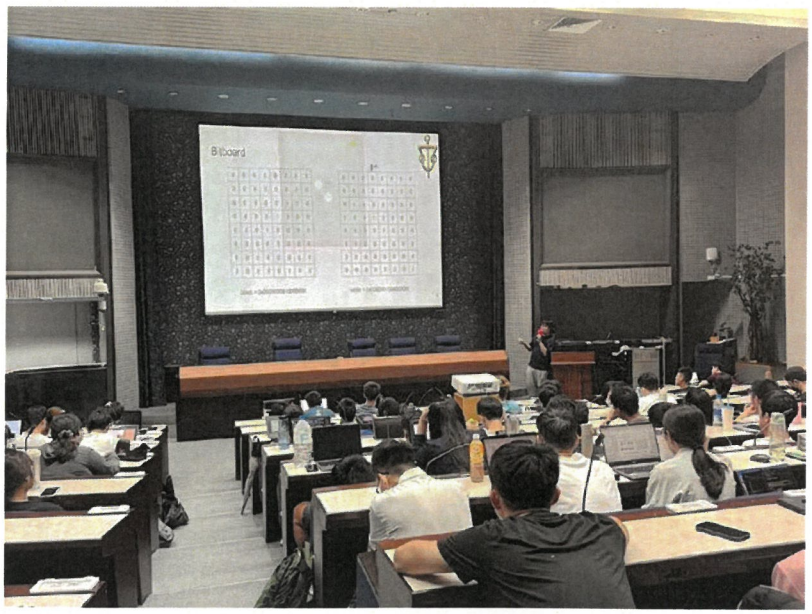
邀請中華民國斐陶斐榮譽學會榮譽會員演講成果報告

主辦單位	國立臺灣師範大學資訊工程學系
時　　間	112 年 9 月 6 日（三）14:20～16:00
地　　點	臺師大公館校區綜合館 3 樓國際會議廳
講　　題	如何打造一支厲害的黑白棋程式
講　　者	陳彥吉
主 持 人	葉梅珍教授

演講摘要

介紹講者在國內外比賽多次榮獲金牌的黑白棋程式的實作細節，其中包含了：走步產生、估值函數的設計、搜尋算法的改良、平行化遊戲樹搜索時的負載平衡、開局資料庫的設計。

活動照片（請呈現「中華民國斐陶斐榮譽學會」字樣或 Logo）



團體會員學校校長簽章：校長吳正己

年　　月　　日

如何打造一支厲害的黑白棋程式

講者:陳彥吉

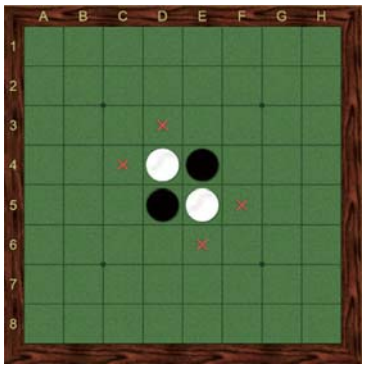
陳彥吉

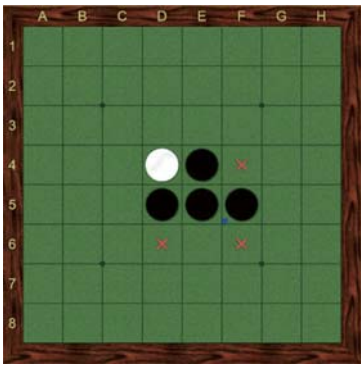
- 學歷
  - 國立臺灣師範大學數學系＋資訊工程系雙主修
  - 國立臺灣師範大學資訊工程所
- 就業？
  - 師大資工研究助理
  - 中研院研究助理
- 今天分享的內容
  - 跟畢業論文無關
  - 我大三至研究所畢業還做了 啥？
  - 黑白棋戰績: 16金6銀2銅

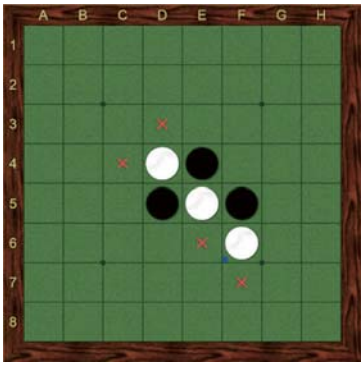
Outline

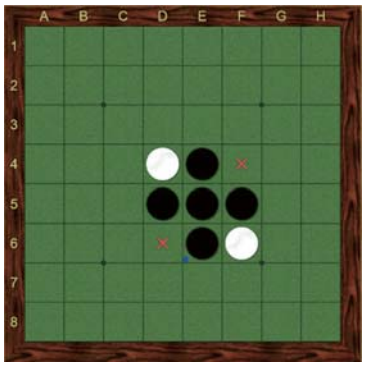
1. Introduction
2. Action generator
3. Evaluation function
4. Search algorithm
5. Parallel search algorithm
6. Opening book
7. Conclusion

Rule

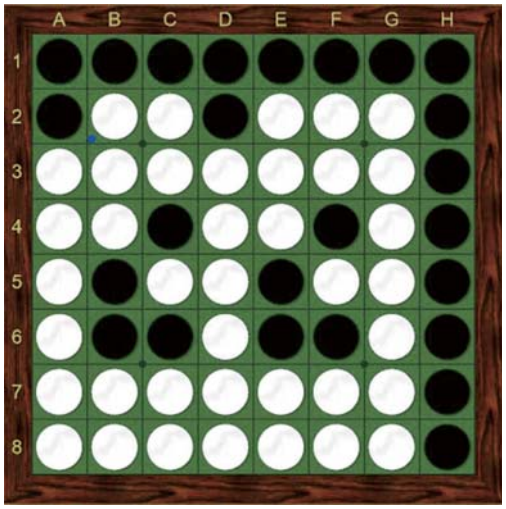




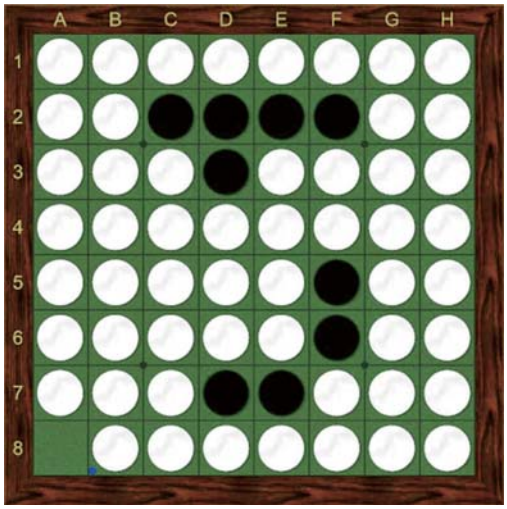




Rule



25-**39**



9-**54**

Maverick

- My Othello AI program, Maverick
  - Based on AlphaBeta search
  - Perfect end game search for final 24 layers
  - Opening book
- There is a trade-off between speed and accuracy.

	AlphaBeta	MCTS	AlphaZero
Speed (nodes/s)	10,000,000	100,000	1,000
Accuracy	Low ⟷ High		

Outline

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Bitboard

0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	1	0	0	0
0	0	0	1	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0

black = 0x0000000810000000

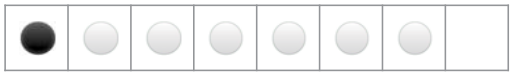
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	1	0	0	0	0
0	0	0	0	1	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0

white = 0x0000001008000000

Sequential

```
mask = 0x7e7e7e7e7e7e7e7e
m = white & mask
empty = ~(black | white)
t = (black >> 1) & m
t |= (t >> 1) & m
t |= (t >> 1) & m
t |= (t >> 1) & m
t |= (t >> 1) & m
t |= (t >> 1) & m
actions |= (t >> 1) & empty
```


Sequential



```
mask = 0x7e7e7e7e7e7e7e7e
m = white & mask
empty = ~(black | white)
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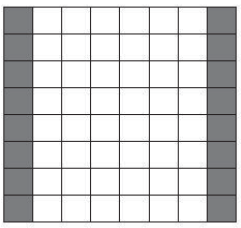
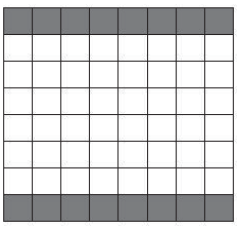
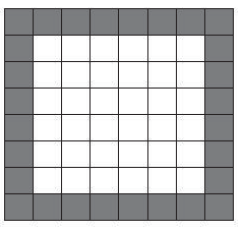


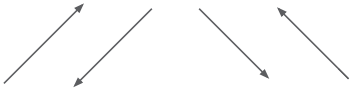




0x7e7e7e7e7e7e7e7e

0x00ffffffffffff00

0x007e7e7e7e7e7e00



Sequential

```
mask = 0x7e7e7e7e7e7e7e7e
m = white & mask
empty = ~(black | white)
t = (black >> 1) & m
t |= (t >> 1) & m
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t |= (t >> 1) & m
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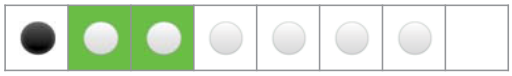
Sequential



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```

x8 directions

```
+9   +8   +7
  \  ^  /
+1 <  0  > -1
  /  v  \
-7   -8   -9
```

Kogge-Stone

```
mask = 0x7e7e7e7e7e7e7e7e
m = white & mask
empty = ~(black | white)
t = black | ((black >> 1) & m)
m =  (m >> 1) & m
t |= (t >> 2) & m
m =  (m >> 2) & m
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actions |= ((t & white) >> 1) & empty
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Kogge-Stone

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Kogge-Stone

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t |= (t >> 4) & m
actions |= ((t & white) >> 1) & empty
```

x8 directions

Hybrid

```
mask = 0x7e7e7e7e7e7e7e7e
m = white & mask
empty = ~(black | white)
t = (black >> 1) & m
t |= (t >> 1) & m
m =  (m >> 1) & m
t |= (t >> 2) & m
t |= (t >> 2) & m
actions |= (t >> 1) & empty
```

x8 directions

Hybrid

```
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m = white & mask
empty = ~(black | white)
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t |= (t >> 1) & m
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t |= (t >> 2) & m
t |= (t >> 2) & m
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```

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t |= (t >> 2) & m
t |= (t >> 2) & m
actions |= (t >> 1) & empty
```


Hybrid

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t |= (t >> 2) & m
actions |= (t >> 1) & empty
```

Hybrid

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empty = ~(black | white)
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t |= (t >> 2) & m
actions |= (t >> 1) & empty
```


Hybrid

```
mask = 0x7e7e7e7e7e7e7e7e
m = white & mask
empty = ~(black | white)
t = (black >> 1) & m
t |= (t >> 1) & m
m =  (m >> 1) & m
t |= (t >> 2) & m
t |= (t >> 2) & m
actions |= (t >> 1) & empty
```

Comparison

<Sequential>
```
mask = 0x7e7e7e7e7e7e7e7e
m = white & mask
empty = ~(black | white)
t = (black >> 1) & m
t |= (t >> 1) & m
t |= (t >> 1) & m
t |= (t >> 1) & m
t |= (t >> 1) & m
t |= (t >> 1) & m
actions |= (t >> 1) & empty
```

<Hybrid>
```
mask = 0x7e7e7e7e7e7e7e7e
m = white & mask
empty = ~(black | white)
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m =  (m >> 1) & m
t |= (t >> 2) & m
t |= (t >> 2) & m
actions |= (t >> 1) & empty
```

<Kogge-Stone>
```
mask = 0x7e7e7e7e7e7e7e7e
m = white & mask
empty = ~(black | white)
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m =  (m >> 1) & m
t |= (t >> 2) & m
m =  (m >> 2) & m
t |= (t >> 4) & m
actions |= ((t & white) >> 1) & empty
```
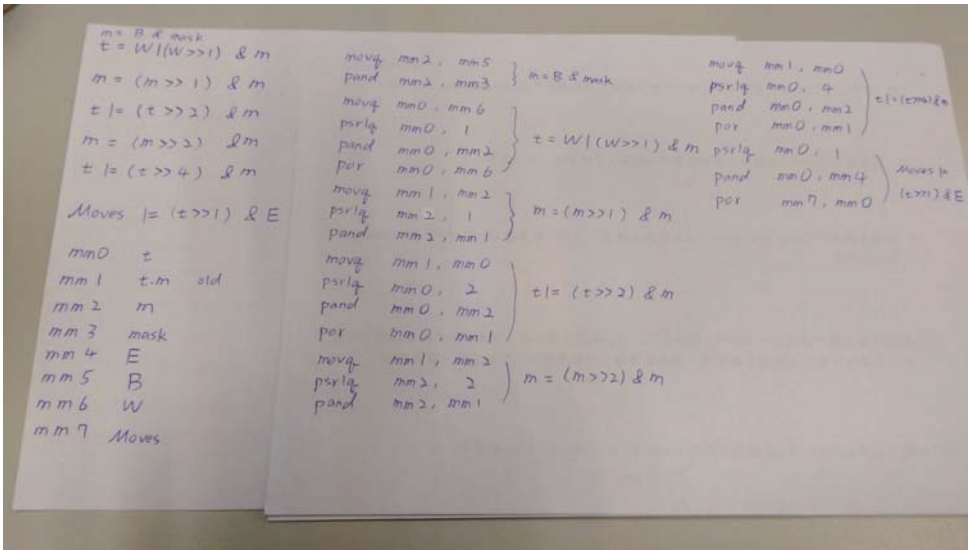

	Operator			Extra variables
	&	|	>>	
Sequential	7	6	7	t
Hybrid	6	4	6	t, m
Kogge-Stone	7	4	6	t, m

Assembly: MMX

- Generate actions in CPU without cache



Assembly: AVX2

組合語言的用書的問題

me
to [redacted]

[redacted]老師你好：
首先得謝謝老師願意開放名額來讓我修課。上個學期在林老師開的人工智慧課程中，為了加速搜尋演算速度，以及為了減少走步時反覆從記憶體要值次數，而研究了MMX指令。
最近，在與實驗室的學長們交流當中得知了AVX的存在。但是一直無法在intel網站上找到其規格書，後來改往尋找教學書(如附檔)。想詢問[redacted]老師，這本書適合學習AVX嗎?

...

bok%3A978-1-4842-0064-3.pdf
PDF

[redacted]同學:

我認為你想學習的東西，在我的組合語言課，都學不到。

我的課連浮點運算都不會上到，更別提MMX和SSE。

你說的AVX，我還是第一次聽到。

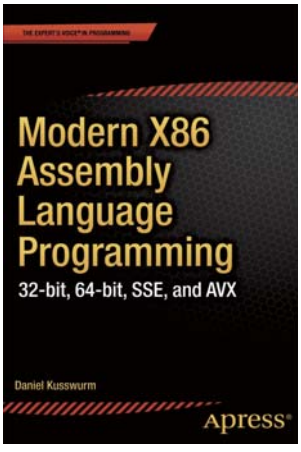
我自己的應用是在硬體的控制，用的都是基本的指令，浮點運算都用不到。

因此，除了因在計算機結構課程中有簡單的認識外，我可以說不了解。

我們的同學對於基本的組合語言指令都無法搞清楚，那些高級的指令實在沒有時間教到。

你若已經達到這個程度，我覺得來上我的組合語言課只是浪費時間而已。

Learning…



685 pages

3603 pages

Kogge-Stone with AVX2

Compute 4 directions at the same time

What is AVX2?

Advanced Vector Extensions (AVX)

AVX are extensions to the x86 instruction set architecture for microprocessors from Intel and AMD.

For example,

11 + 43 = 54

63 + 36 = 99

1163 + 4336 = 5499

Kogge-Stone with AVX2

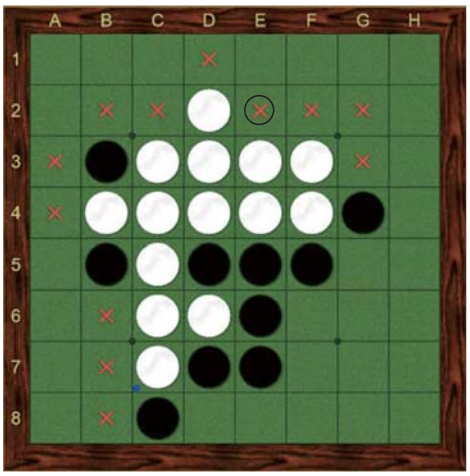
Compute 4 directions at the same time

```
mask = (0x007e7e7e7e7e7e00, 0x007e7e7e7e7e7e00,
        0x00ffffffffffff00, 0x7e7e7e7e7e7e7e7e)
shift1 = ( 9,  7,  8, 1)
shift2 = (18, 14, 16, 2)
shift4 = (36, 28, 32, 4)
empty = ~(black | white)
black = (black, black, black, black)
white = (white, white, white, white)
m = white & mask
t = black | ((black >> shift1) & m)
m =  (m >> shift1) & m
t |= (t >> shift2) & m
m =  (m >> shift2) & m
t |= (t >> shift4) & m
actions |= ((t & white) >> shift1) & empty
```

x2 for << and >>

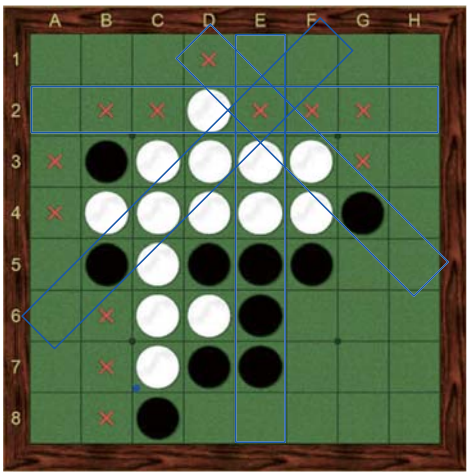
Reverse

Other othello programs



Reverse

Other othello programs



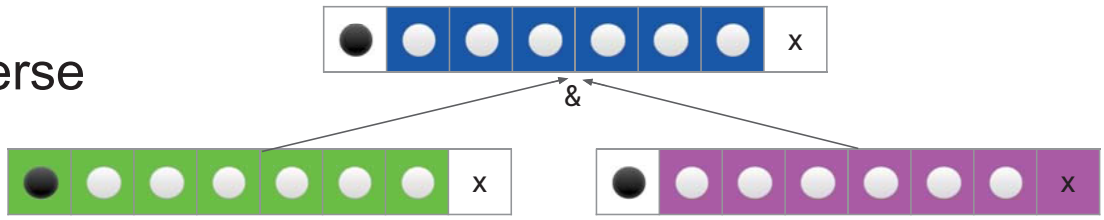
Look up a table: 64 * 4 * 3^8

Reverse


```
mask = 0x7e7e7e7e7e7e7e7e
m = white & mask
t = black | ((black >> 1) & m)
mr = (mr>> 1) & mr
t |= (t >> 2) & mr
mr = (mr>> 2) & mr
t |= (t >> 4) & mr
reverse |= t & a
```

```
a = action | ((action << 1) & m)
ml = (ml<< 1) & ml
a |= (a << 2) & ml
ml = (ml<< 2) & ml
a |= (a << 4) & ml
```

Reverse




```
mask = 0x7e7e7e7e7e7e7e7e
m = white & mask
t = black | ((black >> 1) & m)
mr = (mr>> 1) & mr
t |= (t >> 2) & mr
mr = (mr>> 2) & mr
t |= (t >> 4) & mr
reverse |= t & a
```

```
a = action | ((action << 1) & m)
ml = (ml<< 1) & ml
a |= (a << 2) & ml
ml = (ml<< 2) & ml
a |= (a << 4) & ml
```


Speed test

Method		**Speed** (nodes/s)
WZebra、Edax、Logistello		6,000,000 ~ 20,000,000
Normal	Sequential	58,783,372
	Hybrid	71,008,942
	Kogge-Stone	74,270,662
AVX2	Sequential	107,426,824
	Hybrid	130,786,882
	Kogge-Stone	139,810,153

Outline

1. Introduction
2. Action generator
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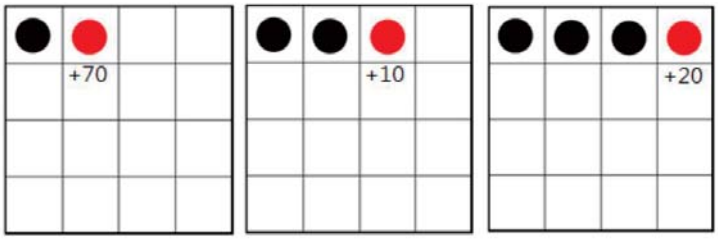
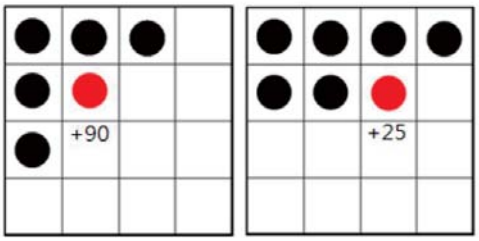
4. Search algorithm
5. Parallel search algorithm
6. Opening book
7. Conclusion

Position value + stability

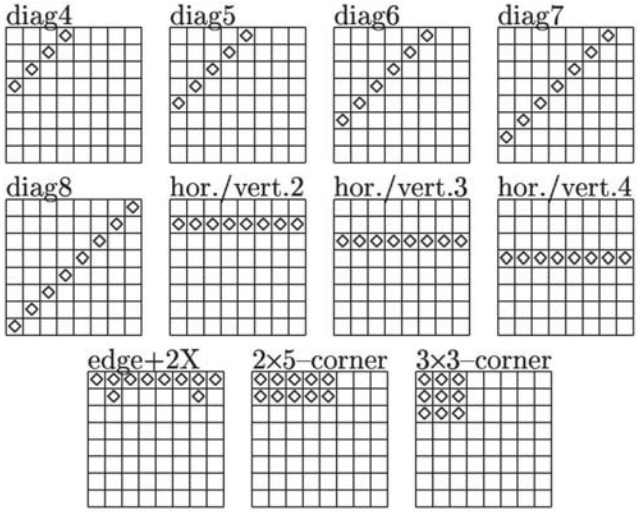
100	C -50	10	0				
	X -70	-5	-10				
		-10	-5				
			0				



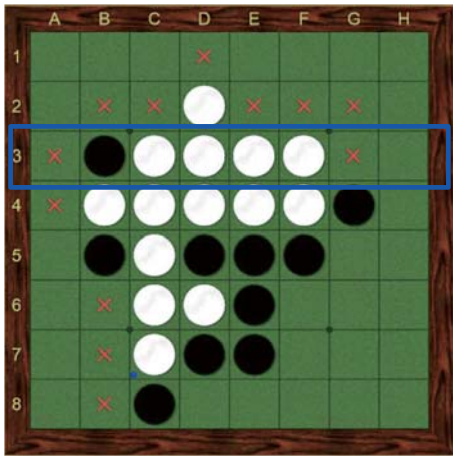


General Linear Evaluation Model (GLEM)

A pattern-based model



GLEM



$$(01222200)_3 = 1449$$

$$f_{p,i}(s) = \begin{cases} 1, & \text{if } s \text{ matches } p, i \text{ pattern} \\ 0, & otherwise \end{cases}$$

e.g. $f_{l3,1449}(s) = 1$

$$v(s) = \sum_{p \in P} \sum_{i=0}^{N_p} w_{p,i} f_{p,i}(s)$$

TD Learning: $v(s) = v(s) + \alpha\left(r + \gamma v(s') - v(s)\right)$

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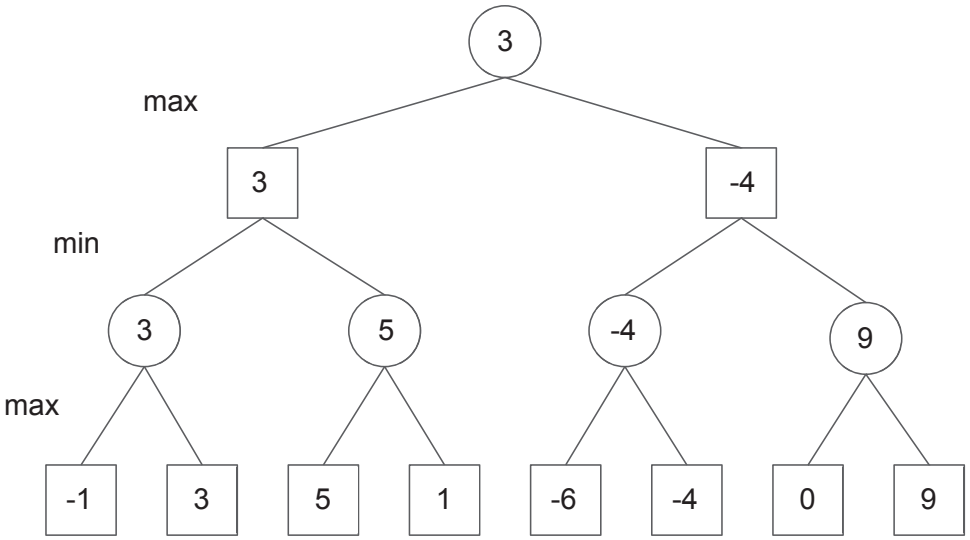
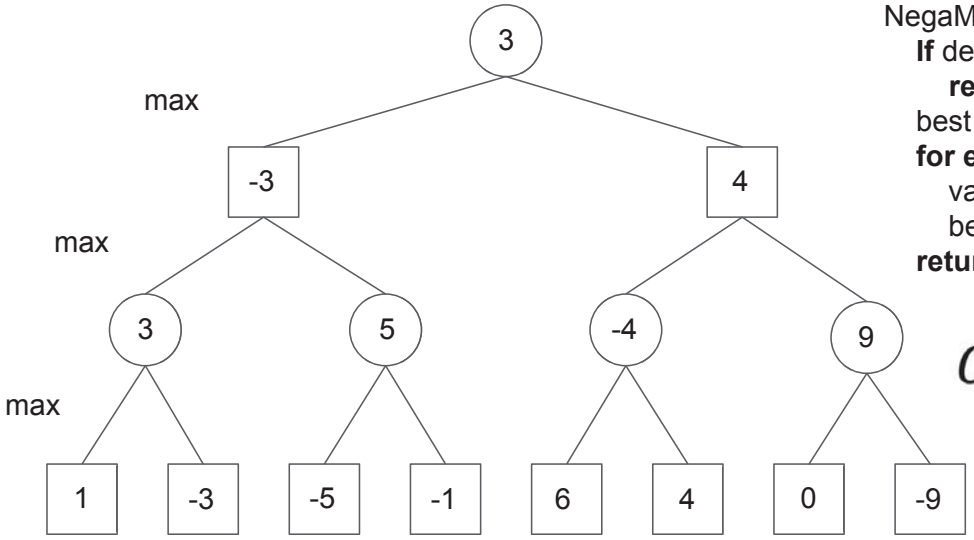
Minimax



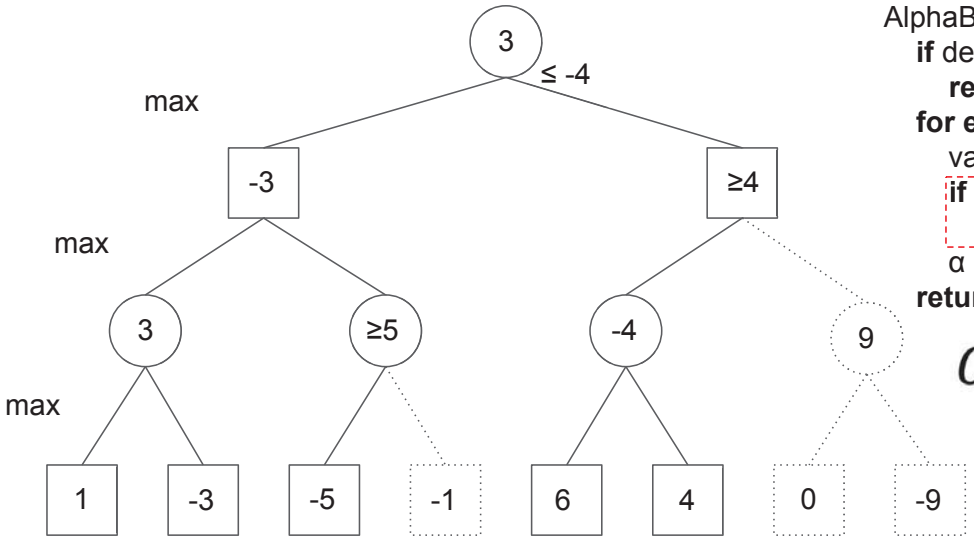
NegaMax




```
NegaMax(state, depth)
    If depth == 0 then
        return evaluate(state)
    best = -∞
    for each child of state
        value = -NegaMax(child, depth-1)
        best = max(best, value)
    return best
```

$$O(b^d)$$

Alpha-Beta pruning




```
AlphaBeta(state, α, β, depth)
    if depth == 0 then
        return evaluate(state)
    for each child of state
        value = -AlphaBeta(child, -β, -α, depth-1)
        if value >= β then
            return value
        α = max(α, value)
    return α
```

$$O(b^d) \rightarrow O(b^{d/2})$$

Move ordering

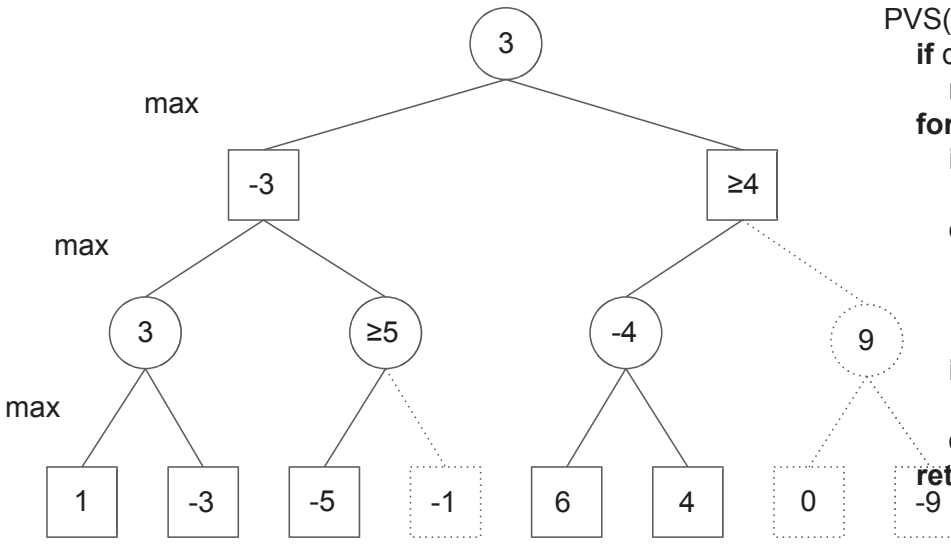
1. Ordering in advance

```
[A1, A8, H1, H8,
 C1, F1, H3, H6, F8, C8, A6, A3,
 C3, F3, F6, C6,
 D1, E1, H4, H5, E8, D8, A5, A4,
 D3, E3, F4, F5, E6, D6, C5, C4,
 D2, E2, G4, G5, E7, D7, B5, B4,
 C2, F2, G3, G6, F7, C7, B6, B3,
 B1, G1, H2, H7, G8, B8, A7, A2,
 B2, G2, G7, B7]
```

2. Previous search result

	A	B	C	D	E	F	G	H
1	1	8	2	4				
2		9	7	6				
3			3	5				
4								
5								
6								
7								
8								

Principal Variation Search (like NegaScout)




```
PVS(state, α, β, depth)
  if depth == 0 then
    return evaluate(state)
  for each child of state
    if child is first child then
      value = -PVS(child, -β, -α, depth-1)
    else                                  null window
      value = -PVS(child, -α-1, -α, depth-1)
      if α < value < β then
        value = -PVS(child, -β, -α, depth-1)
    if value >= β then
      return value
    α = max(α, value)
  return α
```

Narrow window

Score

- #winner - #loser

  Final score: -64, -63, …, -2, -1, 0, 1, 2, …, 63, 64 (integer)

  [α, β] : [-64, 64]

  [α, β] : [-1, 1] get 1 → [0, 2] or [1, 3]?

- #winner + #empty - #loser

  Final score: -64, -62, …, -4, -2, 0, 2, 4, …, 62, 64 (even number)

  [α, β] : [-1, 1] get 1 → [1, 3]...

Narrow window

Score

- #winner - #loser

  Final score: -64, -63, …, -2, -1, 0, 1, 2, …, 63, 64 (integer)

  ~~[α, β] : [-64, 64]~~

  [α, β] : [-1, 1] get 1 → [0, 2] or [1, 3]?

- #winner + #empty - #loser

  Final score: -64, -62, …, -4, -2, 0, 2, 4, …, 62, 64 (even number)

  [α, β] : [-1, 1] get 1 → [1, 3]...

Narrow window

Score

- #winner - #loser

  Final score: -64, -63, …, -2, -1, 0, 1, 2, …, 63, 64 (integer)

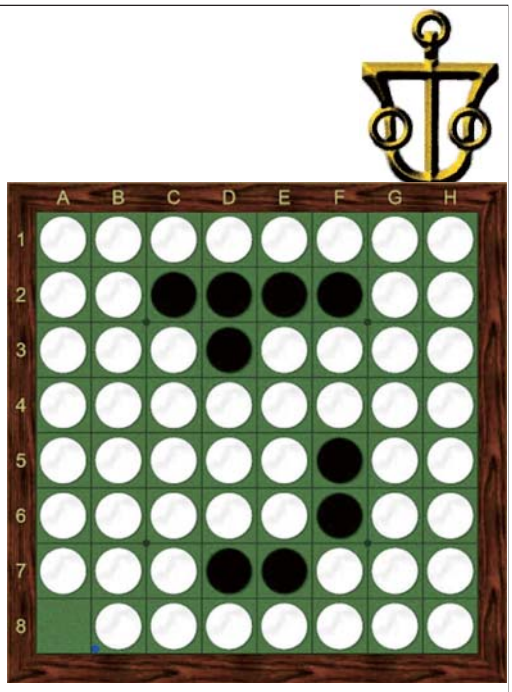
  ~~[α, β] : [-64, 64]~~

  [α, β] : [-1, 1] get 1 → [0, 2] or [1, 3]?

- #winner + #empty - #loser

  Final score: -64, -62, …, -4, -2, 0, 2, 4, …, 62, 64 (even number)

  [α, β] : [-1, 1] get 1 → [1, 3]...

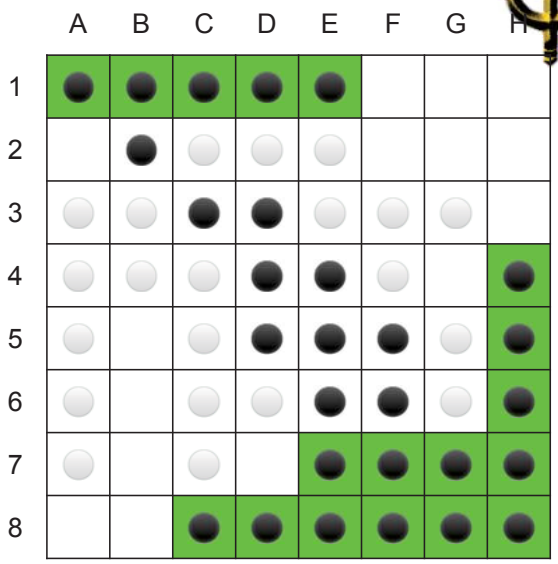


9-**54**

Stability

stability = #my_stability - (64 - #my_stability)

```
PVS(state, α, β, depth)
    if depth == 0 then
        return evaluate(state)
    stable_value = stability(state)
    if stable_value >= β then
        return stable_value
    for each child of state
        if child is first child then
            value = -PVS(child, -β, -α, depth-1)
        else
            value = -PVS(child, -α-1, -α, depth-1)
            if α < value < β then
                value = -PVS(child, -β, -α, depth-1)
        if value >= β then
            return value
        α = max(α, value)
    return α
```

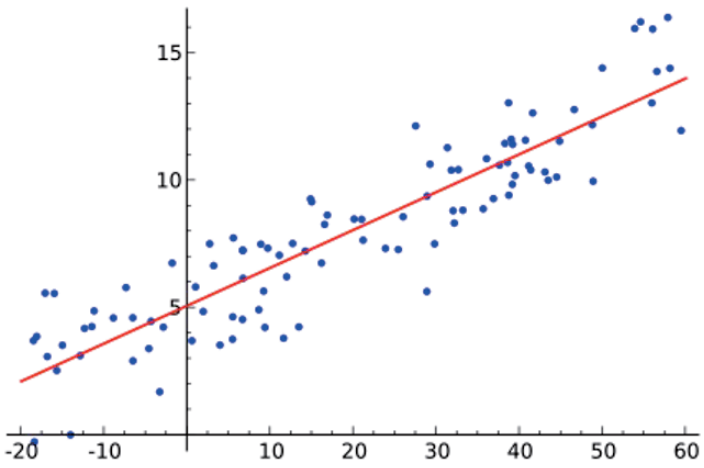


18 - 46 = -28

ProbCut

Just use a little math…

Linear Regression



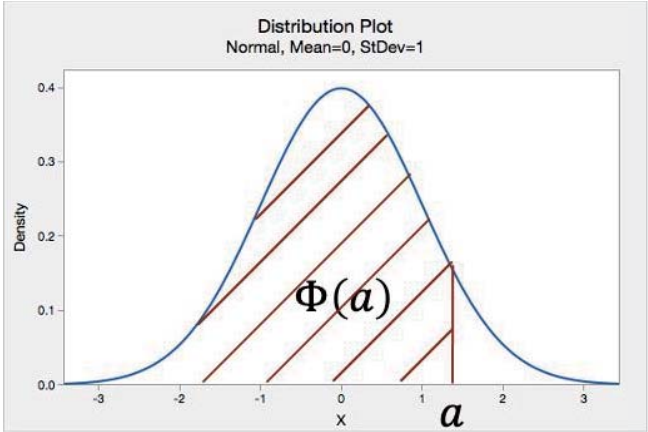
Normal distribution

PDF

$$\varphi(x) = \frac{1}{\sqrt{2\pi}} e^{-\frac{1}{2}x^2}$$

CDF

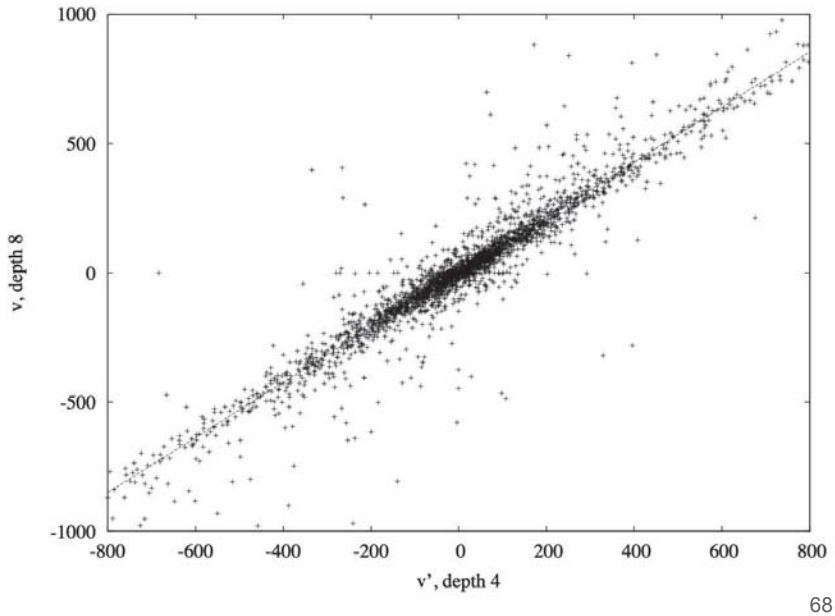
$$\Phi(x) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{x} e^{-\frac{1}{2}t^2} dt$$



Linear Regression with game

$$v = av' + b + e$$

$$e \sim \mathcal{N}(0, \sigma^2)$$
$$depth(v) > depth(v')$$



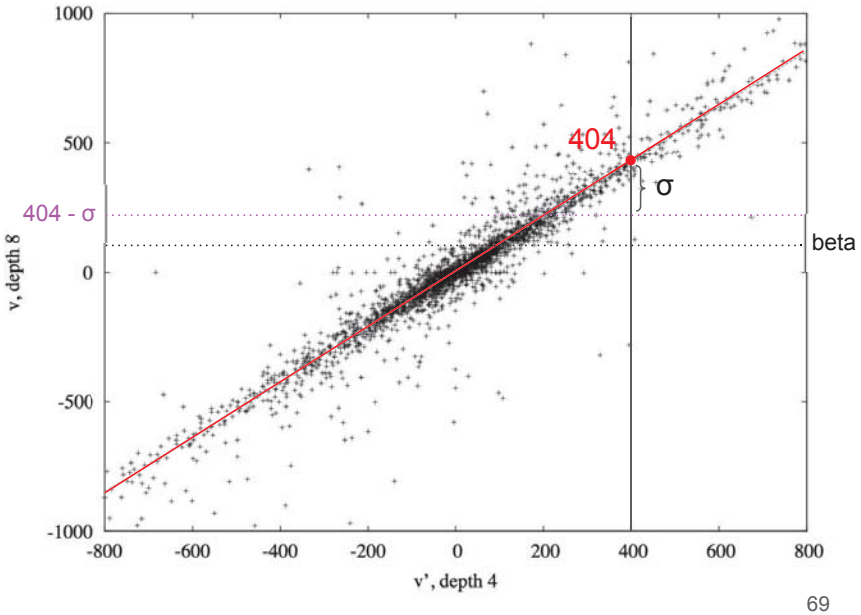
Beta cut

$$v = av' + b + e$$

$$e \sim \mathcal{N}(0, \sigma^2)$$
$$depth(v) > depth(v')$$

If we have
- v' = 400
- a = 1.01, b = 0, σ = 200
- beta = 100

Then v = 404 + e



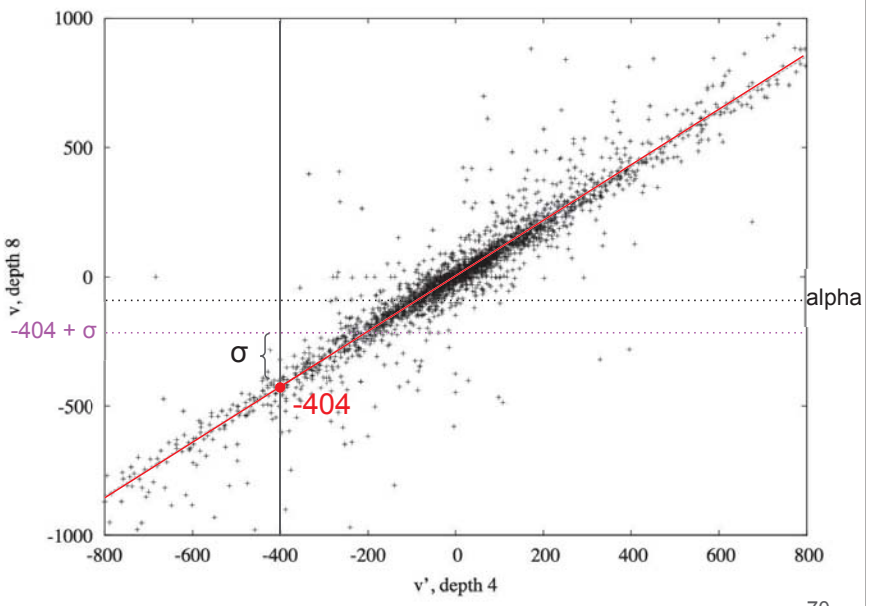
Alpha cut

$$v = av' + b + e$$

$$e \sim \mathcal{N}(0, \sigma^2)$$
$$depth(v) > depth(v')$$

If we have
- v' = -400
- a = 1.01, b = 0, σ = 200
- alpha = -100

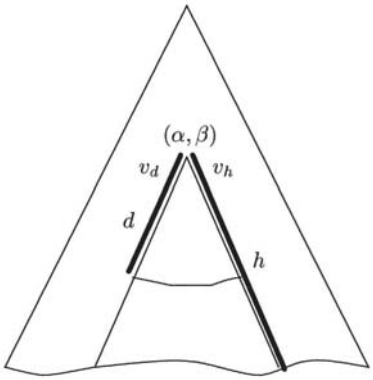
Then v = -404 + e



ProbCut

- $v_h \geq \beta$ // beta cut
- $\Leftrightarrow a \times v_d + b + e \geq \beta$
- $\Leftrightarrow (a \times v_d + b - \beta)/\sigma \geq -e/\sigma$
- $\Leftrightarrow (a \times v_d + b - \beta)/\sigma \geq \Phi^{-1}(p)$
- $\Leftrightarrow v_d \geq (\Phi^{-1}(p) \times \sigma + \beta - b)/a$

- $v_h \leq \alpha$ // alpha cut
- $\Leftrightarrow v_d \leq (-\Phi^{-1}(p) \times \sigma + \alpha - b)/a$



ProbCut pseudocode

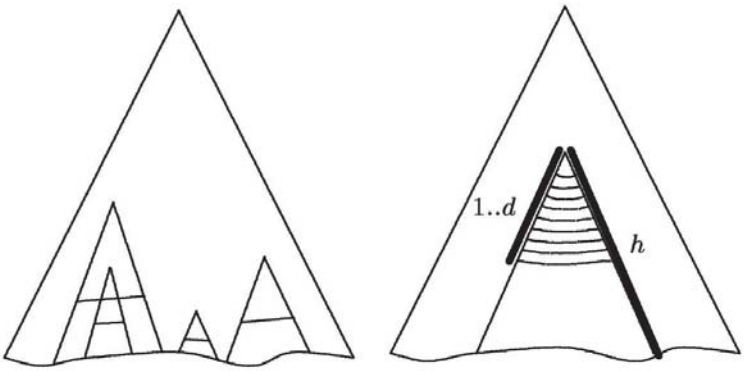
```
int PC(int α, int β, int depth) {
    const float T = 1.5;
    const int DP = 4;
    const int D = 8;

    if (depth == 0) return evaluate();
    if (depth == D) {
        int bound;
        bound = round((T*σ+β-b)/a);
        if (PC(bound-1, bound, DP) >= bound)
            return β;
        bound = round((-T*σ+α-b)/a);
        if (PC(bound, bound+1, DP) <= bound)
            return α;
    }
    /* and then alpha-beta search */
    ...
}
```

Multi-ProbCut

Let's play ProbCut anywhere!

- Situation (occupy the corner?)
- Progression
- ProbCut depth



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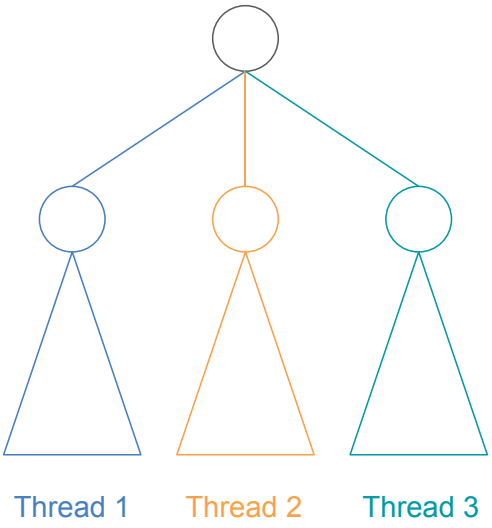
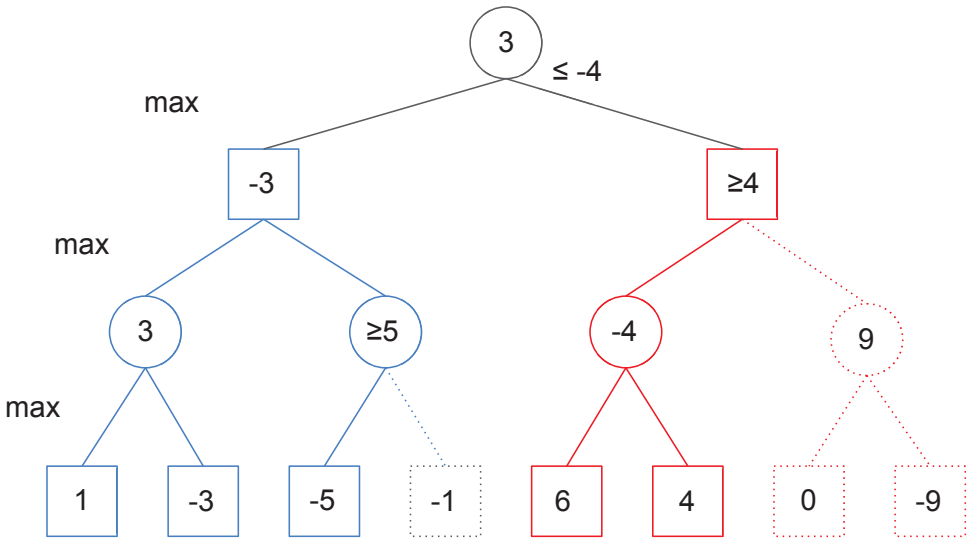
Root parallel

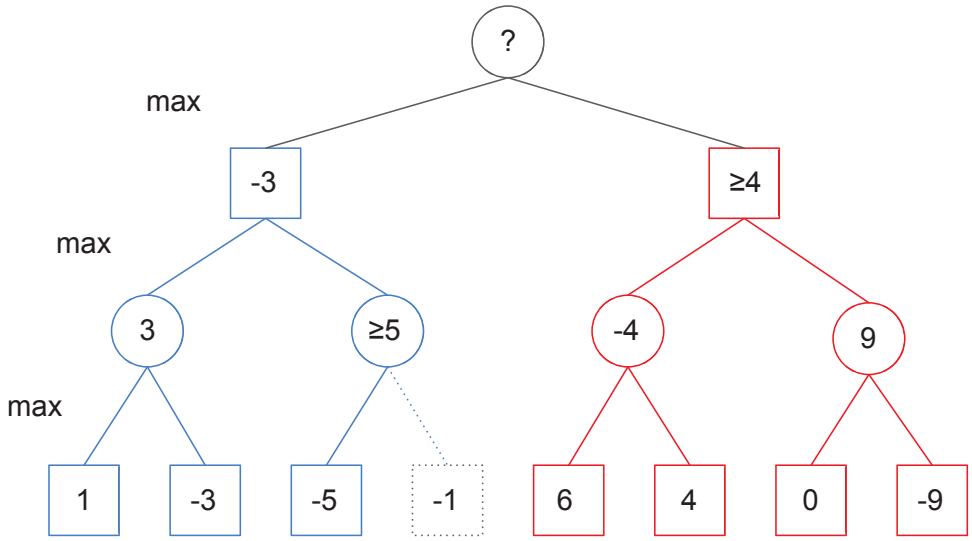


Root parallel issue



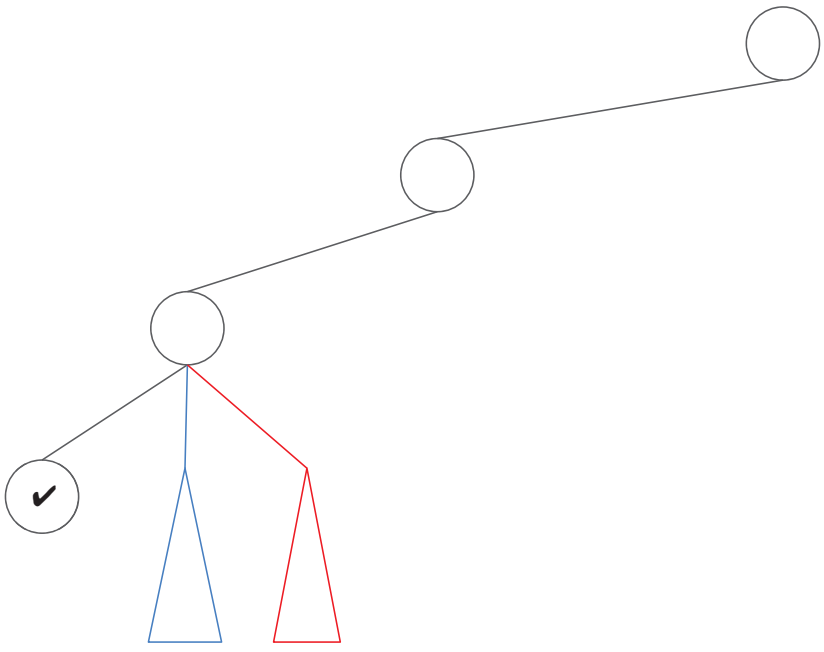
$$O\left(b^{d/2}\right) \rightarrow O\left(b^{d}\right)/n$$

Root parallel issue

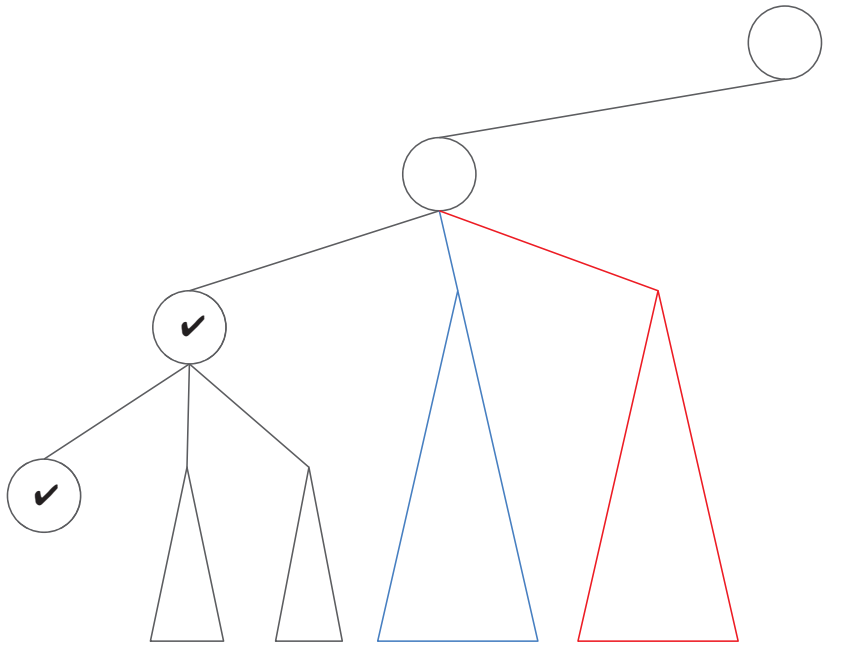


$$O(b^{d/2}) \rightarrow O(b^d)/n$$

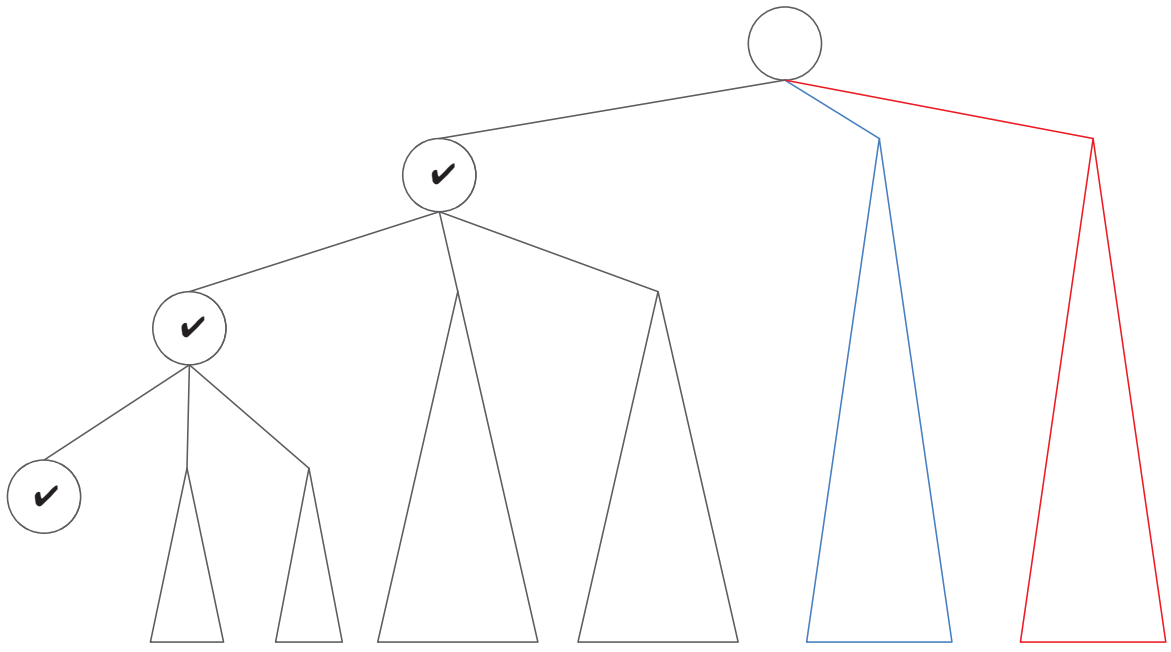
Principal Variation Splitting



Principal Variation Splitting



Principal Variation Splitting



Pseudocode (using openmp)

AlphaBeta → Principal Variation Splitting

```
AlphaBeta(state, α, β, depth)
    if depth == 0 then
        return evaluate(state)
    for each child of state
        value = -AlphaBeta(child, -β, -α, depth-1)
        if value >= β then
            return value
        α = max(α, value)
    return α
```

Command: g++ main.cpp -fopenmp

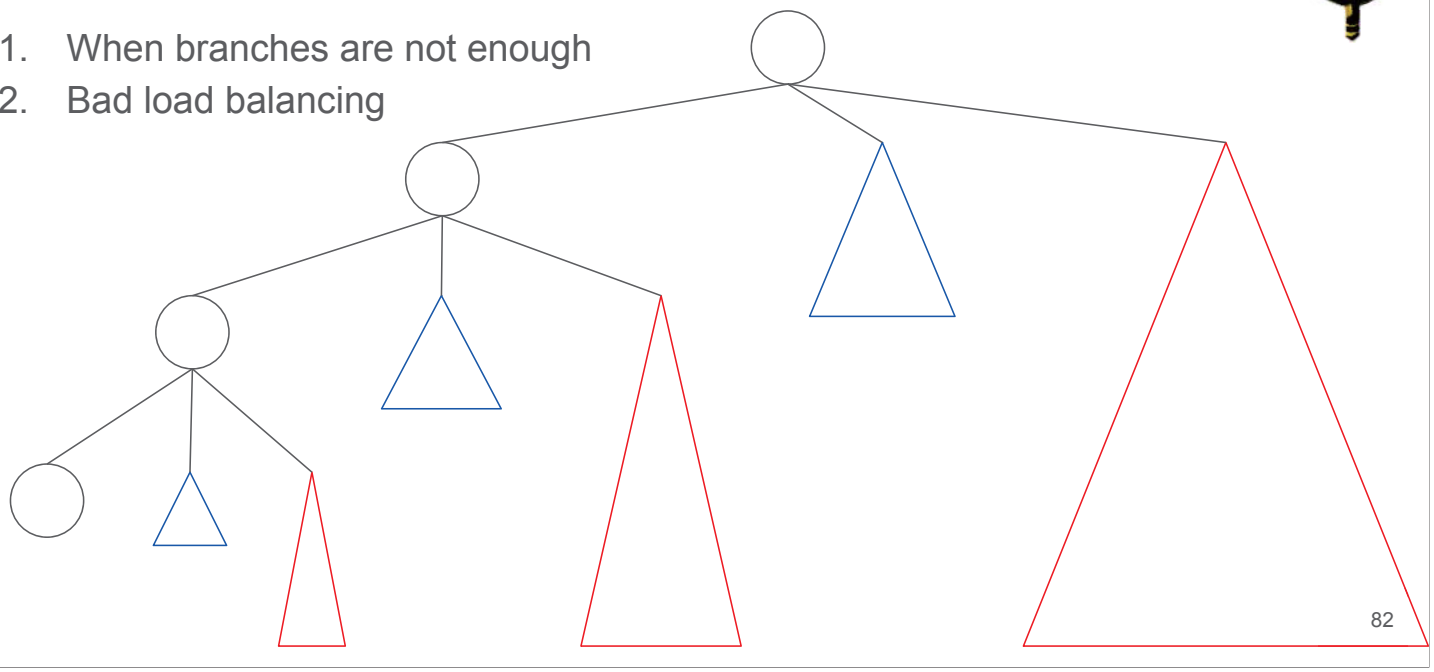
```
#include "omp.h"
PVS(state, α, β, depth)
    if depth == 0 then
        return evaluate(state)
    children = child_list(state)
    n = len(children)
    value = -PVS(children[0], -β, -α, depth-1)
    α = max(α, value)
    values = [None] * n

#pragma omp parallel for
    for (i = 1; i < n; i++) {
        values[i] = -AlphaBeta(children[i], -β, -α, depth-1)
    }

    for i = 1...n
        value = values[i]
        if value >= β then
            return value
        α = max(α, value)
    return α
```

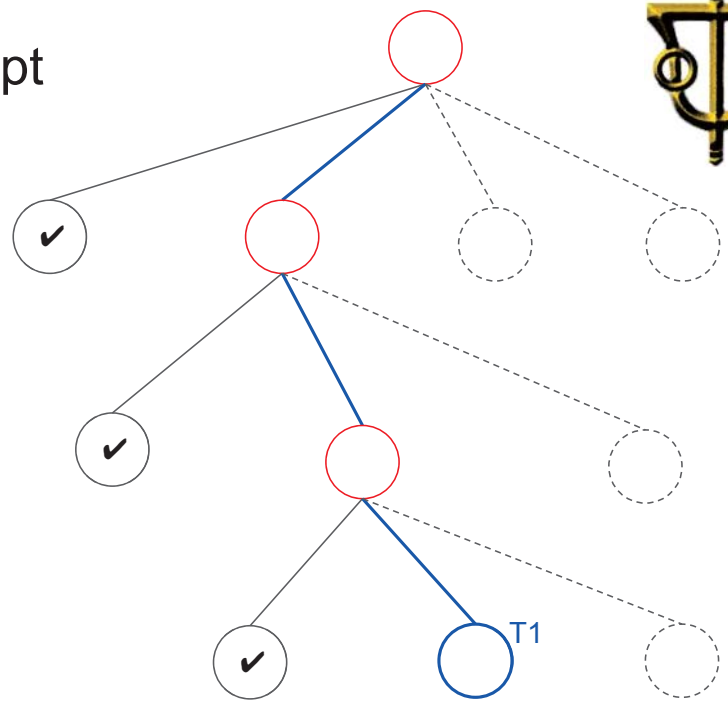

Principal Variation Splitting issue

1. When branches are not enough
2. Bad load balancing



Young Brothers Wait Concept

- Split point
  - The search for first child has been completed
- Highest split point
  - Idle processor finds the highest split point to search
- Example
  - Thread 1
  - Thread 2 (idle)
  - Thread 3 (idle)
  - Thread 4 (idle)



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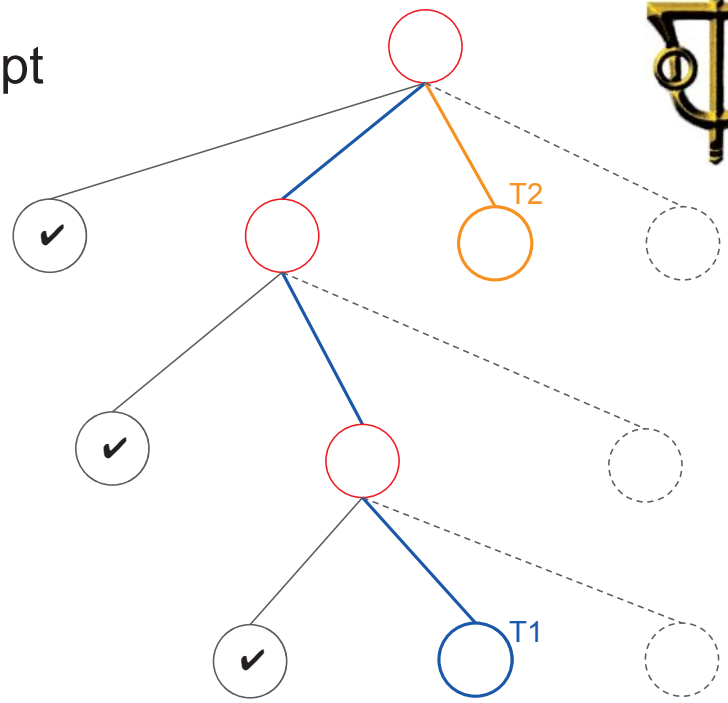

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- Split point
  - The search for first child has been completed
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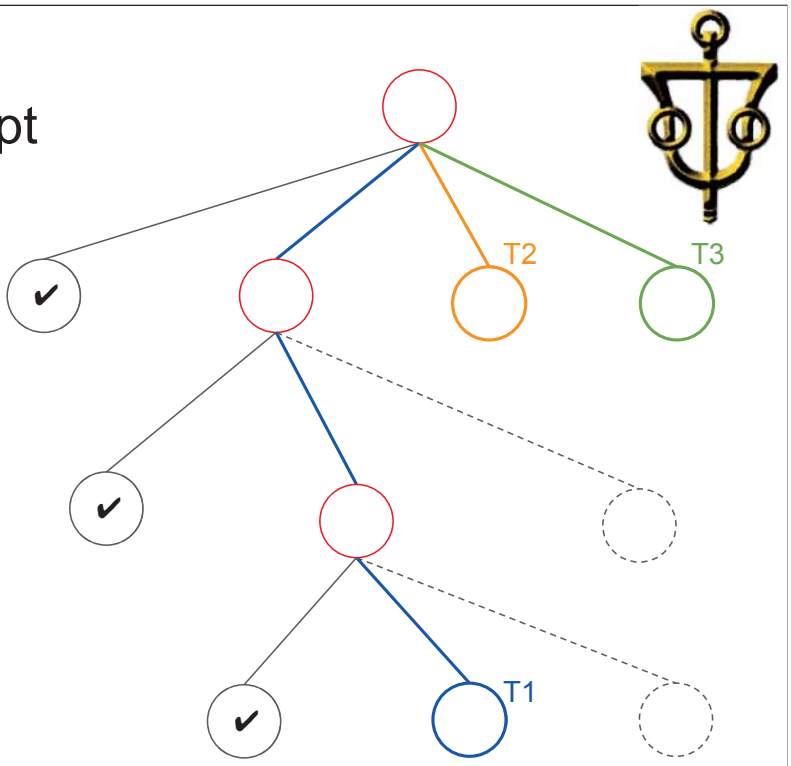
- Example
  - Thread 1
  - Thread 2
  - Thread 3
  - Thread 4 (idle)



Young Brothers Wait Concept

- Split point
  - The search for first child has been completed
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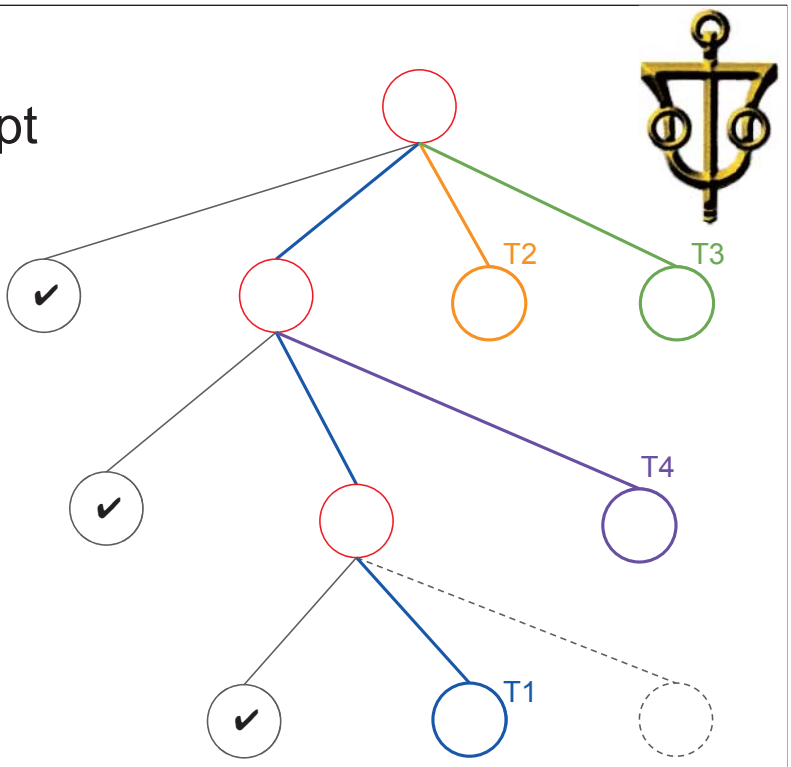
  - Idle processor finds the highest split point to search
- Example
  - Thread 1
  - Thread 2
  - Thread 3
  - Thread 4



Benchmark

Method	**Speed** (nodes/s)	**Ratio**
Single Thread	140,000,000	1.00
PVS (16 threads)	540,000,000	3.85
PVS (32 threads)	750,000,000	5.35
YBWC (16 threads)	1,250,000,000	8.92
YBWC (32 threads)	2,230,000,000	15.92

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5. Parallel search algorithm
6. Opening book
7. Conclusion

Opening book

Store the search result in advance

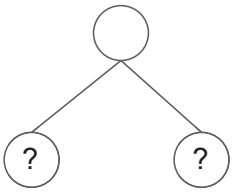
- Required
  - A Search Engine which can evaluate given states
    - GLEM + alphabeta
    - policy-value network + MCTS (i.e. AlphaZero)
- Optional
  - Expert games
  - Other strong engines

Opening book

Method

1. Select
   - Minimax, MCTS or Game Trajectory
2. Expand all children
3. Search for all children
4. Save

Opening book



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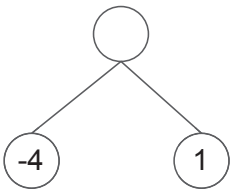

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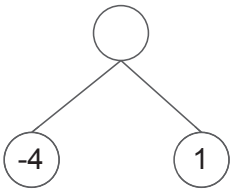

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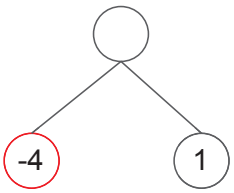

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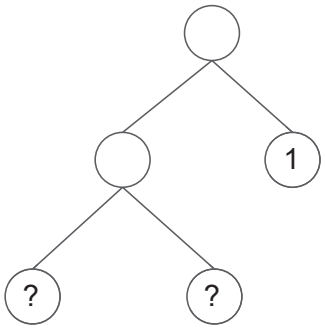

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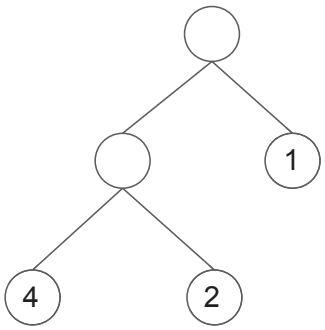

Opening book

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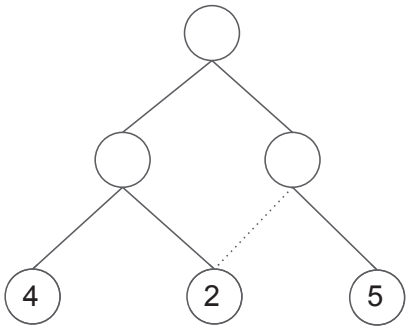

Opening book

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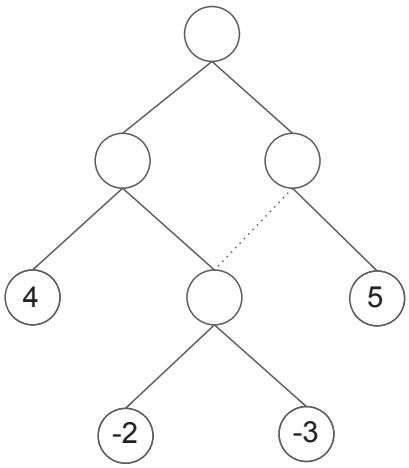
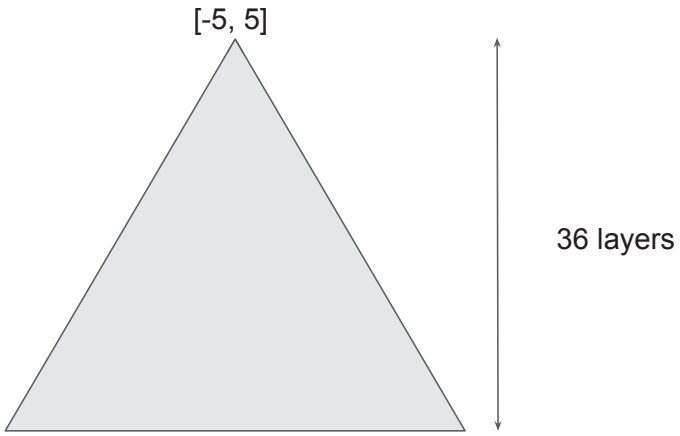


…

My big opening book

- Width: [-5, 5]
- Depth: 36
  - My program, Maverick, can search the remaining 24 layers of the game tree in 1 second.



Outline

1. Introduction
2. Action generator
3. Evaluation function
4. Search algorithm
5. Parallel search algorithm
6. Opening book
7. Conclusion

幫大家整理一下

- 走步生成
  - Kogge-Stone + AVX2：約140000000 nodes/s
- 估值函數
  - GLEM：單層網路，兼具效能的精確估 值
- 算法優化
  - Null window
  - Narrow window
  - MPC：基於數學統計結果，97.5%的信心來減少搜尋深度
- 多執行緒
  - 更好的附載平衡：Root Parallel ➔ PVS ➔ YBWC
- 開局庫
  - 大局觀不輸AlphaZero

Thanks for your attention