I238 計算の理論

上原 隆平

2019年I-1期（4-5月）

Announce

- June 6：最後の講義(Last Lecture):
  - 最近の計算量の話題より(Recent topics on Computational Complexity)
  - 講義アンケート(Questionnaire)
- Tutorial Hour on June 6：居室にて質問受付(Feel free to ask me at my laboratory)
- June 11：期末試験(Final Examination)

I238 Computation Theory

by

Prof. Ryuhei Uehara

Term I-1, April-May, 2018

時間計算量と領域計算量

- 計算時間に基づく計算量と同様，計算領域に関する計算量がある.
  - モデルとしては，より安定している（上原の指導教員談）
  - 今日の話の中では以下が登場:

    PSPACE={ L | 多項式領域を使うDTMでLを受理可能}

    NSPACE={ L | 多項式領域を使うNTMでLを受理可能}

定理1 [Savitch 1970]:　$NPSACE(f(n)) \subseteq DSPACE((f(n))^2)$

系1: NPSPACE=PSPACE

Time complexity v.s. space complexity

- We can consider “space complexity” like as “time complexity”
  - More stable model than time complexity (as my supervisor said 30 years ago)
  - Today’s classes:

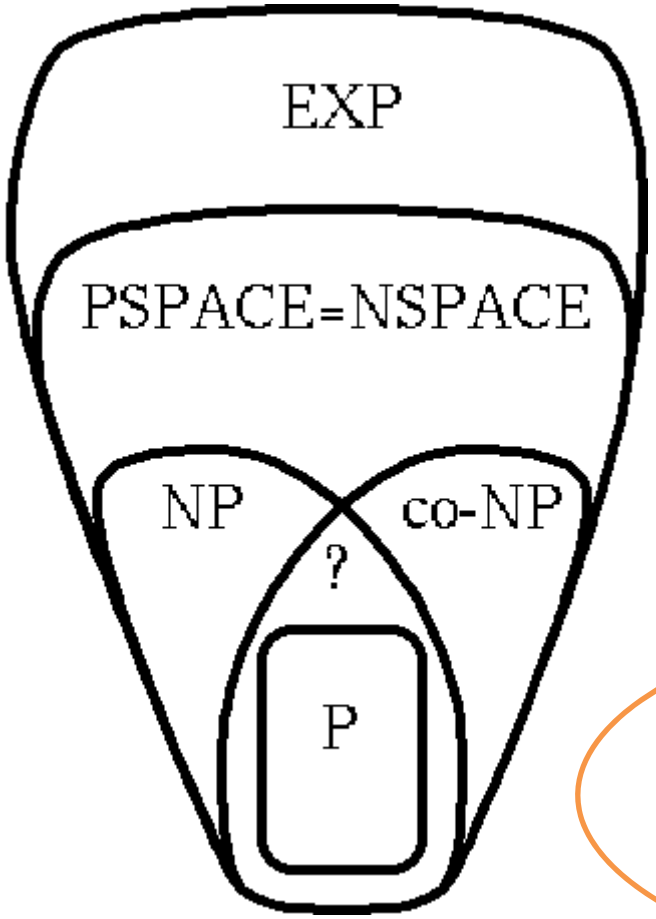
    PSPACE={ L | A DTM accepts L with polynomial space}

    NSPACE={ L | An NTM accepts L with polynomial space}

Theorem 1 [Savitch 1970]: $NPSACE(f(n)) \subseteq DSPACE((f(n))^2)$

Corollary 1: NPSPACE=PSPACE

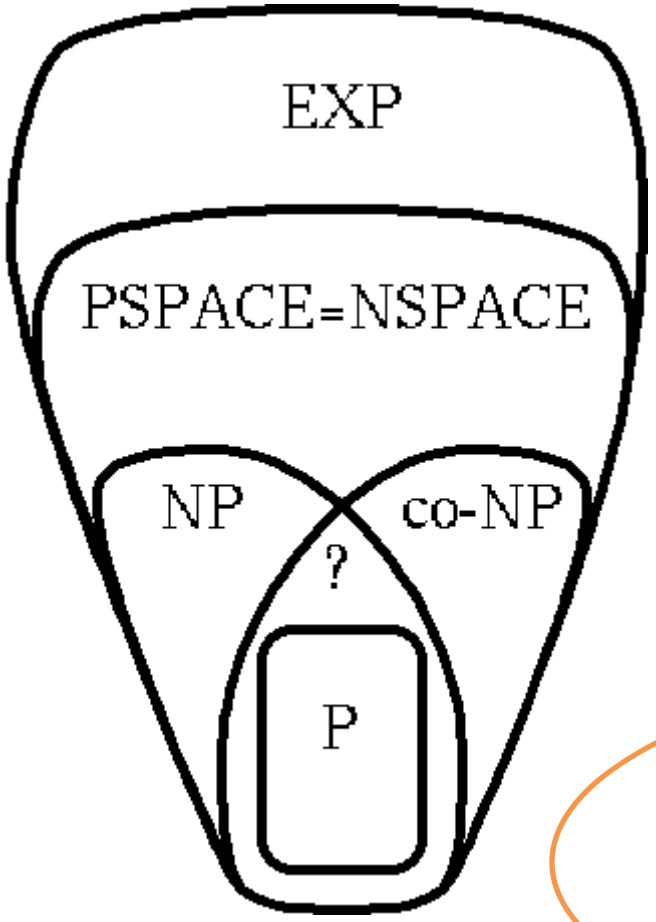
PSPACEに関する階層構造



- 自明な階層構造以外はあまりわかってない
- 多くのパズルやゲームがこの階層構造における完全問題となっている.

ゲームやパズルの完全問題の解析が計算量クラスの（新しい着眼点による）理解を与えてくれる！

Hierarchy around PSPACE



- It is not well-known except trivial inclusions
- Many puzzles & games are XX-complete problems in this hierarchy.

Analyses of XX-complete games and puzzles bring us better understanding (from the different aspects)

ICALP Masterclass Talk: Algorithms and Complexity for Japanese Puzzles

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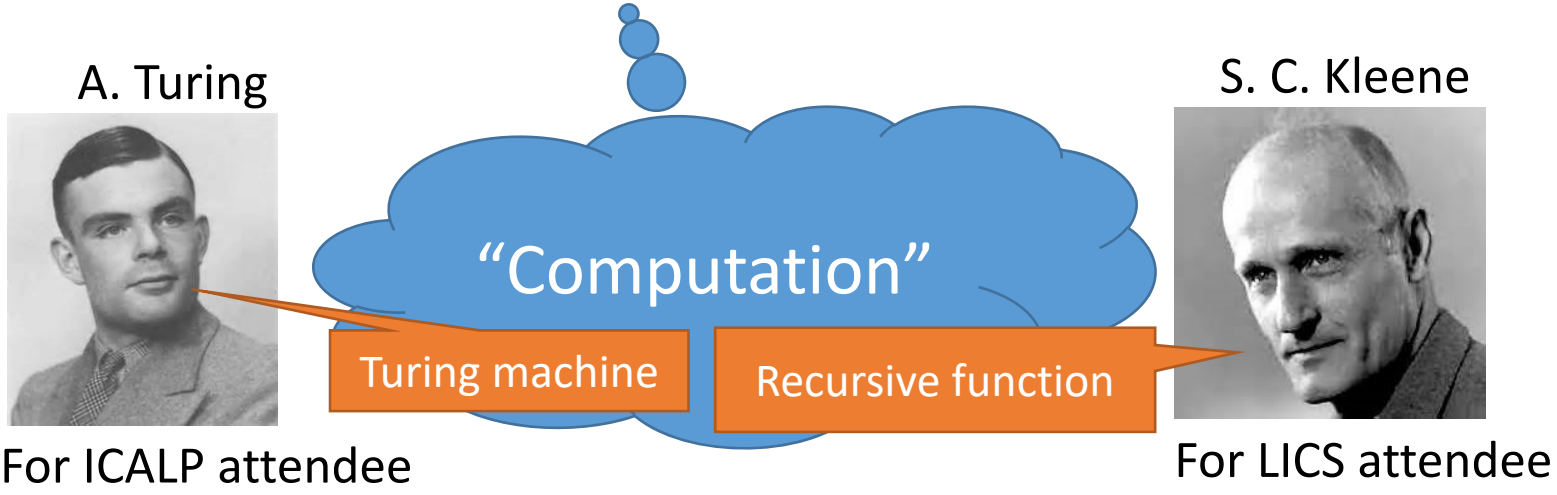
Complexity v.s. Puzzles & Games

1. Computational Complexity v.s. Puzzles & Games
2. Complexity Classes characterized by Games and Puzzles
   - Classic
     - Historical results
   - Modern
     - What have been considered?
   - Recent and Future
     - What problems on the edge?

Computational Complexity v.s. Puzzles & Games

- What's "computation" could be… (1930s-1940s)

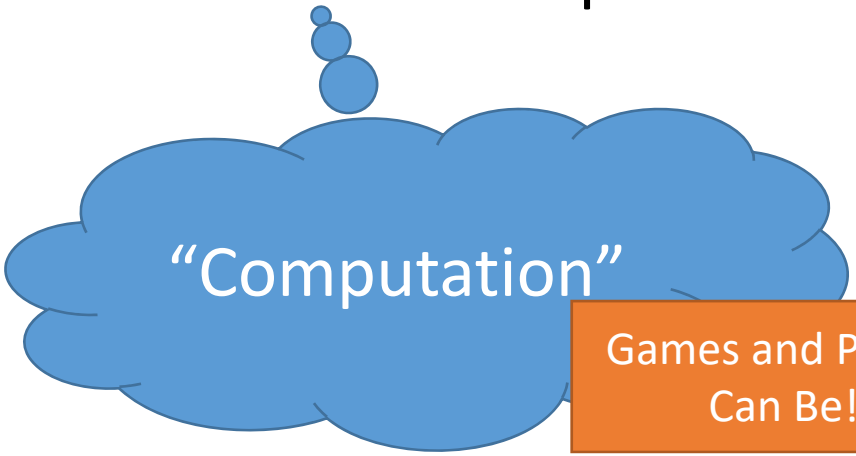


To consider "computation," what we need is

- Basic operations (=model of computation)
- How can we combine them (=algorithms)

Computational Complexity v.s. Puzzles & Games

- What's "computation" could be… (1970s)



John Horton Conway

To consider "computation," what we need is

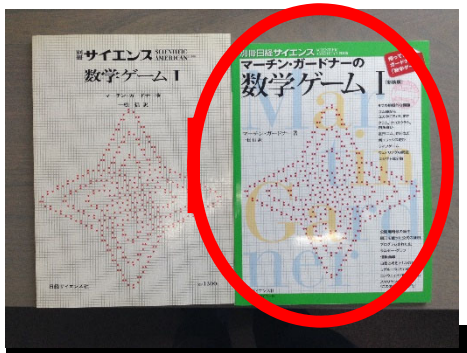
- Basic operations (=model of computation)
- How can we combine them (=algorithms)

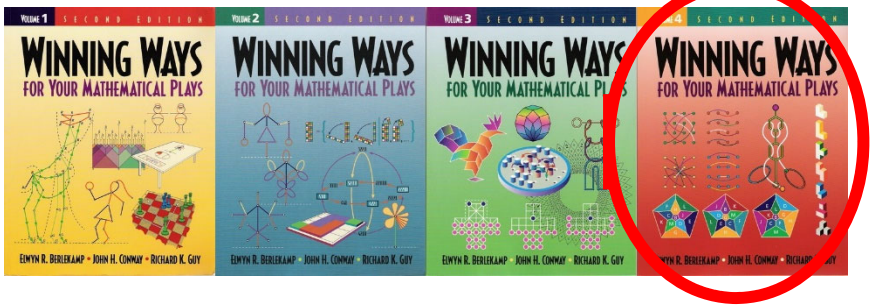
Computational Complexity v.s. Puzzles & Games

- What's "computation" could be… (1970s

  Conway's *Game of Life* (1970)

  - For young guys
    - It is a kind of cellular automaton with quite simple rules.
    - It is "*Universal*", that is, it computes any function!
      - Some nice books:





Simon J. Fraser, John "Horned" (Horton) Conway, *1975*

Computational Complexity v.s. Puzzles & Games

- What's "computation" could be… (1970s

  Conway's *Game of Life* (1970)

  - For young guys
    - It is a kind of cellular automaton with quite simple rules.
    - It is "*Universal*", that is, it computes any function!
  - For veteran folks
    - Quite fancy software "Golly"

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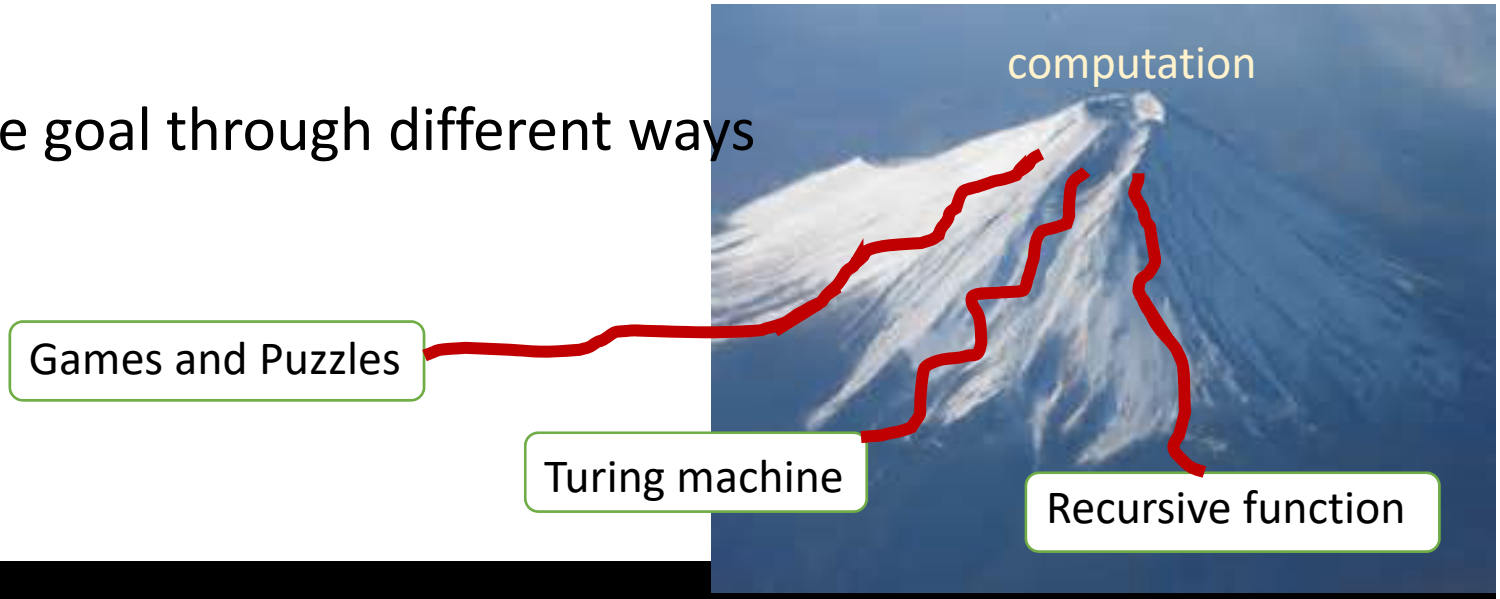
Computational Complexity v.s. Puzzles & Games

- Puzzles and Games to consider "computation"
  - Simple and Uniform (with reasonable model)
  - That may extract the essence of the difficulty of some computation
  - That may give us new aspect of some computation

⇒Same goal through different ways



Short Ads.

- In JAIST, we have "JAIST Gallery" that has around 10000 puzzles called *NOB's Puzzle Collection*!

I'm a director of this gallery!

NOB Yoshigahara
(1936-2004)

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Classic Results (1970s～1980s):

- Game to consider “computation”
  - Characterization by artificial game
  - *Pebble game* (though we have many variants)

    Input: Directed graph *G,* placement of “*pebbles*”

    Rule: Move pebbles along edges and remove some pebbles in certain rules

    Output: Determine if you can move a pebble to a goal
  - It is complete for some computational classes;
    - NLOG, P, NP, PSPACE, EXP

1 player/2 players
Number of pebbles
Acyclic or not

- References:
  - J. Hopcroft, W. Paul and L. Valiant. “On Time versus space,” *J. Assoc. Comput. Mach*. 1977
  - Richard J. Lipton and Robert E. Tarjan. “Applications of a Planar Separator Theorem,” *SIAM J. Comput*. 1980
  - Stephen Cook; Ravi Sethi. "Storage requirements for deterministic polynomial time recognizable languages". *Journal of Computer and System Sciences,* 1976.
  - Takumi Kasai; Akeo Adachi; Shigeki Iwata. "Classes of pebble games and complete problems". *SIAM Journal on Computing,* 1979.

More Classic Results (1980s～):

- Puzzles to consider “computation”
  - Characterization by *natural* games and puzzles
  - *Many puzzles and games*
    - *E.g.,* Geometry (しりとり), Solitaire, Crossword puzzle, Jigsaw puzzle (matching puzzle), UNO, Video games, Pencil puzzles, …

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So far … (1980s～2000s):

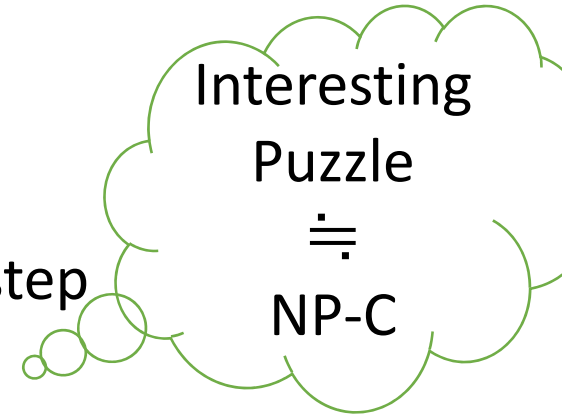
- We had tons of *X*-Complete problems;
  - NP-complete puzzles

    1 player, something decreases in each step
    - Tons of papers…
  - PSPACE-complete / EXP-complete games

    2 player version of these NP-complete problems
- They give some insight of these classes

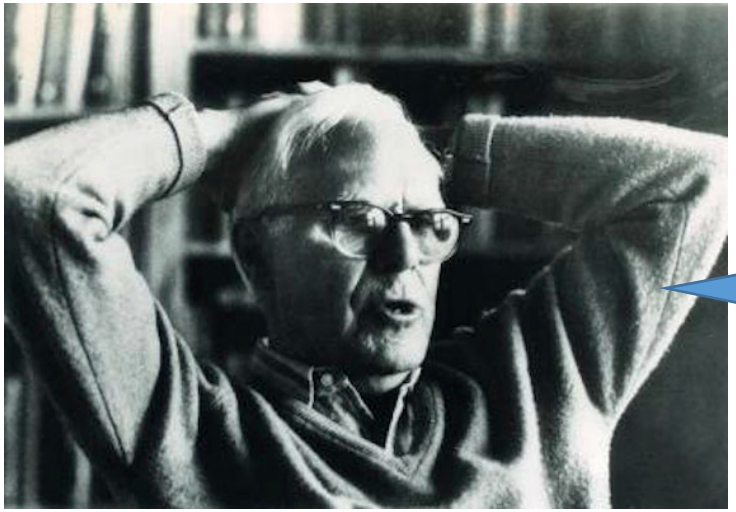
  NP: 1 player, something decreases in each step.

  PSPACE: 2 players (…alternating Turing Machine)
- We needed some general model for them…



So far … (1980s～2000s):

- Still unsolved
  - Sliding Block puzzles like
    “Daddy Puzzle”,
    “Sokoban”
- Martin Gardner said that…

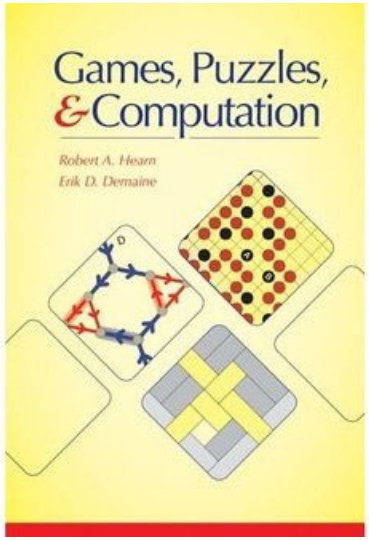


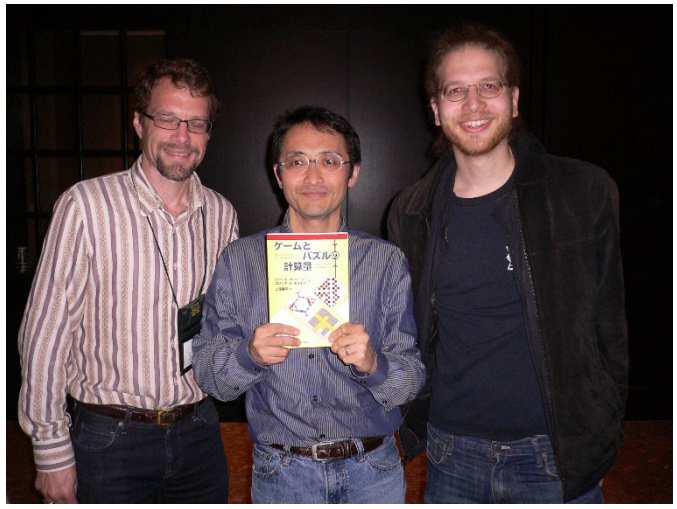
“These puzzles are very much in want of a theory”
Scientific American 210 (1964)

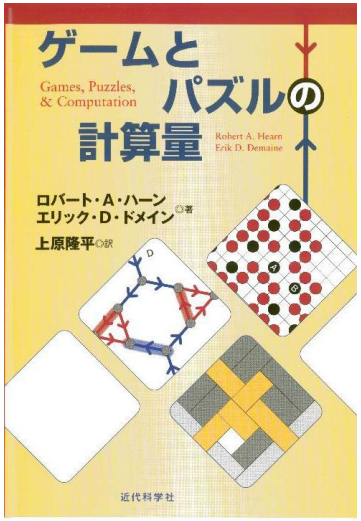
… 40 years later,

Modern Results (2010s～):

- New framework to consider “computation”
  - “Constraint Logic” by Bob Hearn and Erik D. Demaine
  - *Essentially, game (2player) and puzzle (1player)*
    - *That can model many previous known games and puzzles,*
    - *And solves the open problems about sliding block type puzzles.*







Modern Results (2010s〜):

- New framework to consider “computation”
  - “Constraint Logic” by Bob Hearn and Erik D. Demaine
  - *Roughly, it is a game on a graph*

    Input: Directed graph *G*, each edge has weight and direction

    Rule: Each vertex is *balanced*, an operation is flipping an edge

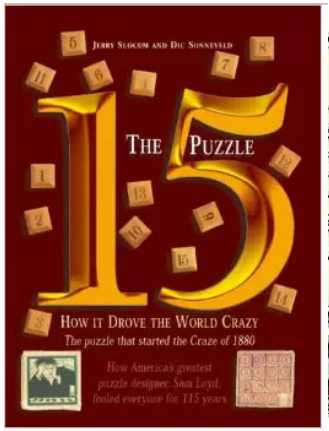
    Output: Determine if you can flip some specified edge
  - Relatively higher classes:

#flips of an edge

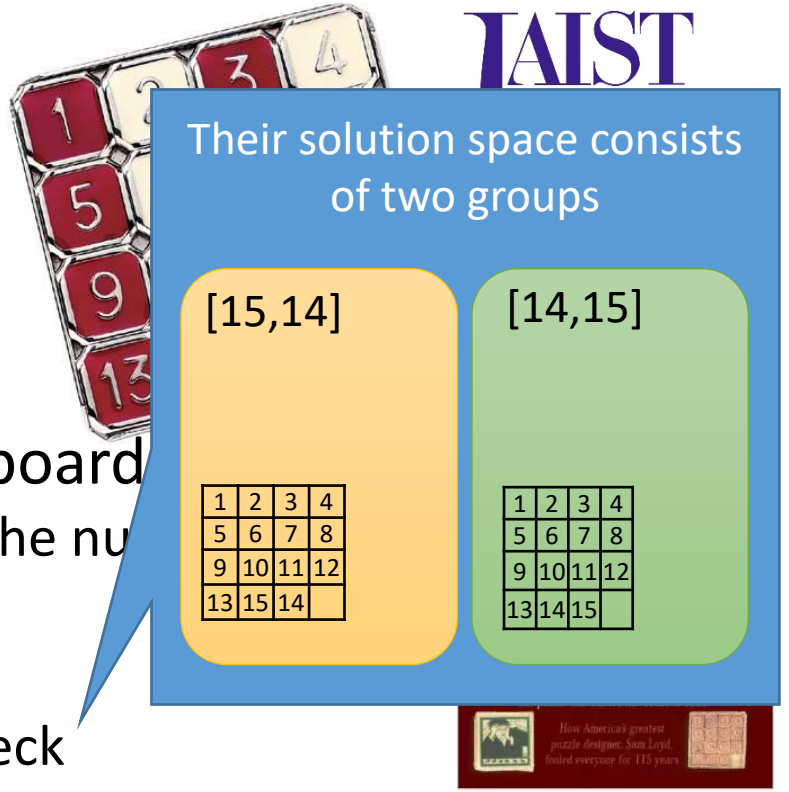
	0 player	1 player	2 player	Team, imperfect information
Unbounded	PSPACE	PSPACE	EXPTIME	RE (undecidable)
Bounded	P	NP	PSPACE	NEXPTIME

Some remarkable puzzles…

- Finally solved
  - Sliding Block puzzles are PSPACE-complete.
  - Unlike other NP-complete problems, it can recover the same state many times… that property makes them to be PSPACE-complete?
- It reminds us a classic puzzle solved in 1990,,,
  - 15 puzzle
  - It has a long and funny stories;
    see “The 15 Puzzle Book”
    by Jerry Slocum, 2006.



Top puzzle collector in the world…



Some remarkable puzzles...

- The 15 Puzzle

  It is easy to generalized to n × n board

  Input: Two arrangements ***s*** and ***t*** of the nu

  Goal: Slide a panel from ***s*** to ***t***

  Output: …

  Yes/No: Linear time by parity check

  If Yes, find a sequence of arrangements: $O(n^2)$ time

  Furthermore, find a sequence: $O(n^3)$ time

  However, find a shortest sequence: NP-complete!!

- Reference:
  - Daniel Ratner and Manfred Warmuth. “The (n^2-1)-Puzzle and Related Relocation Problems,” *J. of Symbolic Computation*, 1990.

Short Ads. 2

- In Japan, there are two major puzzle shops
  1. Torito, around Akihabara, Tokyo.
  2. Puzzlein, Katsuragawa, Kyoto.

From Kyoto Station,
2 stops and 10min walk.

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Recent and Future Results (2010s～):

- *New concept* of problems to consider "complexity" inspired by these puzzles:

  Reconfiguration Problems

  Input: Problem P, two feasible solutions S_1 and S_2

  Operation: Simple rule for modification of a solution

Decision	Problem 1: Determine if S_1 can be transformed to S_2
Find	Problem 2: Find a sequence of solutions between S_1 and S_2
Shortest	Problem 3: Find a shortest sequence between S_1 and S_2

Recent and Future Results (2010s～):

- *New concept* of problems to consider "complexity" inspired by these games/puzzles:

Reconfiguration Problems

	Sliding Block puzzle		(n^2-1) puzzle
Decision	PSPACE-complete		Linear
Find	(PSPACE-complete)	⇔	Poly-time
Shortest	(PSPACE-complete)		NP-complete

Many problems should be here
And they give some new insight of the classes

Recent and Future Results (2010s～):

- Not game-like results for reconfiguration problems:
  - SAT: "Decision problem" is PSPACE-complete

    Reference:

    P. Gopalan, P.G. Kolaitis, E.N. Maneva, C.H. Papadimitriou, "The connectivity of Boolean satisfiability: computational and structural dichotomies," *SIAM J. Comput*. 2009.
  - IS, Clique, Vertex Cover, Set Cover, IP: "Decision problem" is PSPACE-complete

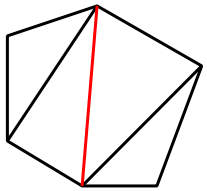
    Reference:

    T. Ito, E. D. Demaine, N. J. A. Harvey, C. H. Papadimitriou, M. Sideri, R. Uehara, and Y. Uno: On the Complexity of Reconfiguration Problems, *Theoretical Computer Science*, 2010.

In my measure, "Sliding-block puzzle type"

Recent and Future Results (2010s～):

- Bit game-like result for reconfiguration problems:
  - Famous open problem in Computational Geometry

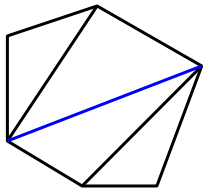


Input: Simple polygon, two triangulations T_1, T_2

Operation: “flip” one diagonal

Known: Every T_1 is flippable to T_2 in $O(n^2)$ flippings

Question: Find a shortest flipping



Result: It is NP-complete!!

It was open 40 years like sliding block puzzle…

Reference:

O. Aichholzer, W. Mulzer, A. Pilz, Flip distance between triangulations of a simple polygon is NP-complete, ESA 2013.

In my measure, “(n^2-1) puzzle type”

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Recent and Future Results (2010s～):

- Not game-like, but something remarkable:
  - SAT: Trichotomy for the classes P, NP, and PSPACE from the viewpoint of "Shortest problem"

    Reference:

    A. E. Mouawad, N. Nishimura, V. Pathak and V. Raman: Shortest Reconfiguration Paths in the Solution Space of Boolean Formulas, *ICALP 2015*, 2015/7/8.

In my measure, this one may be the first example between "Sliding-block puzzle type" and "(n^2-1) puzzle type".

Summary and Future work

- Games and Puzzles give us a new insight about “computation”
- Some new problems are not yet well-settled.
  - Reconfiguration problem, especially, (n^2-1) puzzle type problem.
  - We need new model that characterizes the classes P, NP, PSPACE, (EXP) in this manner.

Conway’s Life Game

Pebble game

Real games/puzzles

Constraint Logic

Games based on “Reconfiguration”

These games are very much in want of a theory!