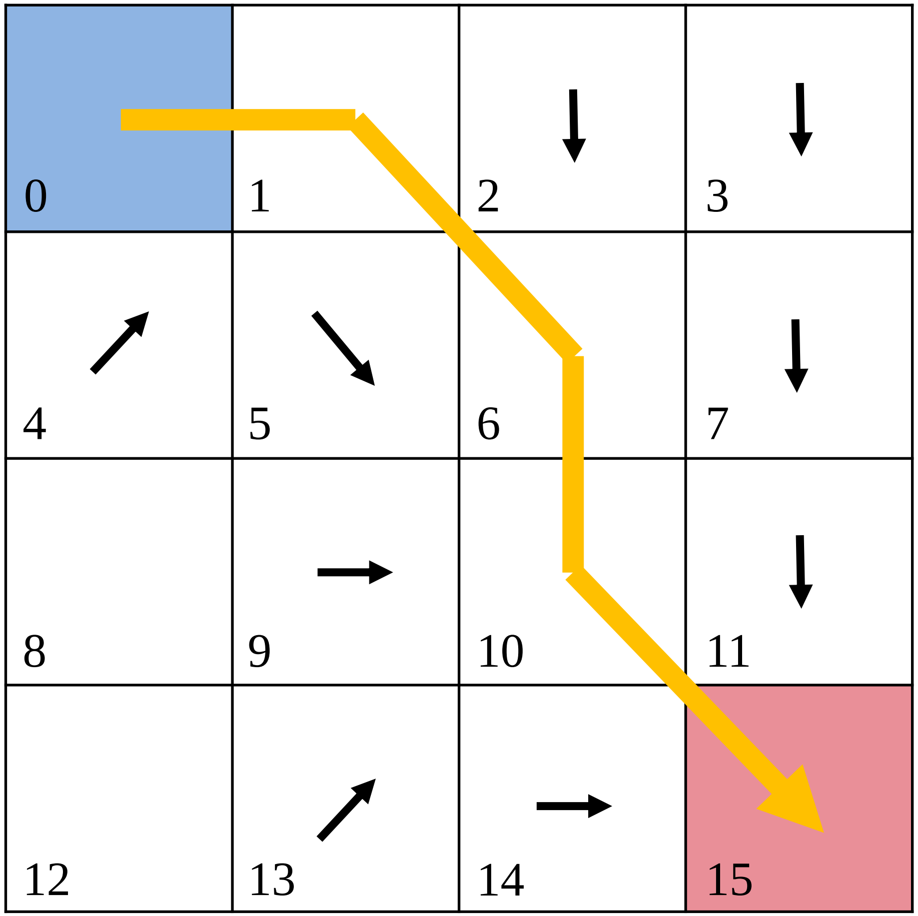




X-Architecture Thermal Driven Routing

Routing Process (Part 3)

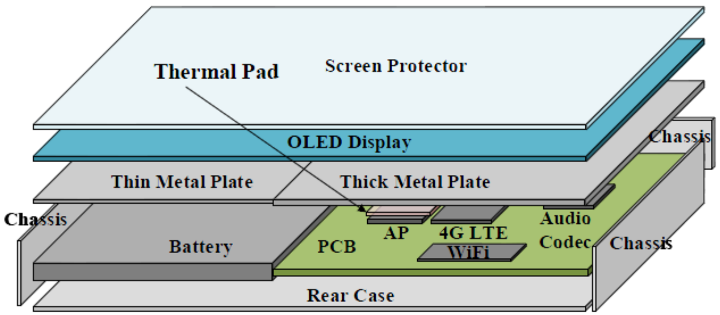




Experimental Results

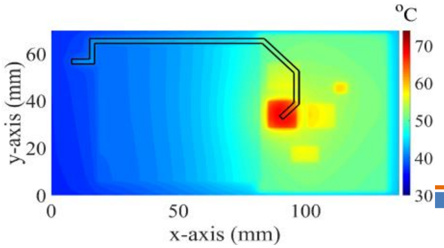
Environmental Settings

- Program language: C++
- Personal computer (PC)
  - RAM: 16G
  - CPU: Intel (R) Core (TM) i7-2600 CPU @3.40GHz
- Experimental target
  - Samsung Galaxy 4 (GS4)
  - Google Nexus 5 (N5)
- Case of power profile, C1-C5 [16]



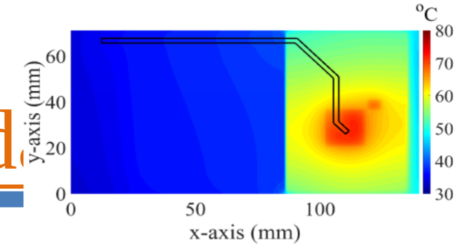
GS4 [16]

N5 [16]



Experimental Results

Pipe Thermal Model Valid



Case	Bends	Fluent	Proposed thermal simulator				
		Runtime (s)	Error (%)			Runtime (s)	SpeedUp (×)
			AP	Sk	Sc		
GS4-C1	5 45-degree: 3 90-degree: 2	1875.00	3.95	8.07	7.96	4.73	396.41
GS4-C2		1825.00	3.78	9.58	12.03	4.37	417.62
GS4-C3		1763.00	3.66	10.05	10.96	4.34	406.22
GS4-C4		1690.00	2.47	8.80	12.67	4.30	393.02
GS4-C5		1669.00	3.34	10.85	12.06	4.30	388.14
N5-C1	3 45-degree: 3 90-degree: 0	1834.00	4.79	6.43	13.58	4.80	382.08
N5-C2		1769.00	4.61	6.04	12.80	5.01	353.09
N5-C3		1644.00	4.43	5.68	12.67	4.86	338.27
N5-C4		1782.00	4.36	5.62	11.49	5.72	311.54
N5-C5		1673.00	4.45	5.58	12.42	4.83	346.38

Maximum error: 4.79%, 10.85%, and 13.58% (AP, skin, screen)
Speedup is with two order of magnitude (311×)

GS4: Samsung Galaxy 4; N5: Google Nexus 5
The results are with the temperature of center application processor (AP), and maximum temperature of skin (Sk), and screen (Sc)

Experimental Results

Temperature Reduction with Heat Pipe Designs

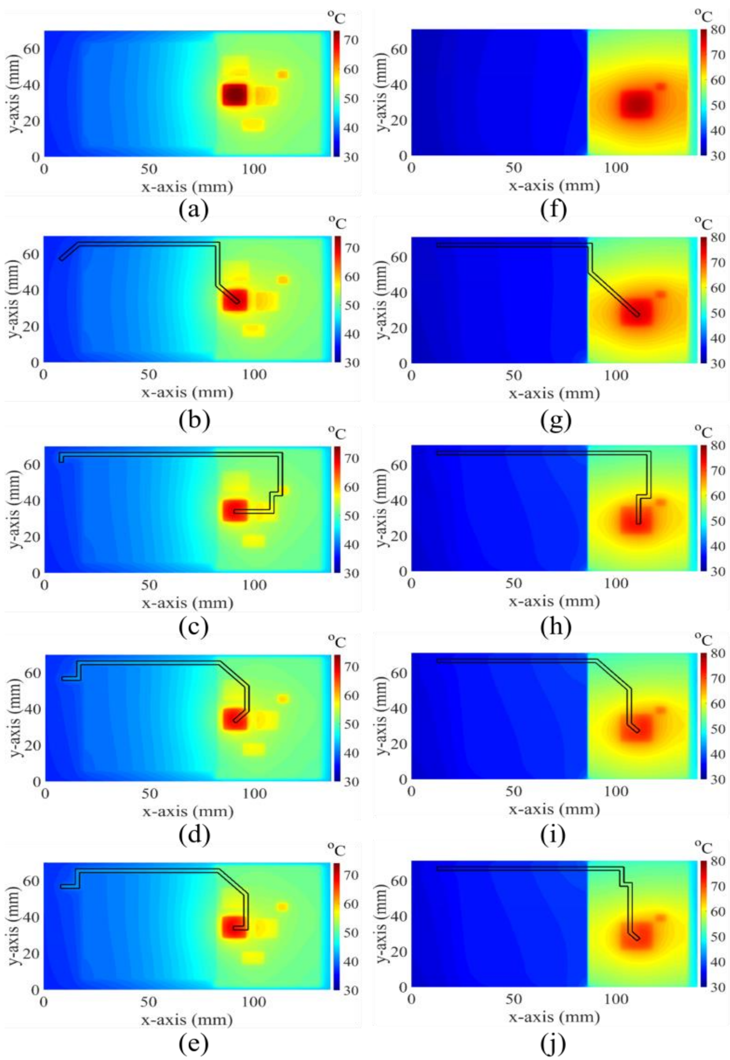
Case	SP-A*			I-MR-D			XHPR			Exhausted method		
	Temperature reduction (℃)											
	AP	Sk	Sc	AP	Sk	Sc	AP	Sk	Sc	AP	Sk	Sc
GS4-C1	2.94	1.36	1.29	5.09	2.83	3.32	6.16	4.97	4.33	66.73	39.66	38.86
GS4-C2	1.88	3.66	3.39	5.67	5.99	4.82	6.17	7.37	6.18	62.59	36.83	35.32
GS4-C3	1.03	2.03	1.47	3.55	2.87	3.20	6.29	4.60	6.85	59.97	35.30	34.67
GS4-C4	1.14	1.11	1.31	3.17	2.80	5.17	6.17	5.47	7.72	60.10	37.18	33.44
GS4-C5	1.14	0.82	2.15	4.33	3.45	4.84	5.10	4.89	7.19	59.10	36.30	33.56
N5-C1	2.57	1.18	0.64	5.53	3.05	2.38	7.34	3.59	2.60	69.61	60.67	48.38
N5-C2	2.34	1.09	0.59	5.24	2.81	2.23	6.70	3.28	2.38	65.92	58.21	46.65
N5-C3	2.14	0.99	0.54	4.82	2.59	2.06	6.16	3.02	2.19	62.85	56.16	45.21
N5-C4	2.10	0.98	0.52	4.73	2.55	2.02	6.05	2.97	2.15	62.23	55.75	44.92
N5-C5	2.13	0.99	0.54	4.80	2.58	2.05	6.13	3.01	2.18	62.63	56.32	45.17
Avg.	1.94	1.42	1.24	4.69	3.15	3.21	6.23	4.32	4.38	6.88	5.36	5.16

XHPR can reduce the temperature of AP at least 13.20%
It shows that XHPR achieves the better cooling ability than others

SP-A*: shortest path A* routing algorithm [17]; I-MR-D: the 90-degree maze routing method in [18];
XHPR: X-architecture thermal driven routing; Exhausted method: [19]

Experimental Results

Thermal Maps & Heat Pipe Routing Paths



NOHP

SP-A*

I-MR-D

XHPR

Exhausted method

GS4-C1 **N5-C1**

Conclusion

- In this work, we present
  - A compact thermal model of multi-angle bended heat pipe for accurate and fast thermal simulation
  - A developed X-architecture thermal driven routing algorithm for heat pipe deign
  - A thermal weight calculator using in the heat pipe routing stage to support heat pipe design
  - The proposed X-architecture thermal driven heat pipe routing engine can reduce the temperature at least 13.20% in application processors

Reference

- [1] https://phandroid.com
- [2] http://t2online.com/tech
- [3] https://www.titan-cd.com
- [4] http:://www.alibaba.com
- [5] http://hottopic.chinatimes.com/20160426005570-260805
- [6] https://mashable.com
- [7] https://en.wikipedia.org/wiki/Heat_pipe
- [8] http://technews.tw/2015/12/24/smart-phone-duct-heater-market/
- [9] https://www.neowin.net
- [10] https://www.lg.com/tw
- [11] https://wccftech.com
- [12] ISAC: Integrated Space-and-Time-Adaptive Chip-Package Thermal Analysis Yonghong Yang, Student Member, IEEE, Zhenyu (Peter) Gu, Student Member, IEEE, Changyun Zhu, Student Member, IEEE, Robert P. Dick, Member, IEEE, and Li Shang, Member, IEEE
- [13] L. L. Jiang, Y. Tang, and M. Q. Pan. Effects of bending on heat transfer performance of axial micro-grooved heat pipe. Journal of Central South University of Technology, 18(2):580–586, 2011
- [14] http://truth.bahamut.com.tw/s01/201407/0a347bef88be0867a7489f860b9876b5.PNG
- [15] A. Faghri. Heat pipes: review, opportunities and challenges. Frontiers in Heat Pipes (FHP), 2014.
- [16] M. J. Dousti, M. Ghasemi-Gol, M. Nazemi, and M. Pedram, “ThermTap:An online power analyzer and thermal simulator for Android devices,”in Int. Symp. Low Power Electron. Des., pp. 341–346, 2015
- [17] S. T. Group, “Amit’s A* Pages.” [Online]. Available: http://theory.stanford.edu/amitp/GameProgramming/AStarComparison.html, 2010.
- [18] H. W. Chiou, Y. M. Lee, H. H. Hsiao, and L. C. Cheng, “Thermal modeling and design on smartphones with heat pipe cooling technique,”in Proc. Int. Conf. on Comput.- Aided Des., pp. 482–489, 2017.
- [19] EQV Martins and MMB Pascoal. A new implementation of yens ranking loopless pathsalgorithm. Quarterly Journal of the Belgian, French and Italian Operations ResearchSocieties, 1(2):121–133, 2003.

Thanks for listening ☺