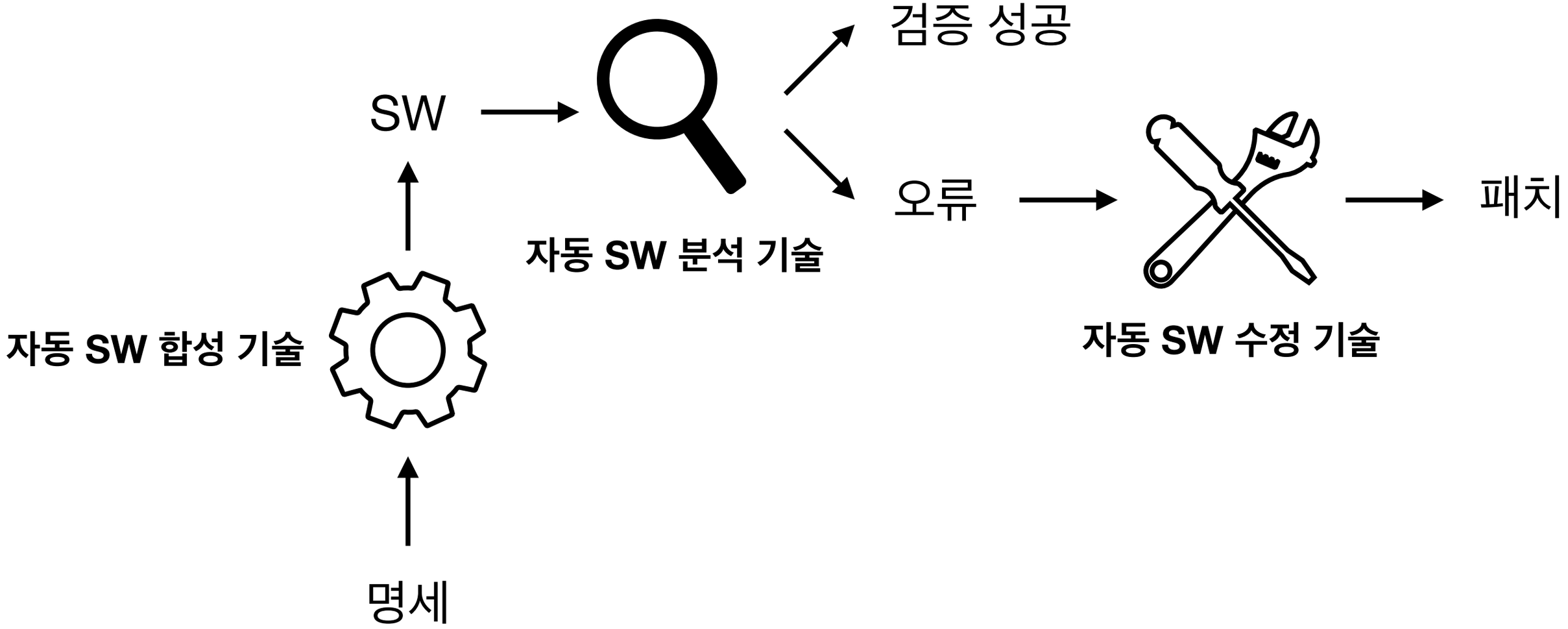
고려대 양자 프로그래밍 연구 소개

오학주
고려대학교 컴퓨터학과

02/03/2023@ERC Workshop

Our Research



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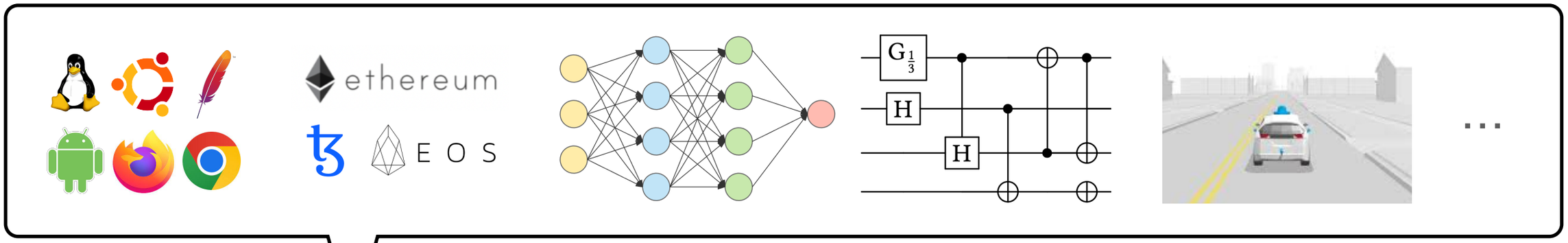
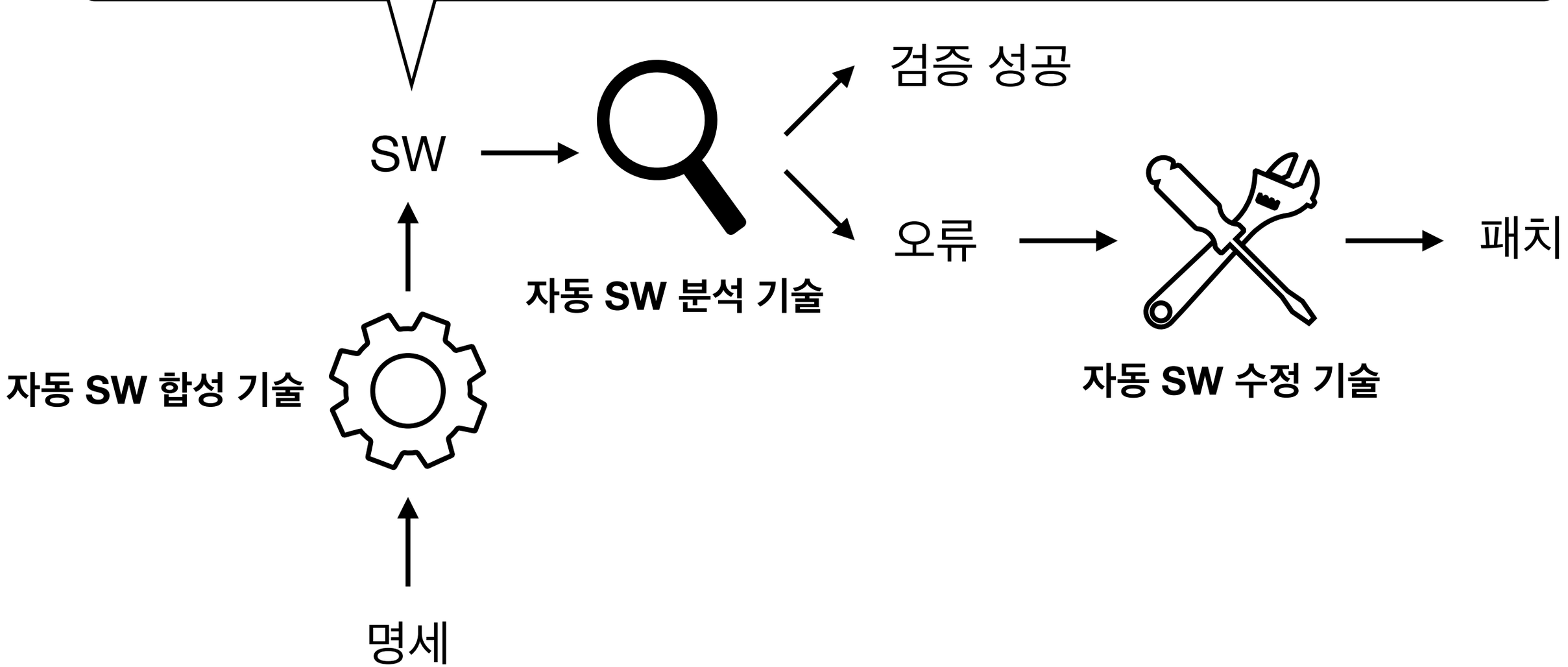
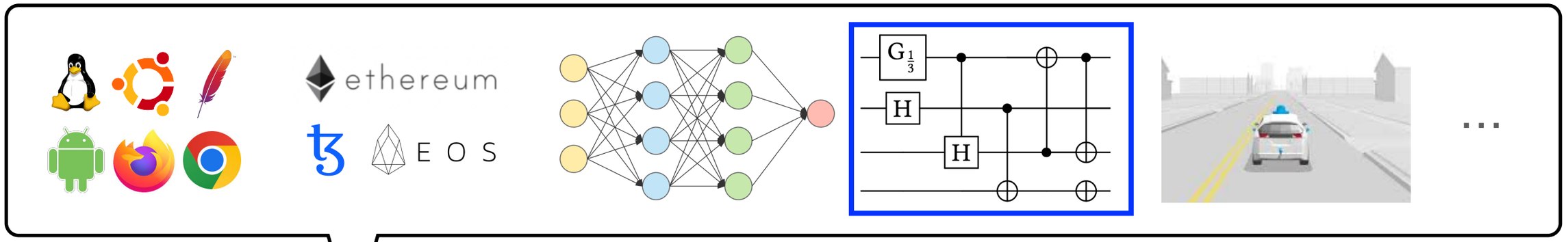
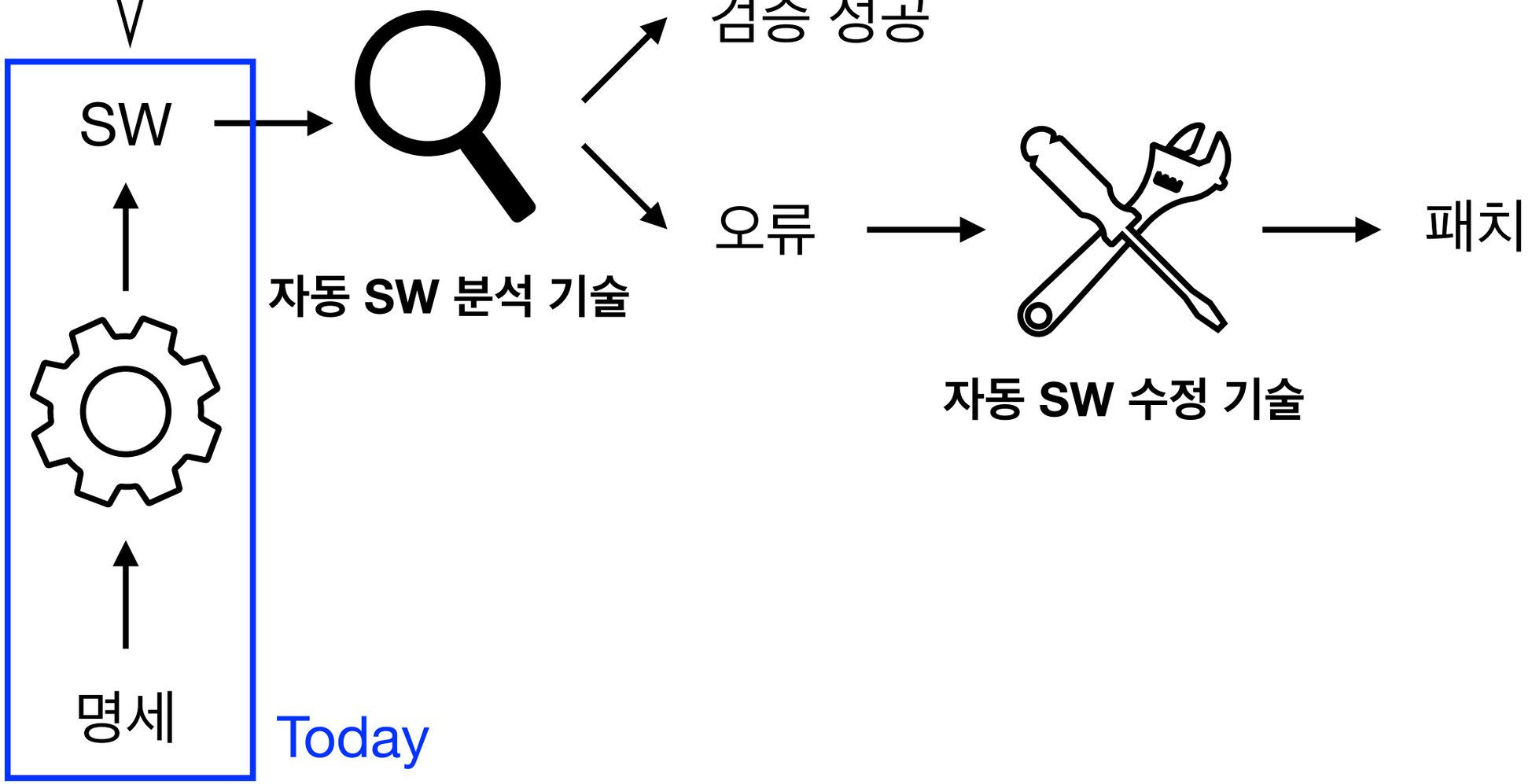


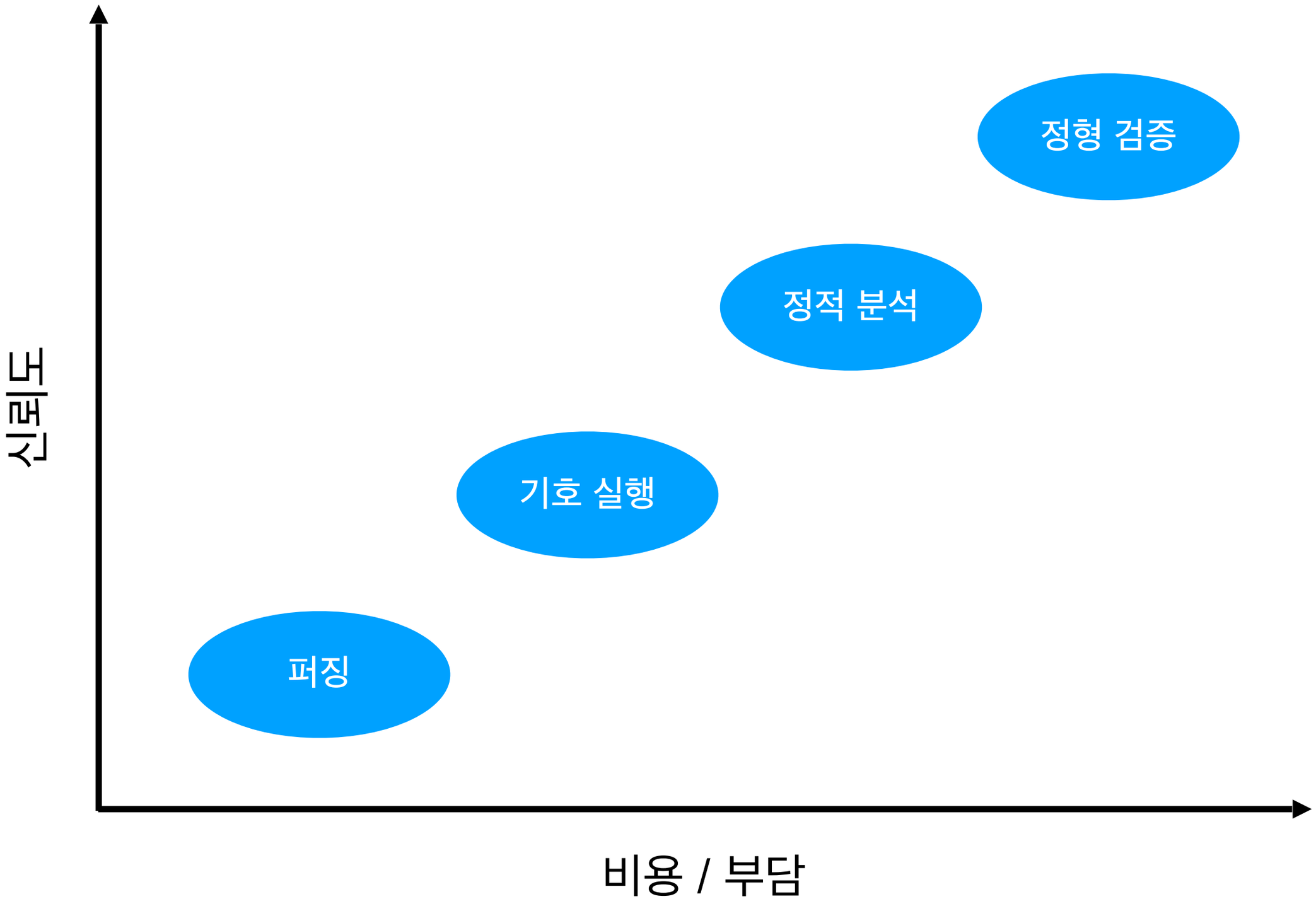


Our Research



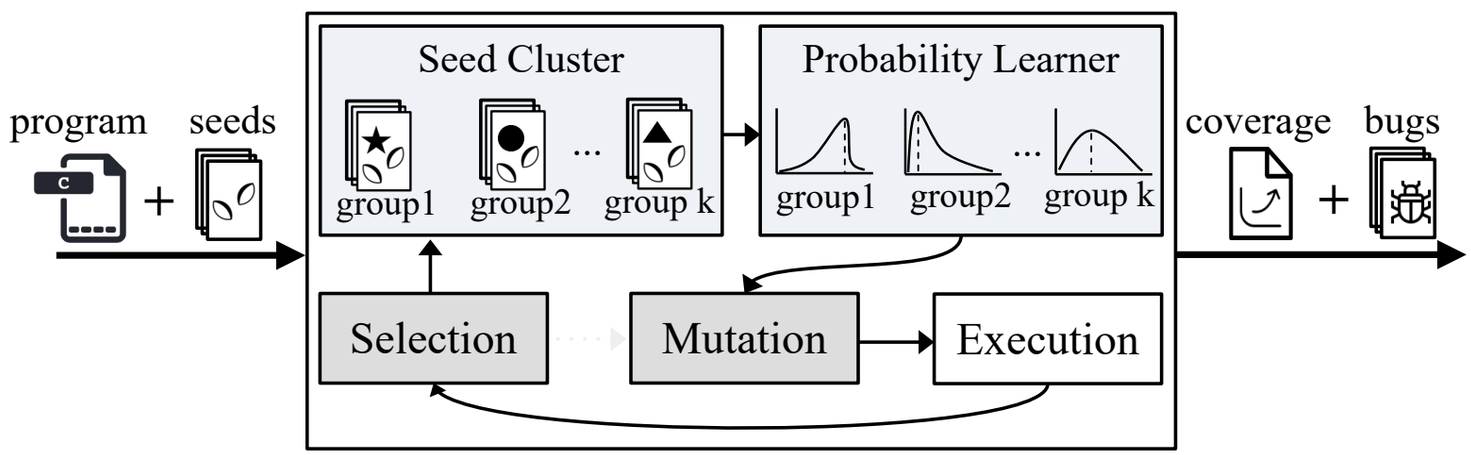


프로그램 분석



퍼징

- Seed-adaptive grey-box fuzzing [ICSE 2023]

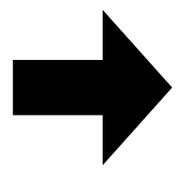


- Finding soundness bugs in SMT solvers [ICSE 2023]

기호 실행

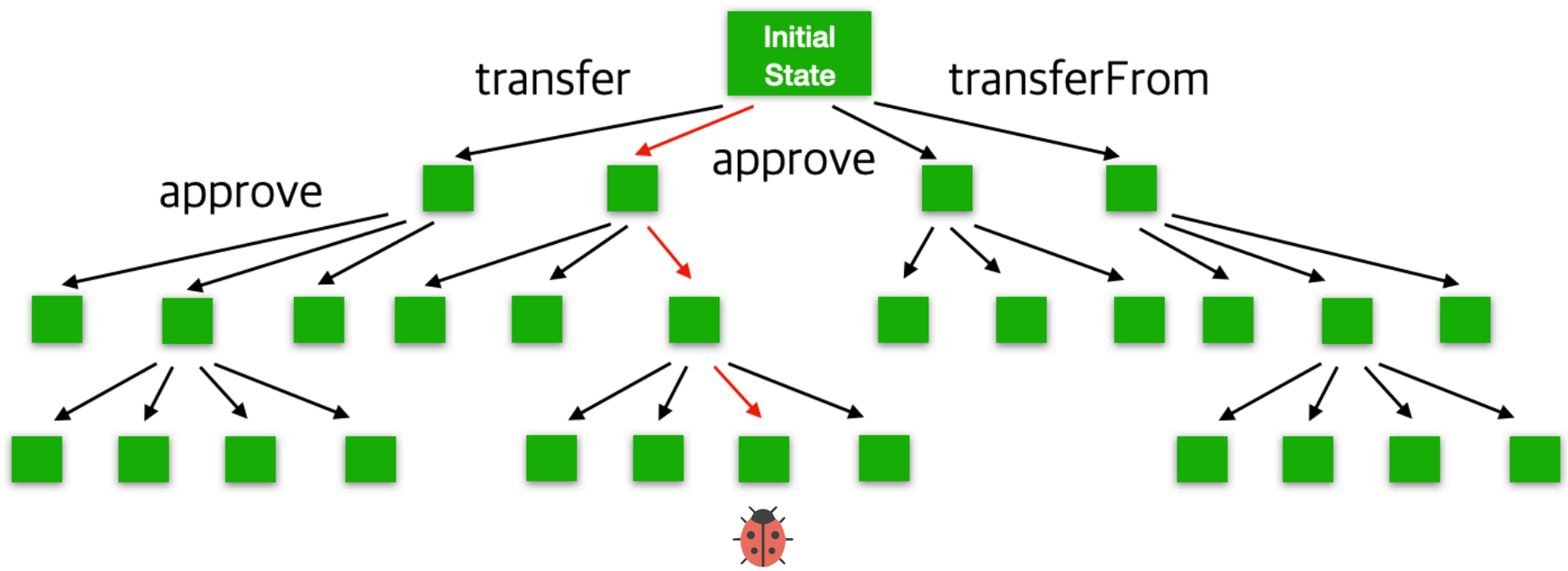
- Automated parameter configuration [ICSE 2022]

```
$ klee --simplify-sym-indices --max-memory=1000 --optimize
      --use-forked-solver --use-cex-cache --external-calls=all
      --max-sym-array-size=4096 --max-instruction-time=30s
      --max-time=60min --max-memory-inhibit=false
      --max-static-fork-pct=1 --max-static-solve-pct=1
      --max-static-cpfork-pct=1 --switch-type=internal
      --search=random-path --search=nurs:covnew
      --batch-instructions=10000 ./pgm.bc --sym-args 0 1 10
      --sym-args 0 2 2 --sym-files 1 8 --sym-stdin 8 --sym-stdout ...
```



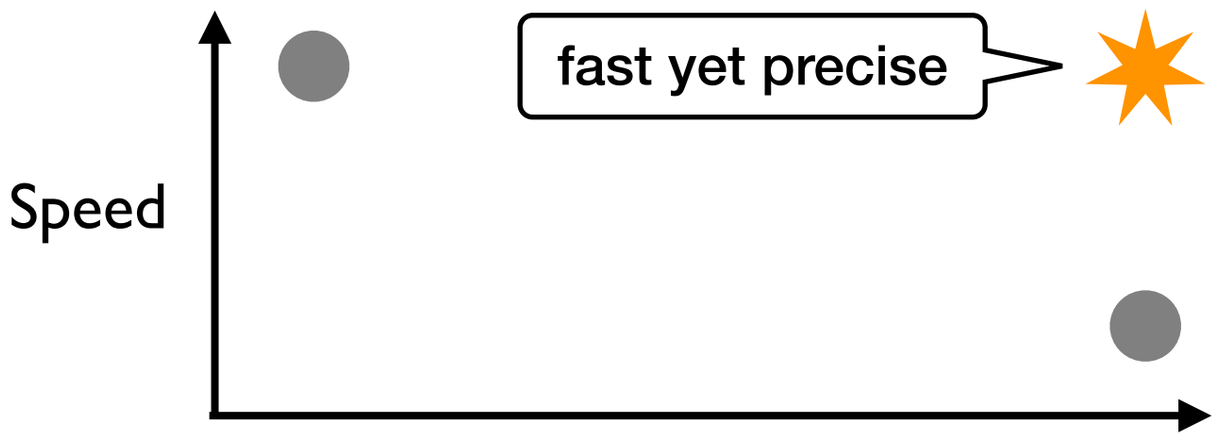
```
$ klee pgm.bc
```

- Language model-guided symbolic execution [Security 2021]

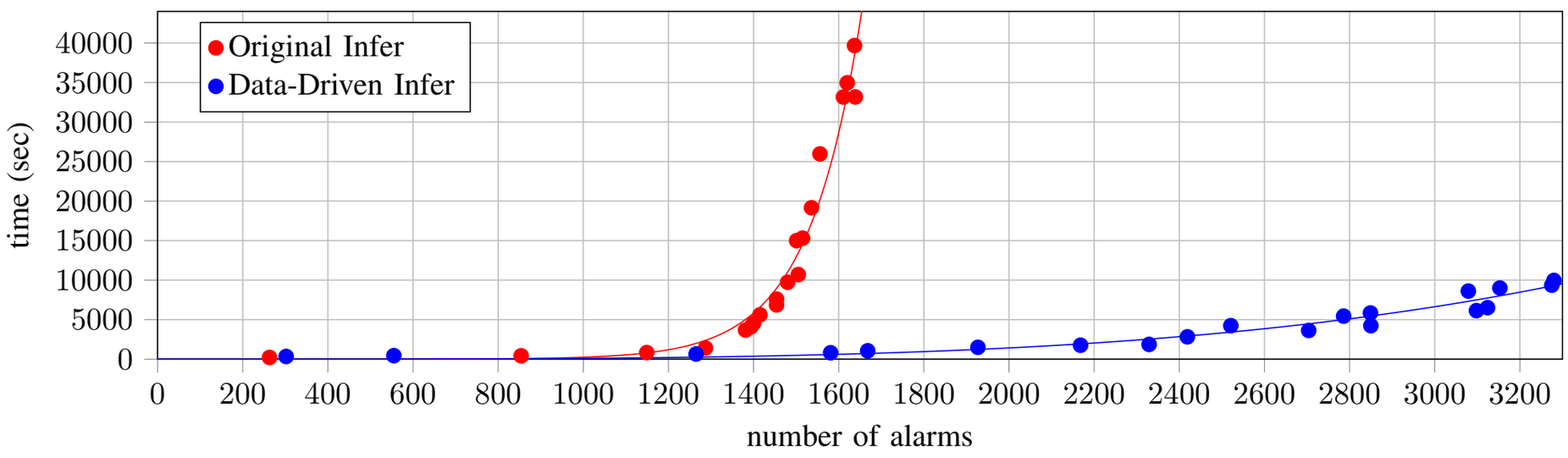


정적 분석

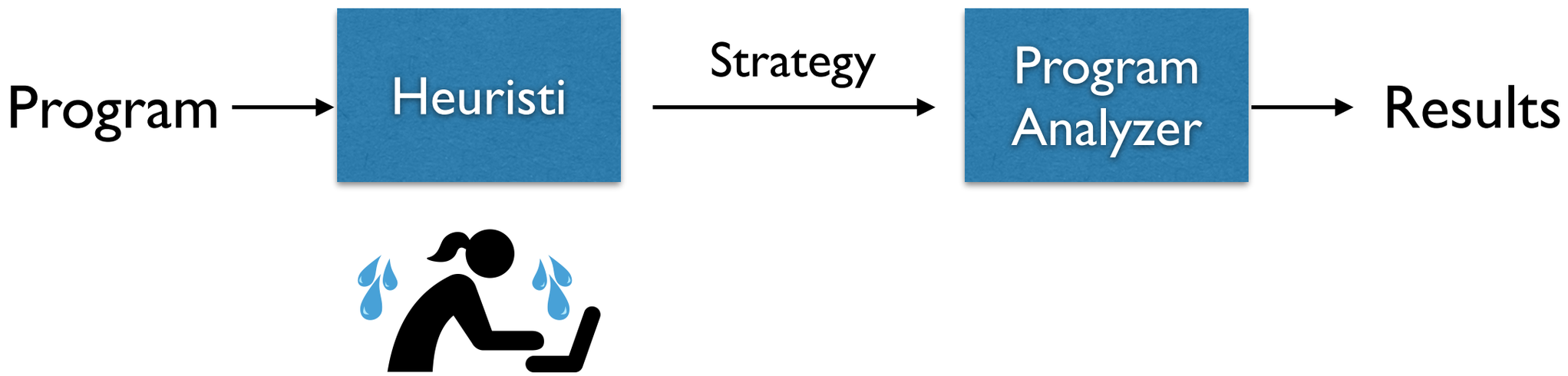
- Balancing precision & scalability of sound analysis [POPL 2022]



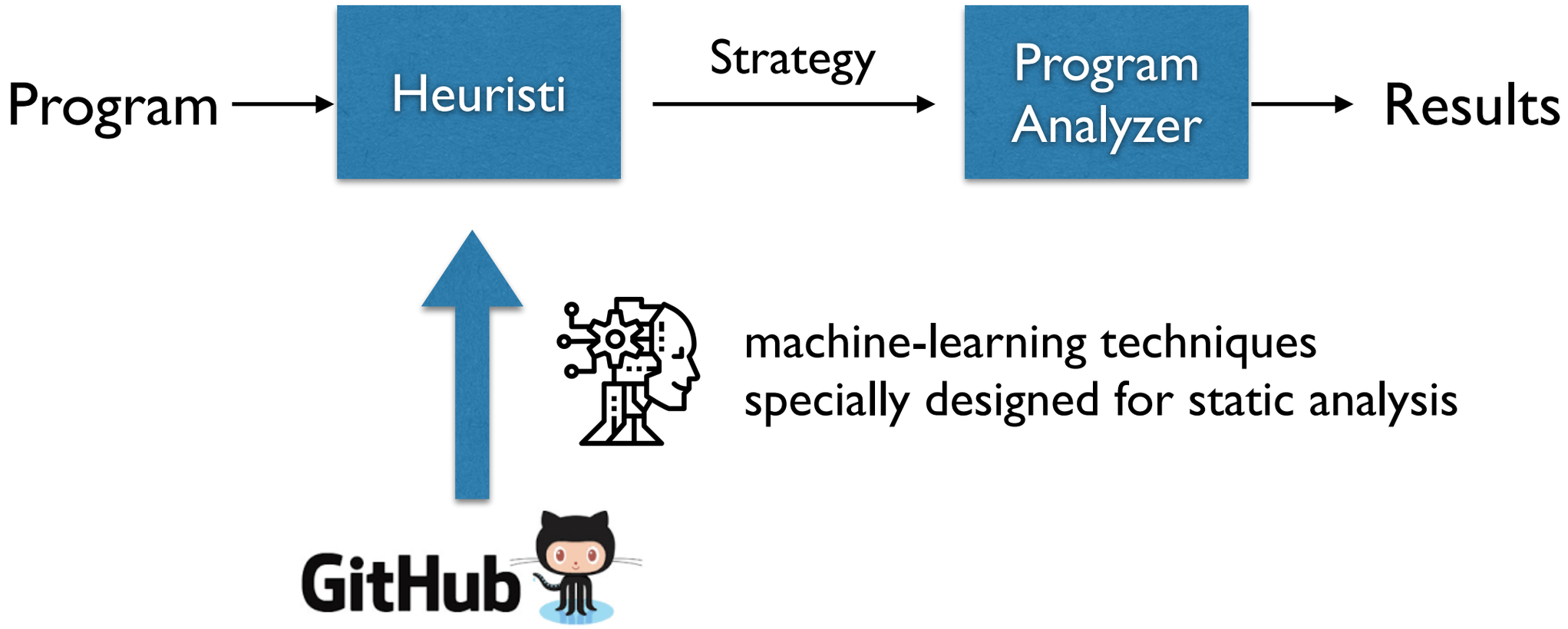
- Boosting unsound, path-sensitive bug-finders [ICSE 2023]



데이터 기반 프로그램 분석

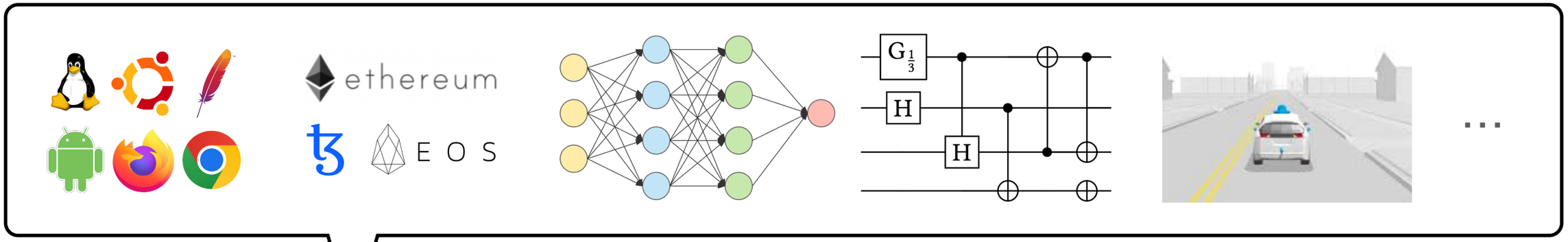


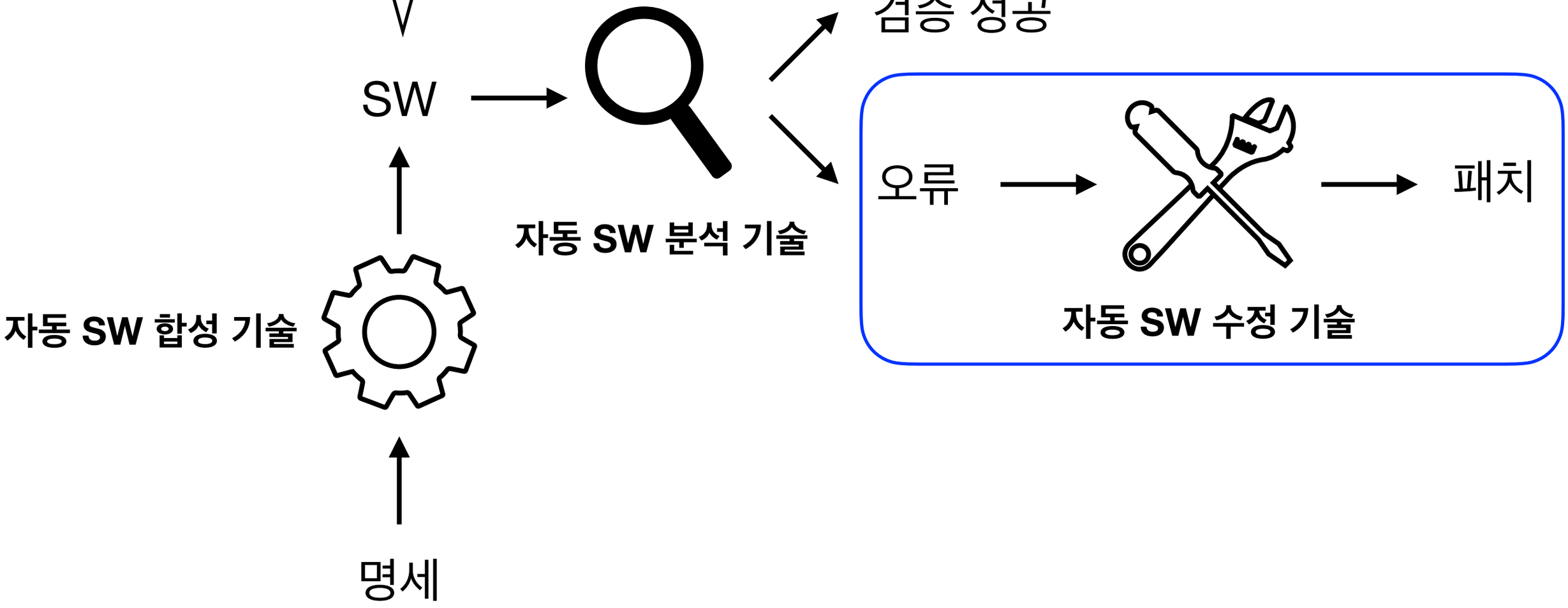
데이터 기반 프로그램 분석



- Automatic: little reliance on analysis designers
- Powerful: machine-tuning outperforms hand-tuning

Our Research





프로그램 자동 수정 연구

- 도메인 특화 기술
  - C/C++ 메모리 오류 자동 수정 [FSE 2018, ICSE 2020]
  - Java 널 포인터 오류 자동 수정 [ICSE 2022]
  - Python 타입 오류 자동 수정 [FSE 2022]
  - Solidity 보안 취약점 자동 수정 (in progress)
  - OCaml 프로그래밍 과제 자동 수정 [OOPSLA 2018/2019, FSE 2021]
- 일반 기술 (테스트 케이스 기반)

일반적 자동 수정 기술 현황

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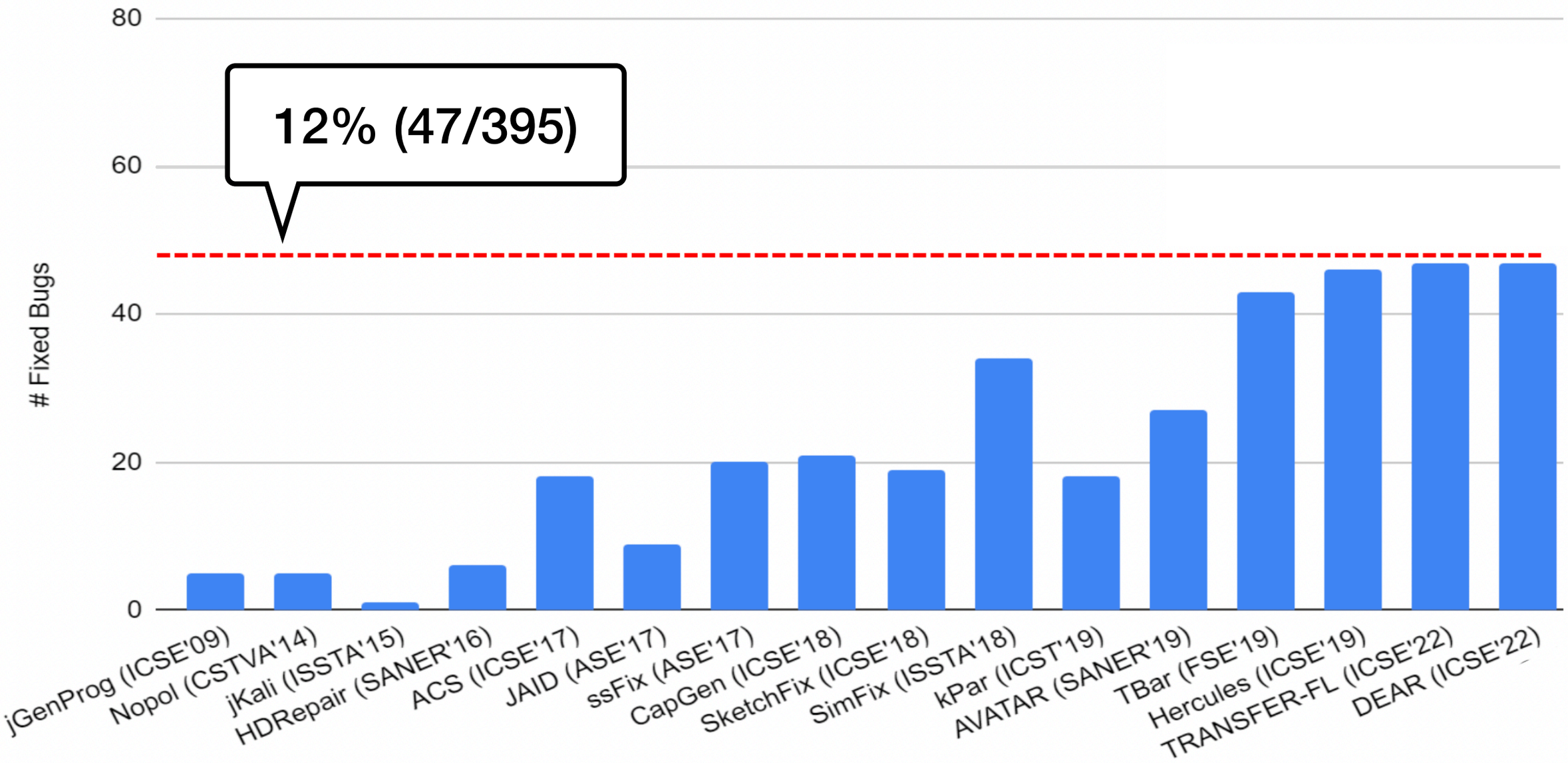
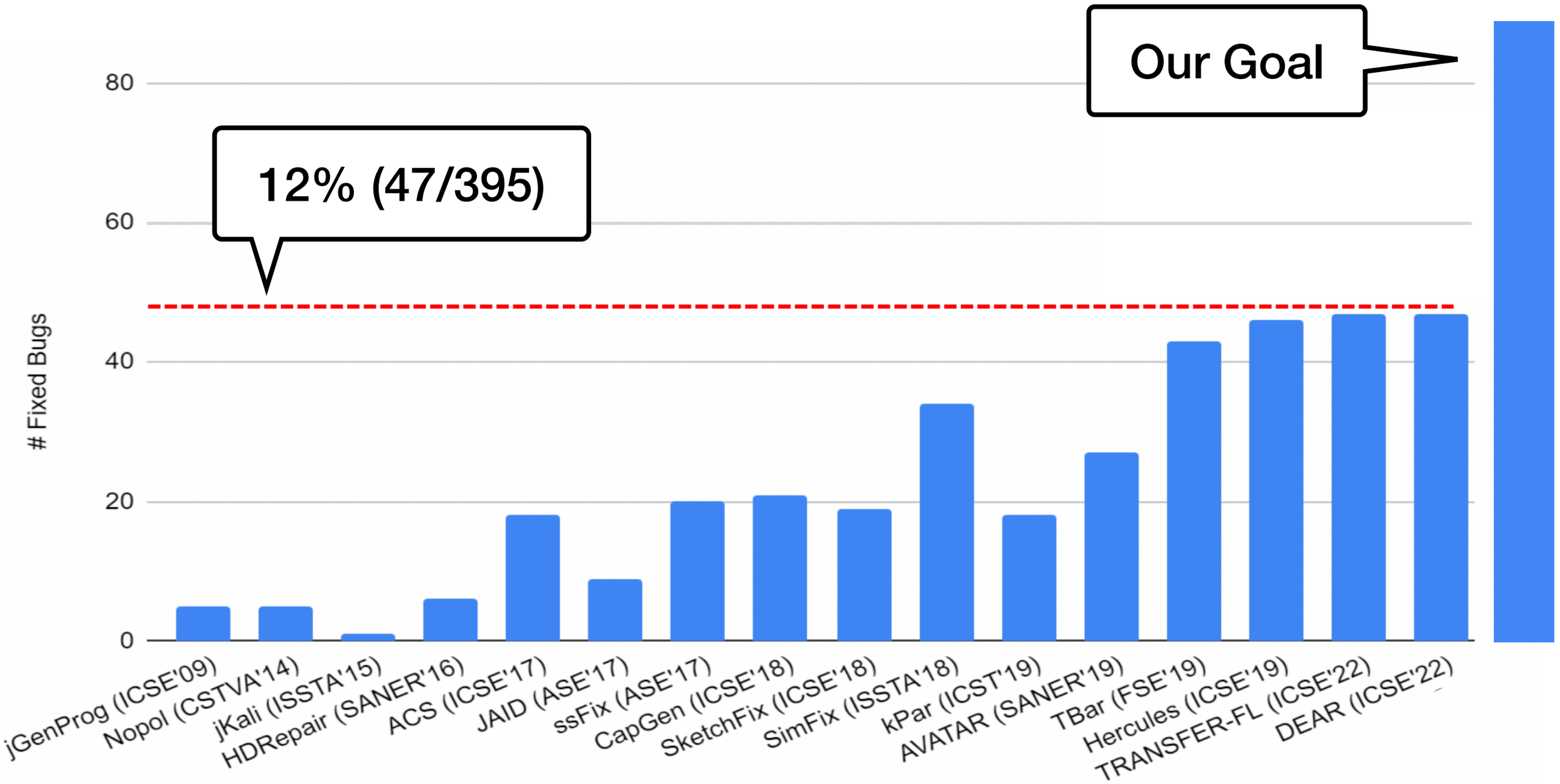


Defects4J 395개 오류 대상 자동 수정 성공률

일반적 자동 수정 기술 현황



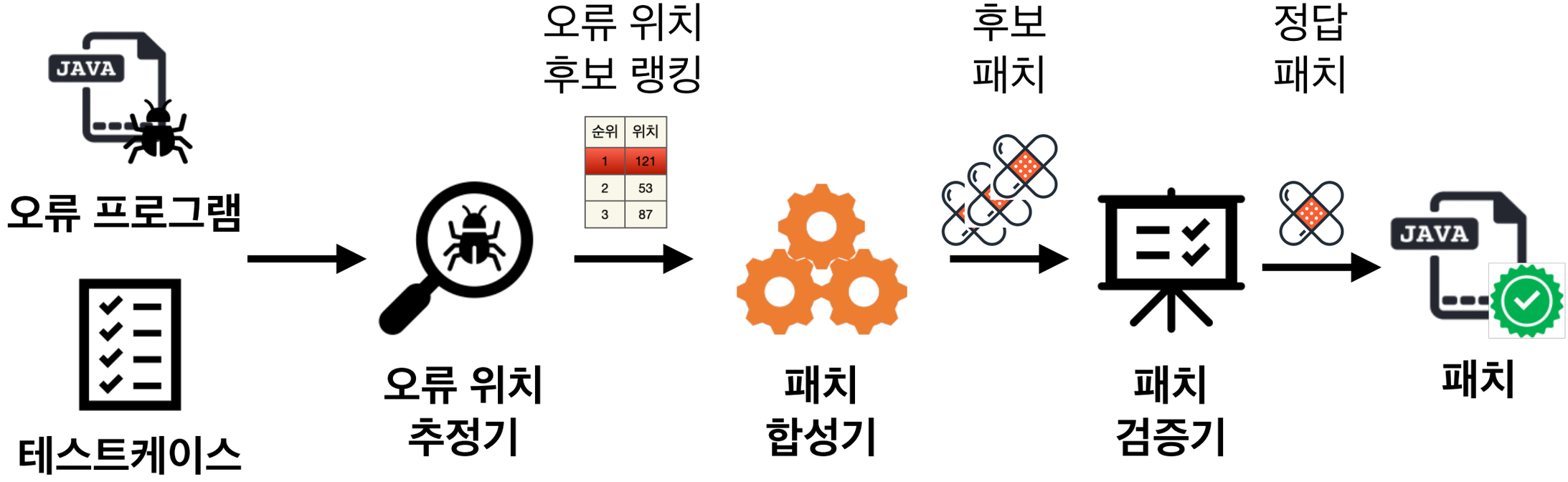
Defects4J 395개 오류 대상 자동 수정 성공률

일반적 자동 수정 기술 현황

Closure-71 (Defects4J) 사례

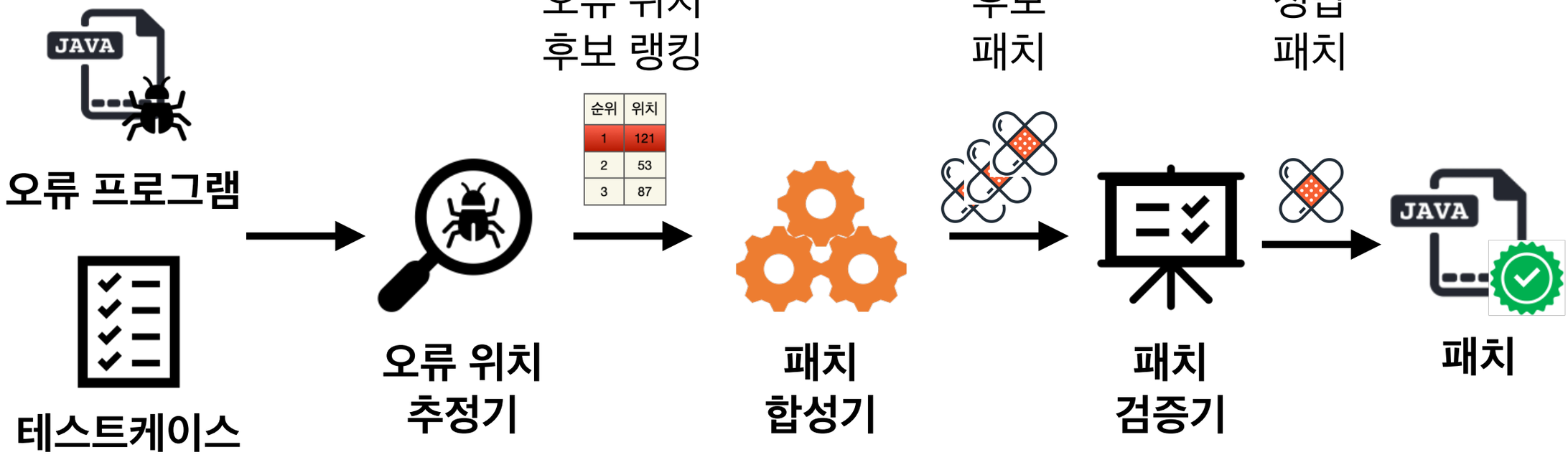
```
    void checkVisibility(Node t, Node parent) {
(-)   boolean isOverride = t.inGlobalScope() && ...
(+)   boolean isOverride = parent.getJSDocInfo() == null && ...

      if (isOverride) {
        compiler.report(PRIVATE_OVERRIDE);
      }
    }
```

일반적 자동 수정 기술 현황



일반적 자동 수정 기술 현황

68위 X 1700만개 X 1초 = 36년



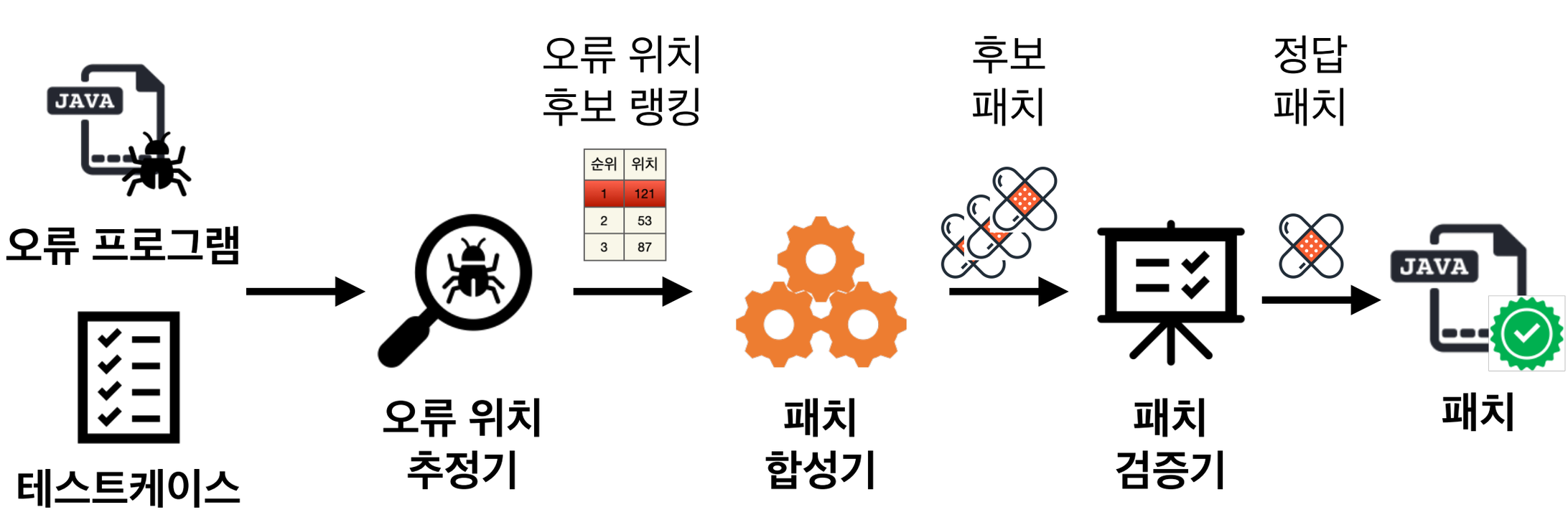
일반적 자동 수정 기술 현황

Our Goal

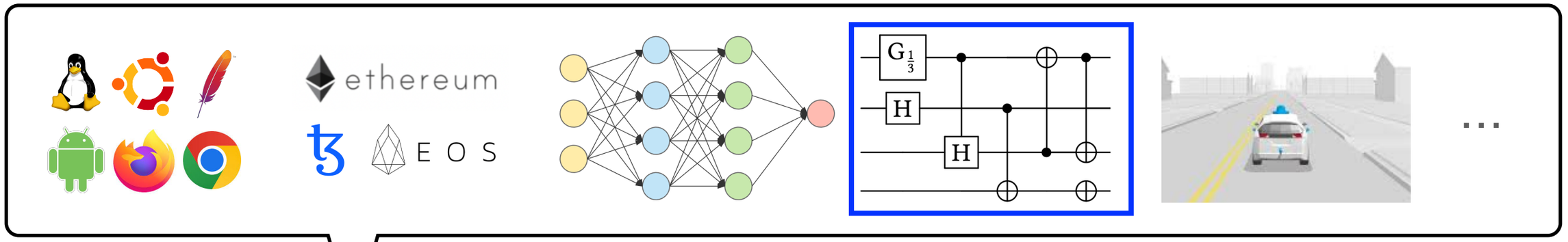
10위 X 10000개 X 0.1초 = 3시간

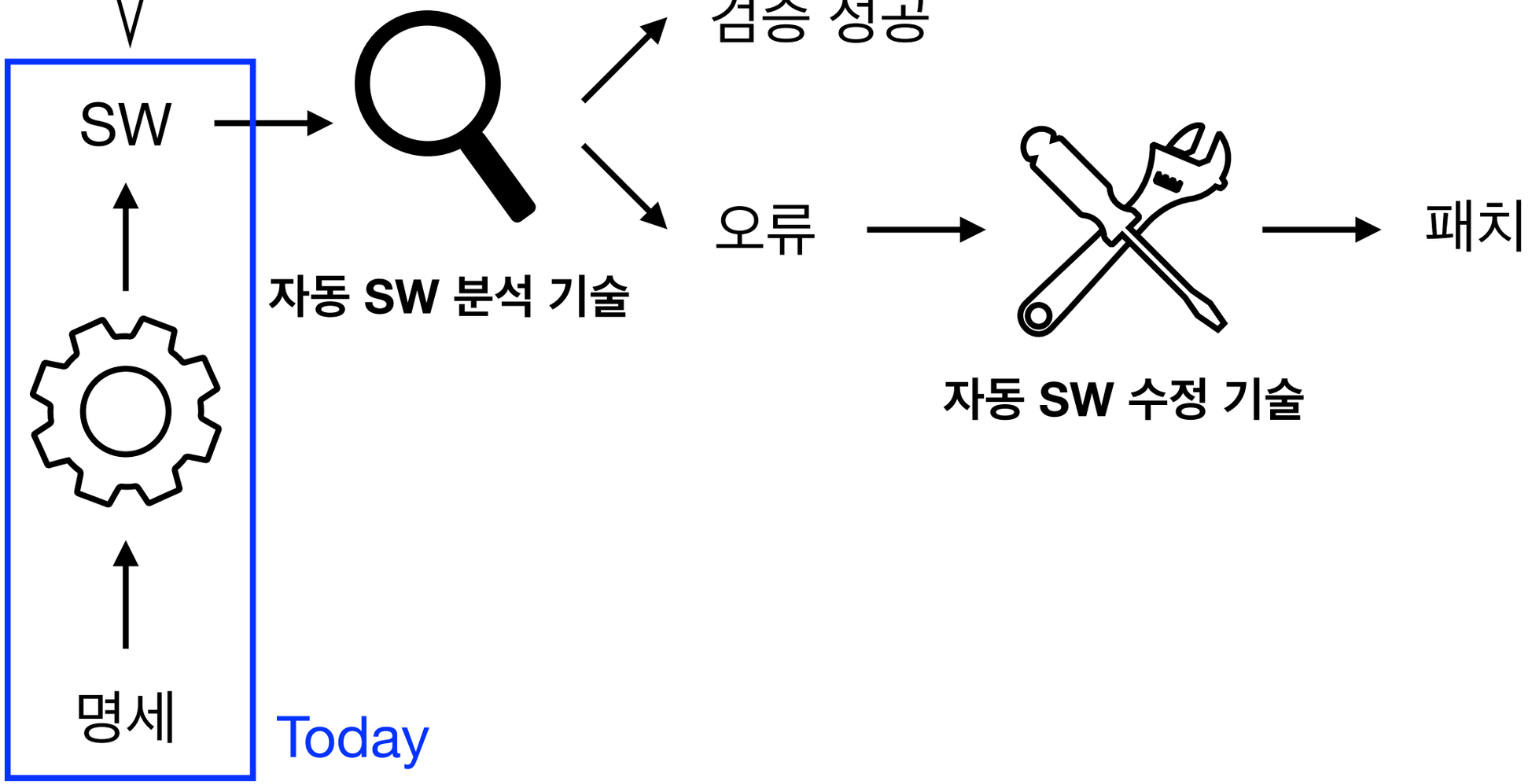
위치 추정 정밀화 | 테스트 통과 가능성 분석 | 의미 기반 패치 검증

68위 X 1700만개 X 1초 = 36년



Our Research





양자 회로 자동 합성 (OOPSLA 2023)

입출력 명세

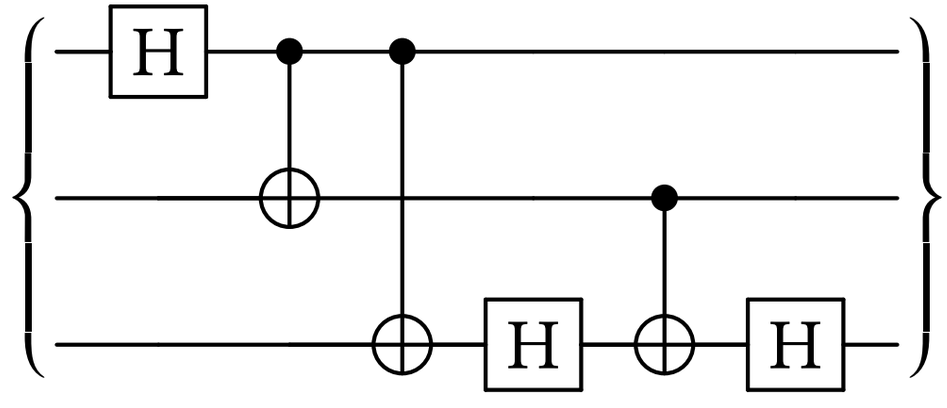
$$|100\rangle \mapsto \frac{1}{\sqrt{2}}(|000\rangle + |111\rangle)$$

컴포넌트 게이트

$$H, CNOT$$

양자 회로 합성기

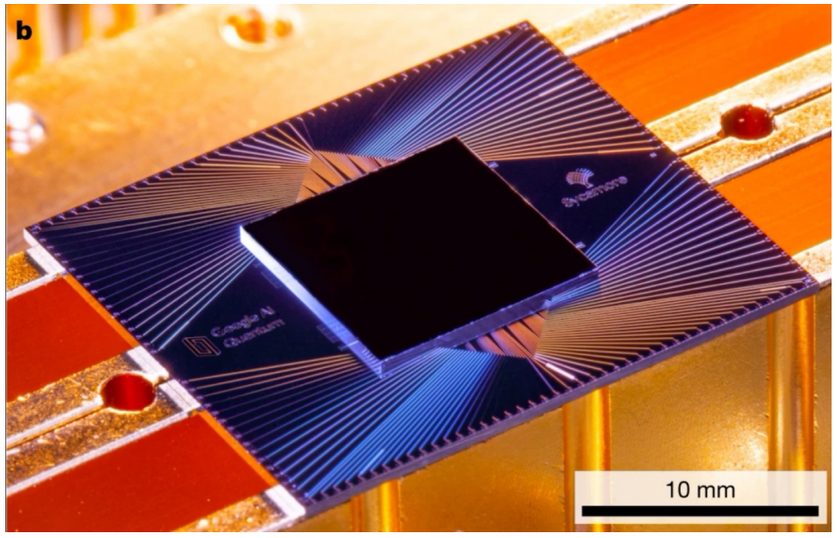
$|100\rangle$



$$|GHZ\rangle = \frac{1}{\sqrt{2}}(|000\rangle + |111\rangle)$$

양자 컴퓨터

- 하드웨어



Google Sycamore (2019)

IBM Hummingbird, Eagle, Osprey (2020-2022)

- 소프트웨어

Qiskit Cirq Q# SILQ

양자 컴퓨터

- 고전 컴퓨터의 일반화

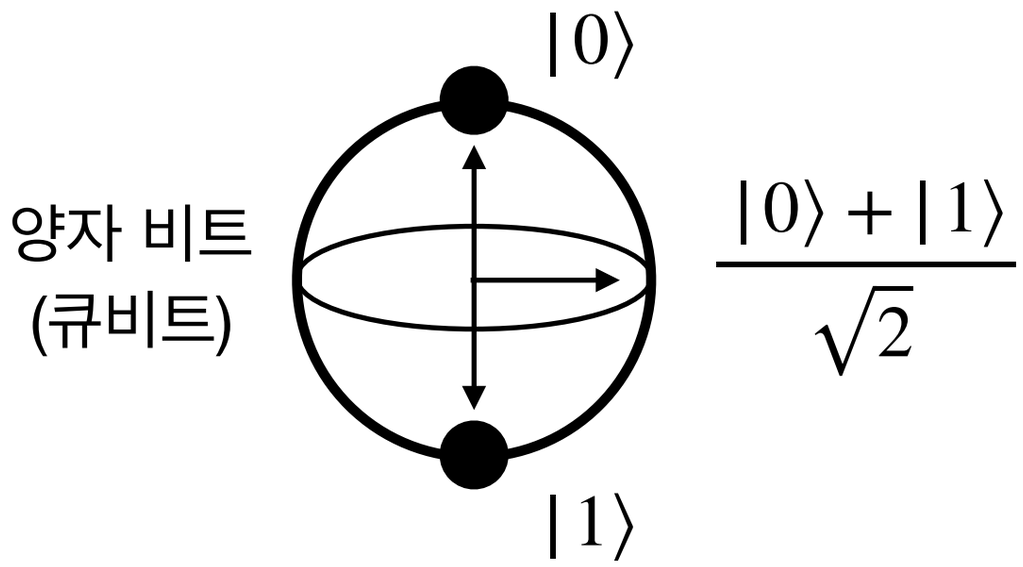
양자 컴퓨터

- 고전 컴퓨터의 일반화

고전 비트

양자 컴퓨터

- 고전 컴퓨터의 일반화



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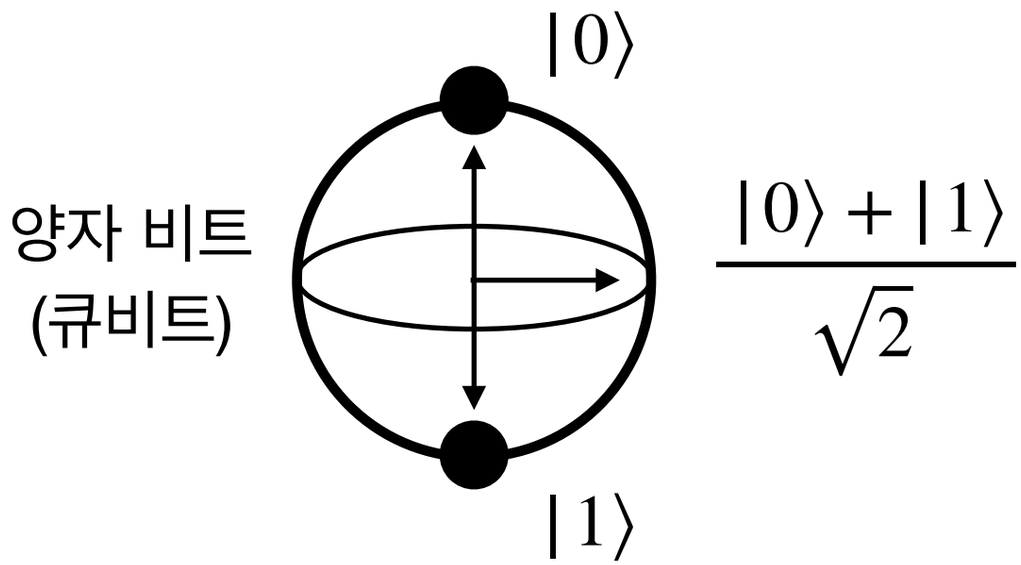
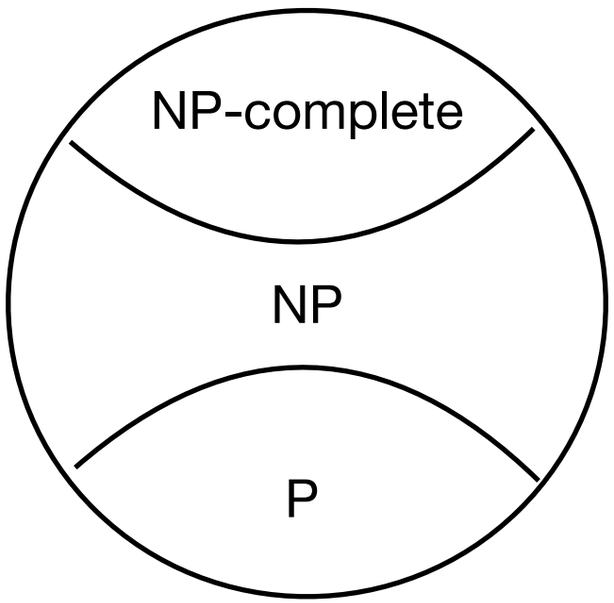


- 가능성 & 한계



양자 컴퓨터

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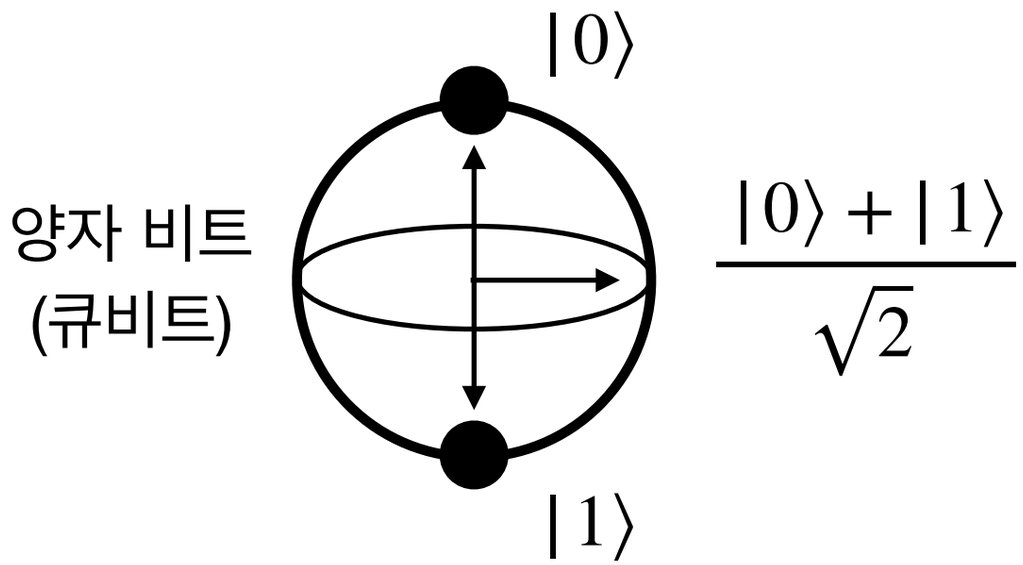

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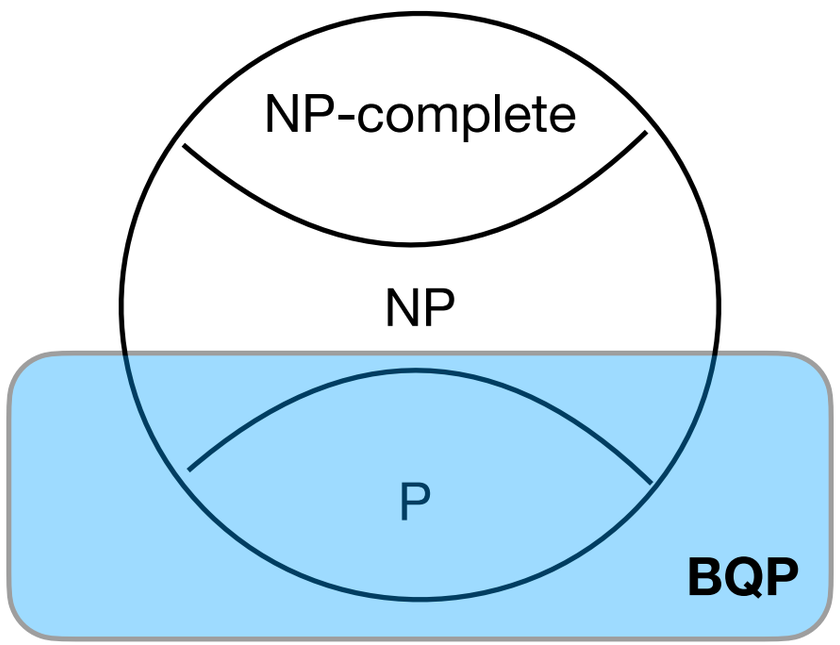

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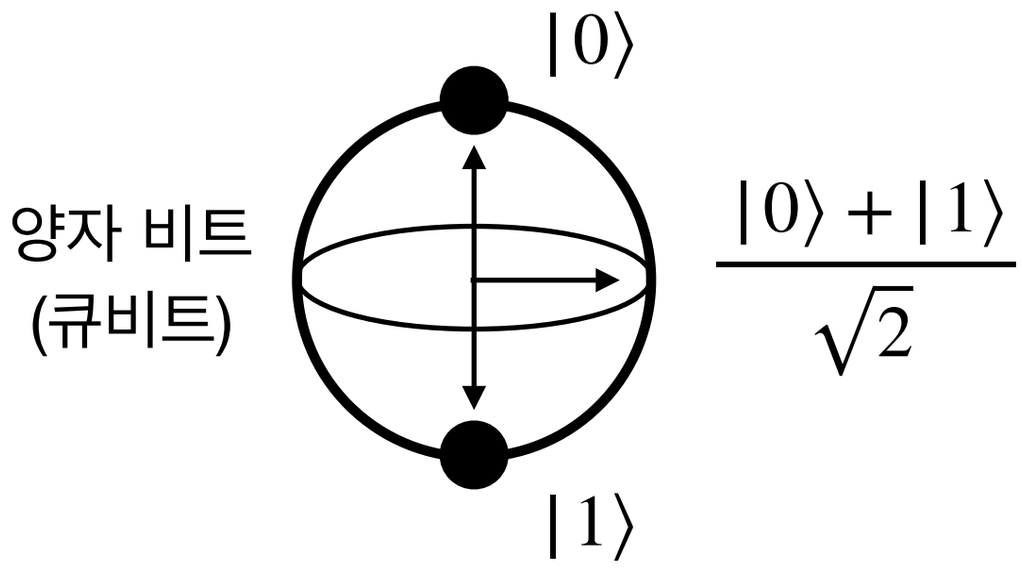

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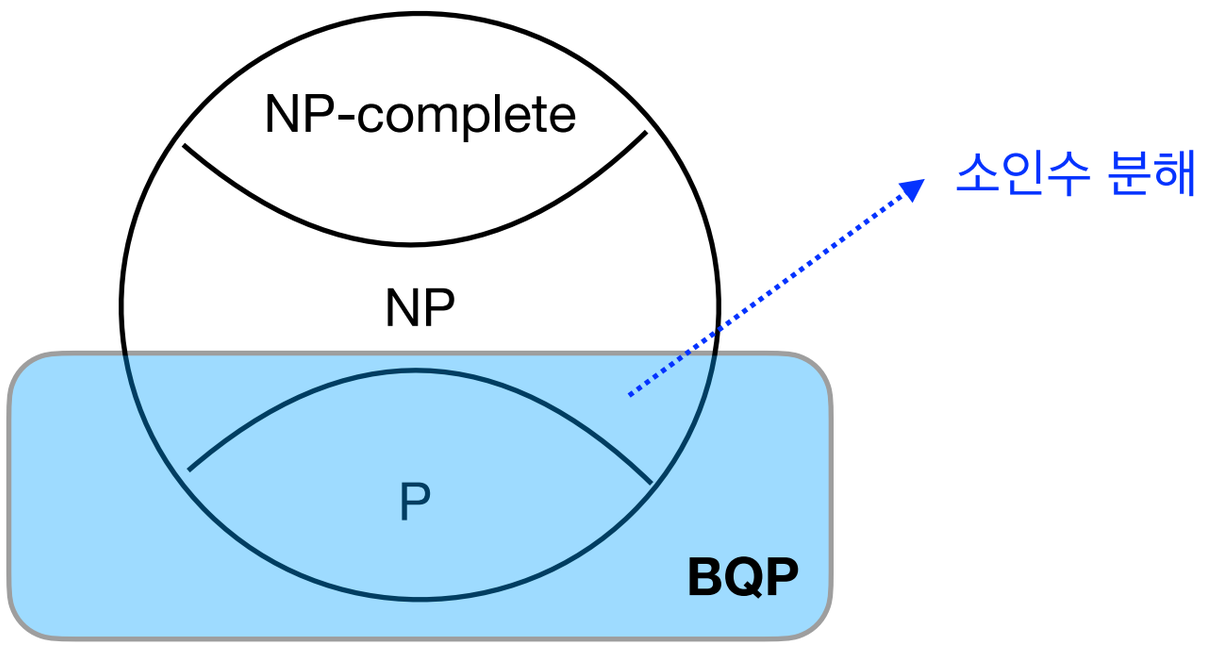
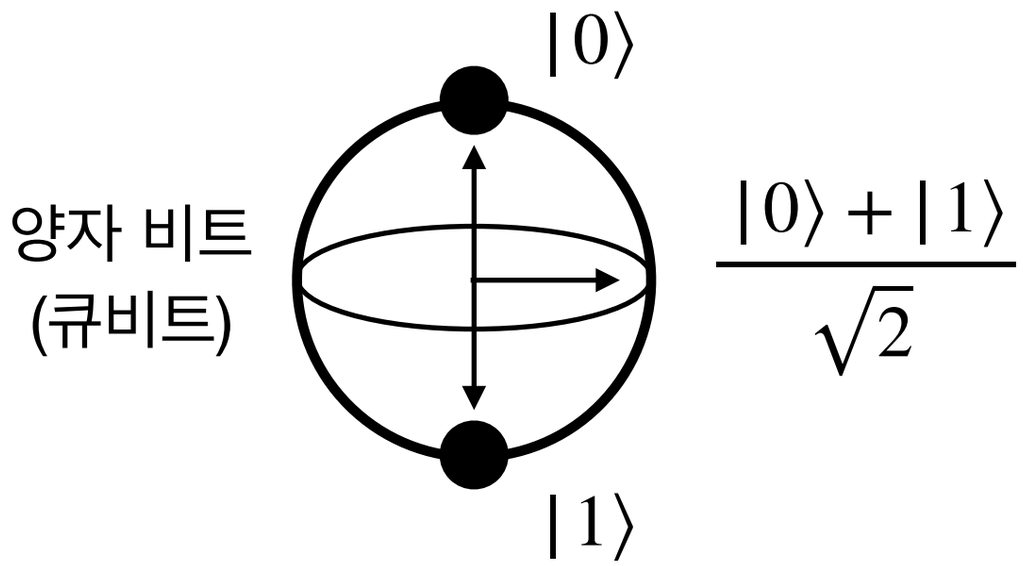


양자 컴퓨터

- 고전 컴퓨터의 일반화



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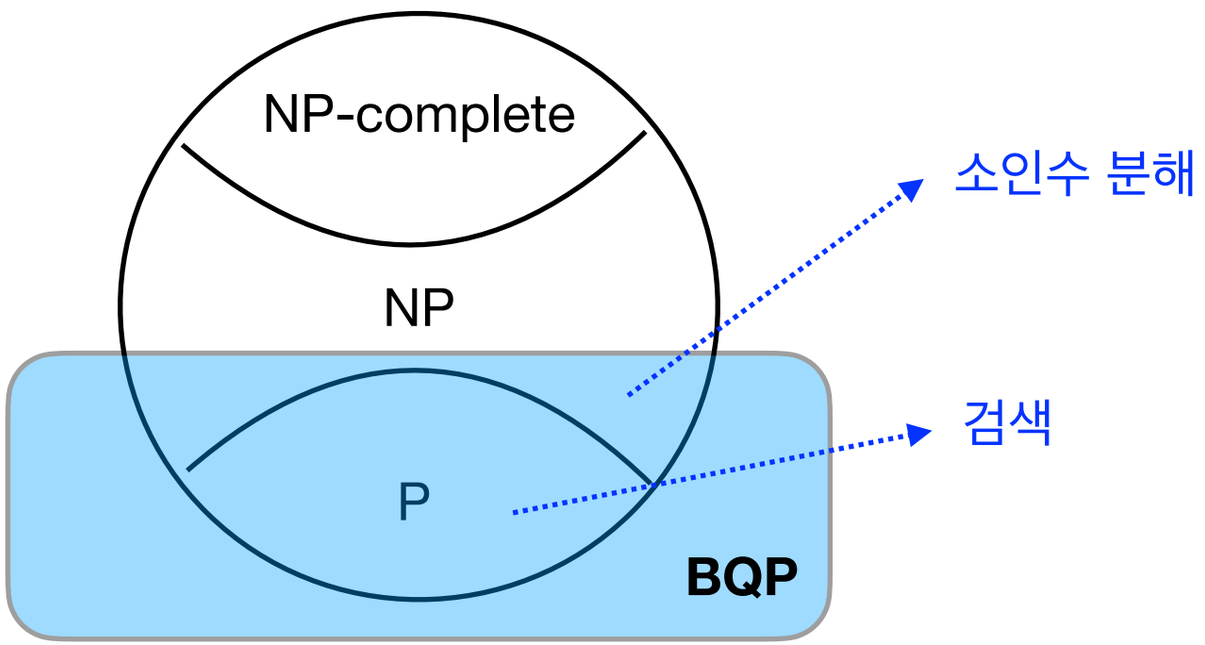
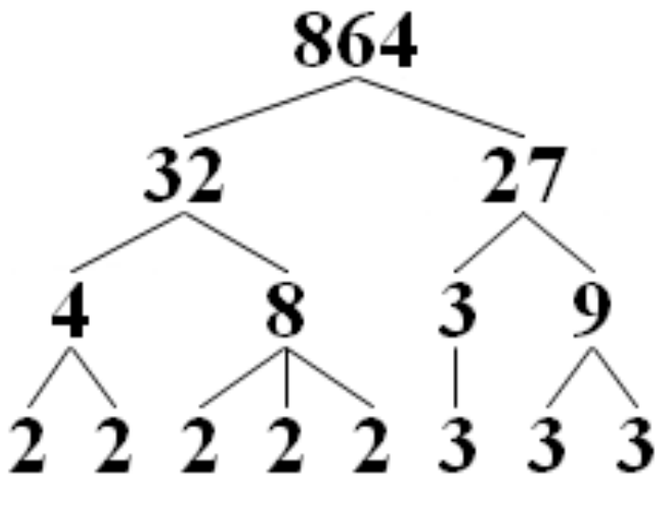


적용 사례

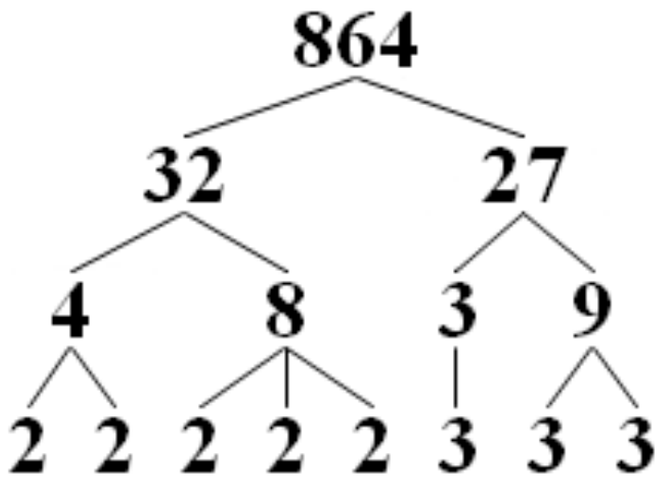
(1) 소인수분해 [Shor 1995]



$O(2^N)$ vs $O(N^3)$

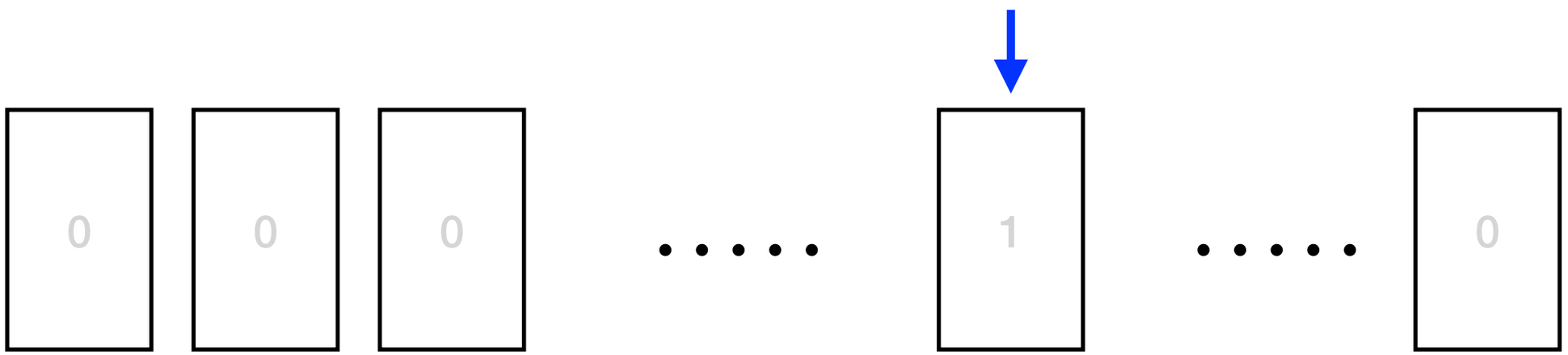
적용 사례

(1) 소인수분해 [Shor 1995]



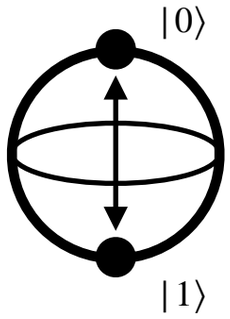
$O(2^N)$ vs $O(N^3)$

(2) 검색 [Grover 1996]



$O(N)$ vs $O(\sqrt{N})$

큐비트



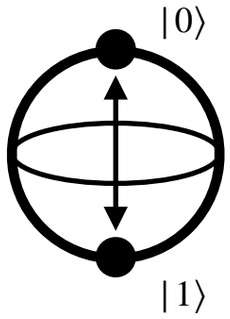
- 비트의 일반화 (0과 1의 중첩—선형 결합)

$$|\psi\rangle = \alpha_0|0\rangle + \alpha_1|1\rangle$$

  - $\alpha_1, \alpha_2 \in \mathbb{C}$: 확률 진폭 (probability amplitude)

$$|\alpha_1|^2 + |\alpha_2|^2 = 1$$

큐비트



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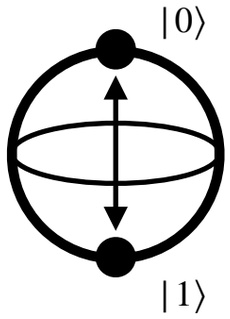
$$|\alpha_1|^2 + |\alpha_2|^2 = 1$$

  - $|0\rangle$
  - $|1\rangle$
  - $\frac{1}{\sqrt{2}}|0\rangle + \frac{1}{\sqrt{2}}|1\rangle$

큐비트



- 비트의 일반화 (0과 1의 중첩—선형 결합)

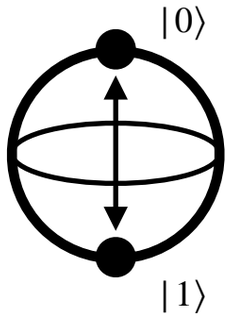
$$|\psi\rangle = \alpha_0|0\rangle + \alpha_1|1\rangle$$

  - $\alpha_1, \alpha_2 \in \mathbb{C}$: 확률 진폭 (probability amplitude)

$$|\alpha_1|^2 + |\alpha_2|^2 = 1$$

  - $|0\rangle$
  - $|1\rangle$
  - $\frac{1}{\sqrt{2}}|0\rangle + \frac{1}{\sqrt{2}}|1\rangle$
  - $\frac{1}{\sqrt{2}}|0\rangle - \frac{1}{\sqrt{2}}|1\rangle$

큐비트



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- $|0\rangle$
- $|1\rangle$
- $\frac{1}{\sqrt{2}}|0\rangle + \frac{1}{\sqrt{2}}|1\rangle$
- $\frac{1}{\sqrt{2}}|0\rangle - \frac{1}{\sqrt{2}}|1\rangle$
- $\sqrt{\frac{3}{4}}|0\rangle + \frac{i}{\sqrt{4}}|1\rangle$

N개 큐비트

- 고전 비트 2개로 만들어지는 상태

$$00, \quad 01, \quad 10, \quad 11$$

- 큐비트 2개 = 고전 2-bit 상태들의 중첩

$$|\psi\rangle = \alpha_0|00\rangle + \alpha_1|01\rangle + \alpha_2|10\rangle + \alpha_3|11\rangle \quad \left(\sum_i |\alpha_i|^2 = 1\right)$$

- 큐비트 N개 = 고전 N-bit 상태들의 중첩

$$|\psi\rangle = \sum_{x\in\{0,1\}^N} \alpha_x |x\rangle$$

2^N개 확률 진폭을 “저장”

병렬처리: 고전 컴퓨터 vs. 양자 컴퓨터

- $f: \{0,1\} \rightarrow \{0,1\}$

$$f(0) \qquad \text{vs.} \qquad f(\frac{|0\rangle + |1\rangle}{\sqrt{2}})$$

$$f(1)$$

병렬처리: 고전 컴퓨터 vs. 양자 컴퓨터

- $f: \{0,1\} \rightarrow \{0,1\}$

$$f(0) \qquad\qquad f(\frac{|0\rangle + |1\rangle}{\sqrt{2}})$$
$$f(1) \qquad \text{vs.}$$

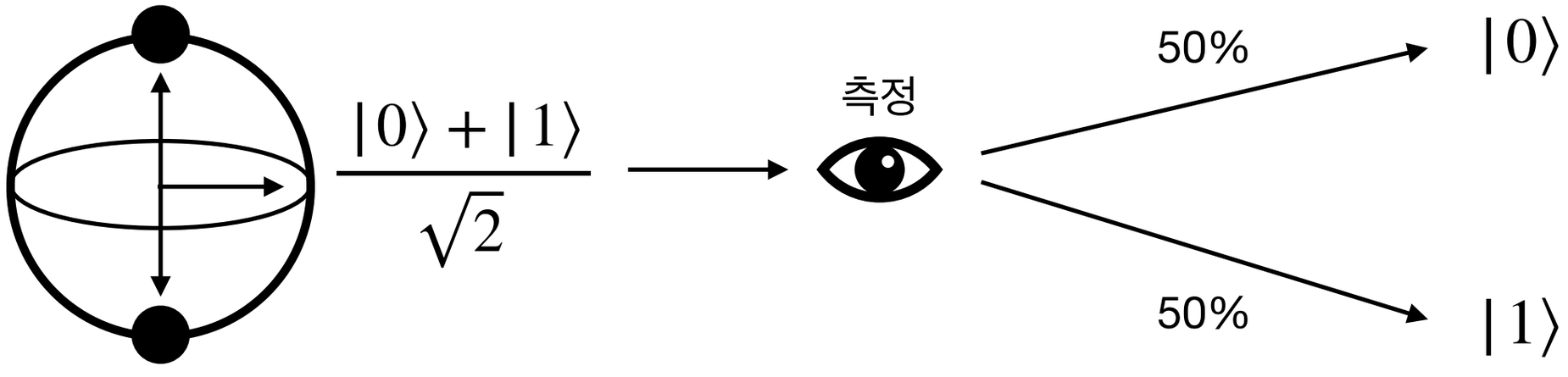
- $f: \{0,1\}^N \rightarrow \{0,1\}$

$$f(0)$$
$$f(1) \qquad \text{vs.} \qquad f(\frac{|0\rangle + |1\rangle + \ldots + |2^N - 1\rangle}{\sqrt{2^N}})$$
$$\vdots$$
$$f(2^N - 1)$$

측정과 붕괴

$$|\psi\rangle = \alpha_0|0\rangle + \alpha_1|1\rangle$$

- 큐비트의 내부 상태(α_1, α_2)는 알 수 없고, 고전 정보만 관측 가능
- 큐비트 $|\psi\rangle$를 측정하면,
  - $|\alpha_0|^2$의 확률로 0이 관측되고 $|\psi\rangle = |0\rangle$ 로 붕괴
  - $|\alpha_1|^2$의 확률로 1이 관측되고 $|\psi\rangle = |1\rangle$ 로 붕괴



N개 큐비트 측정

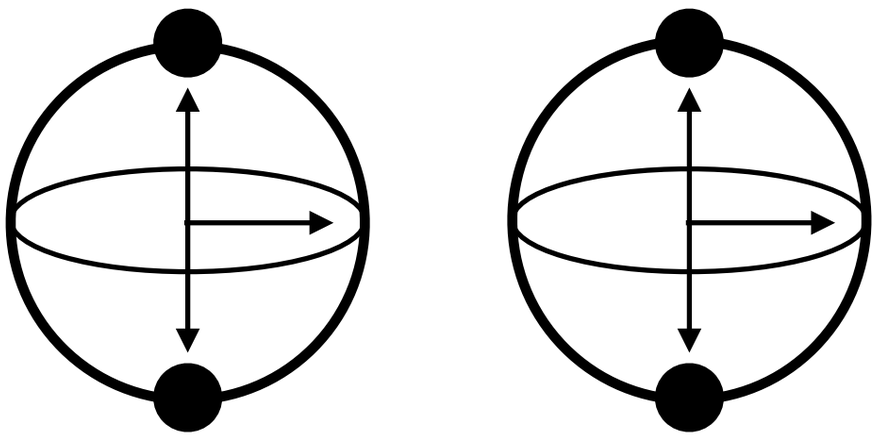
$$|\psi\rangle = \alpha_0|00\rangle + \alpha_1|01\rangle + \alpha_2|10\rangle + \alpha_3|11\rangle$$

- 상태 $|\psi\rangle$를 측정하면,
  - $|\alpha_0|^2$의 확률로 00이 관측되고 $|\psi\rangle = |00\rangle$ 로 붕괴
  - $|\alpha_1|^2$의 확률로 01이 관측되고 $|\psi\rangle = |01\rangle$ 로 붕괴
  - $|\alpha_2|^2$의 확률로 10이 관측되고 $|\psi\rangle = |10\rangle$ 로 붕괴
  - $|\alpha_2|^2$의 확률로 11이 관측되고 $|\psi\rangle = |11\rangle$ 로 붕괴
- 예:

$$|\psi\rangle = \frac{|00\rangle + |01\rangle + |10\rangle + |11\rangle}{2}$$

얽힘 (Entanglement)

- 얽히지 않은 상태 = 개별 큐비트들이 단순 결합된 상태



$$\frac{|0\rangle + |1\rangle}{\sqrt{2}} \qquad \frac{|0\rangle + |1\rangle}{\sqrt{2}}$$

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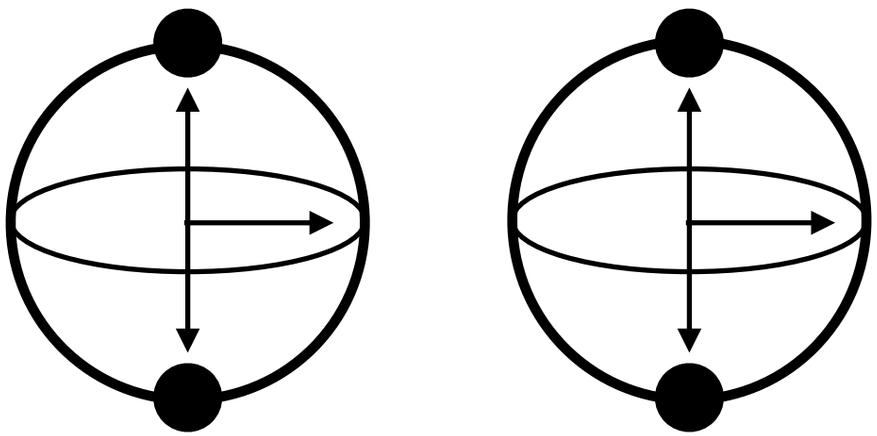

$$\frac{|0\rangle + |1\rangle}{\sqrt{2}} \quad \text{x} \quad \frac{|0\rangle + |1\rangle}{\sqrt{2}} \quad = \quad \frac{|00\rangle + |01\rangle + |10\rangle + |11\rangle}{2}$$

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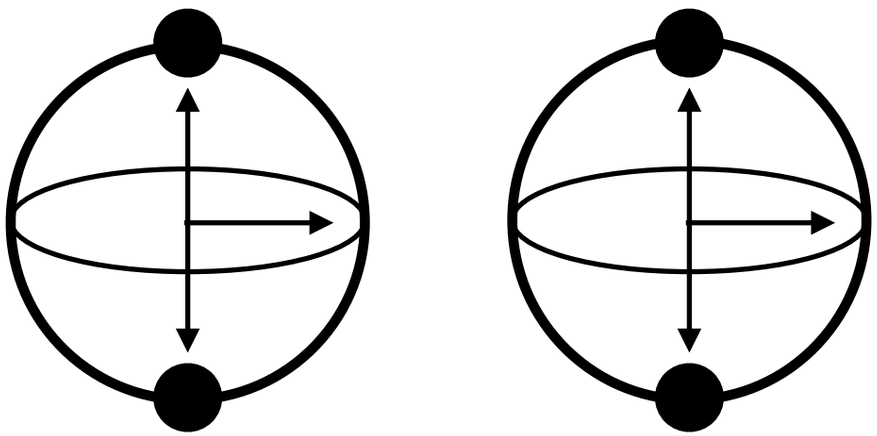
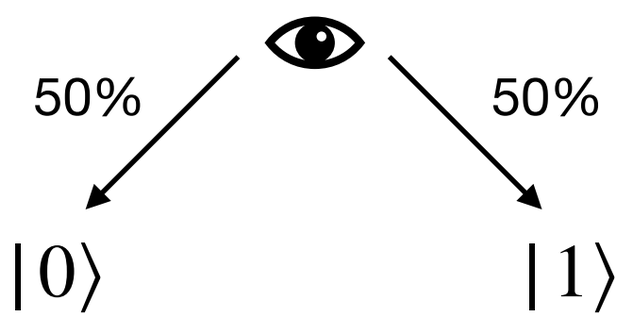


$$\frac{|0\rangle + |1\rangle}{\sqrt{2}} \quad x \quad \frac{|0\rangle + |1\rangle}{\sqrt{2}} \quad = \quad \frac{|00\rangle + |01\rangle + |10\rangle + |11\rangle}{2}$$

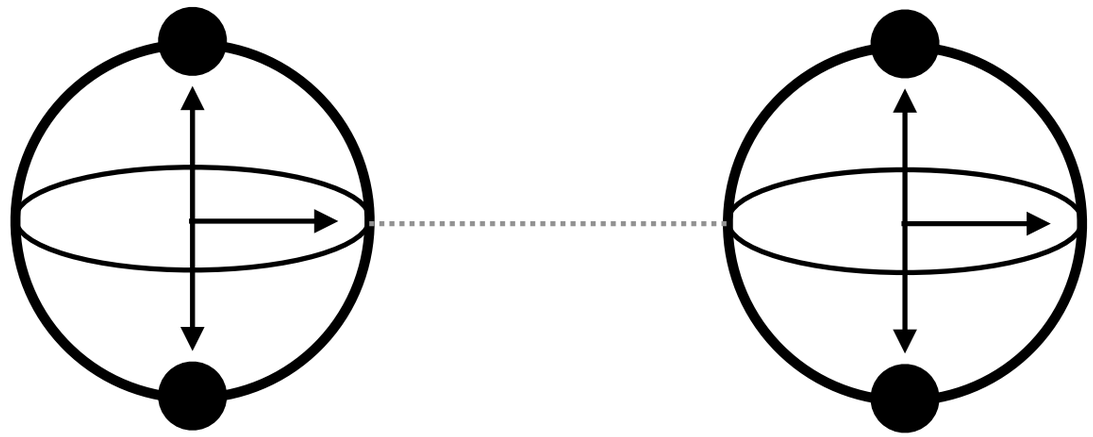


- 하나의 큐비트 관찰 결과가 다른 큐비트 상태에 영향을 주지 않음

얽힘 (Entanglement)

- 얽힌 상태 = 개별 큐비트 상태들로 분리 불가능

$$\frac{|00\rangle + |11\rangle}{\sqrt{2}}$$



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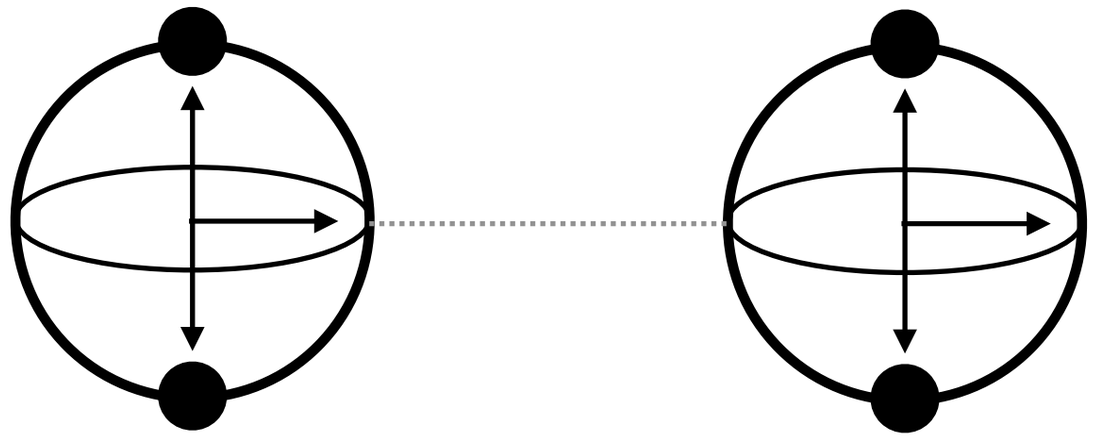

$$\neq (\alpha_0 |0\rangle + \alpha_1 |1\rangle) \times (\beta_0 |0\rangle + \beta_1 |1\rangle)$$

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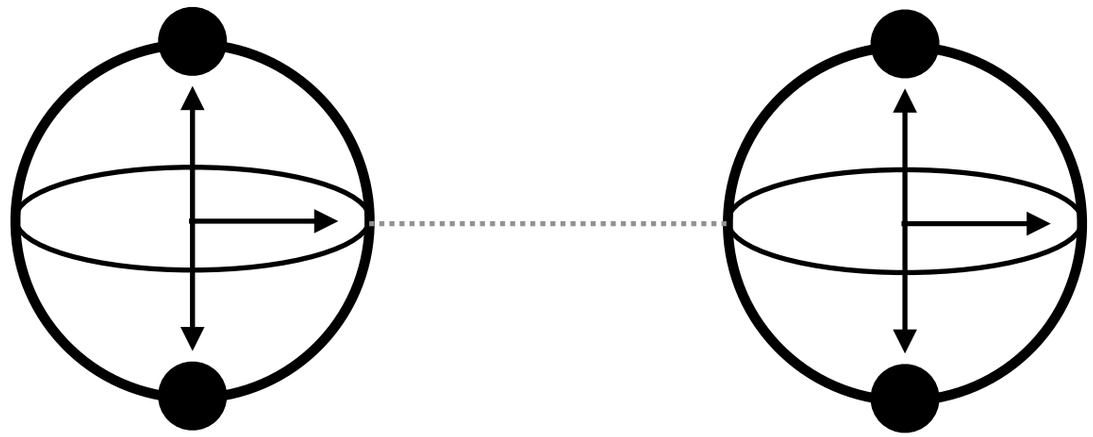
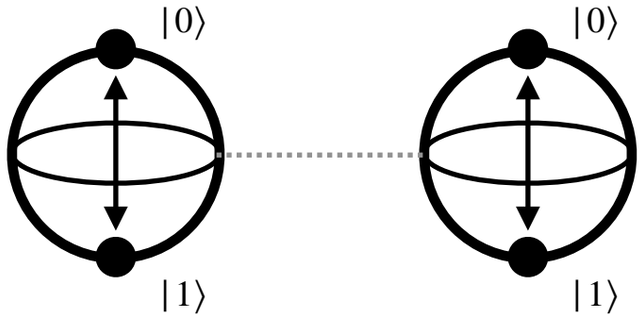


$$\neq (\alpha_0|0\rangle + \alpha_1|1\rangle) \times (\beta_0|0\rangle + \beta_1|1\rangle)$$

- 하나의 큐비트 관찰이 다른 큐비트 상태에 영향을 줌
  - 하나의 큐비트에서 0을 관측하면 다른 큐비트 상태는 $|0\rangle$로 결정
  - 하나의 큐비트에서 1을 관측하면 다른 큐비트 상태는 $|1\rangle$로 결정

EPR 패러독스

1. 두 큐비트 

를 $\frac{|00\rangle + |11\rangle}{\sqrt{2}}$ 상태로 준비

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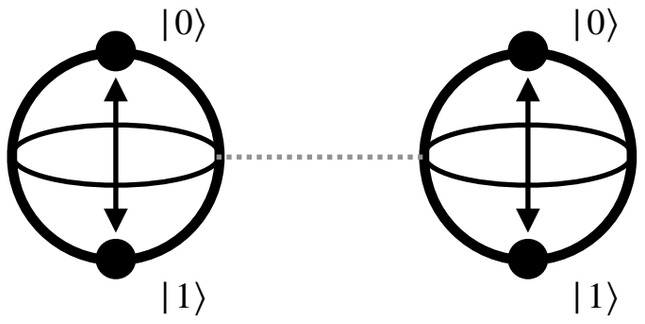
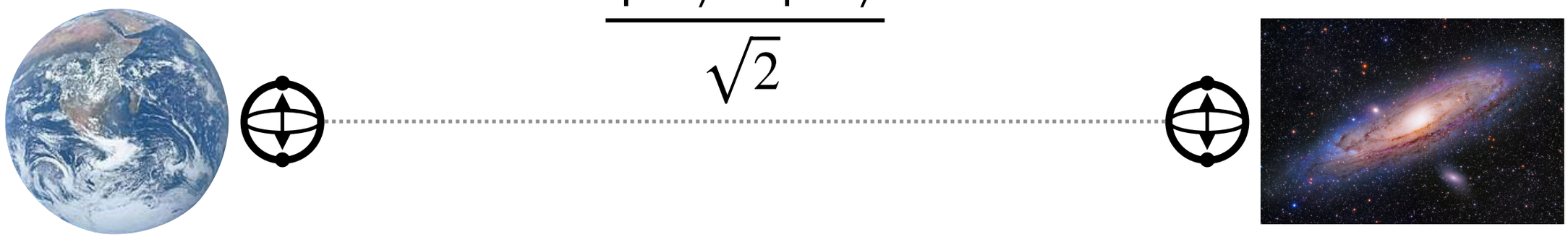
1. 두 큐비트 

를 $\frac{|00\rangle + |11\rangle}{\sqrt{2}}$ 상태로 준비

2. 두 큐비트를 서로 멀리 떨어지도록 이동



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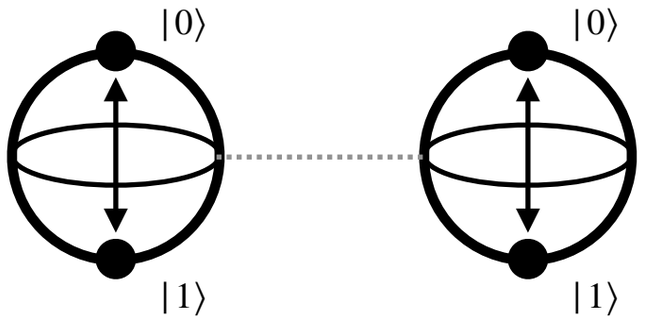
1. 두 큐비트 

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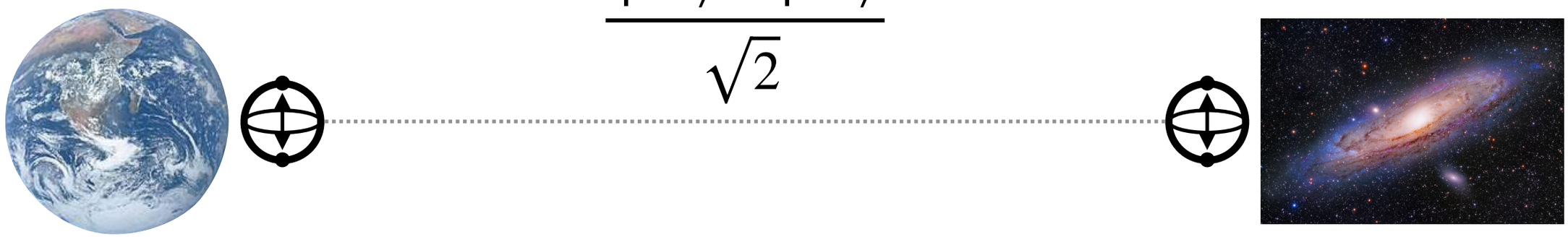

3. 측정

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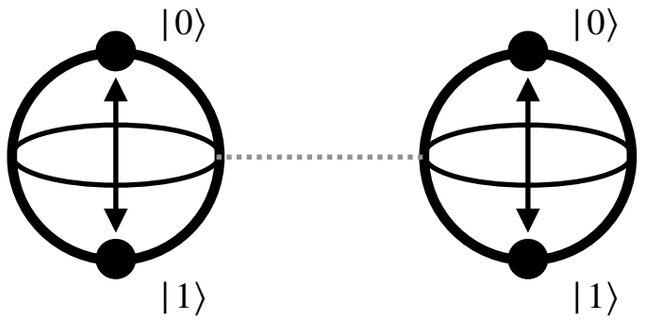
1. 두 큐비트 

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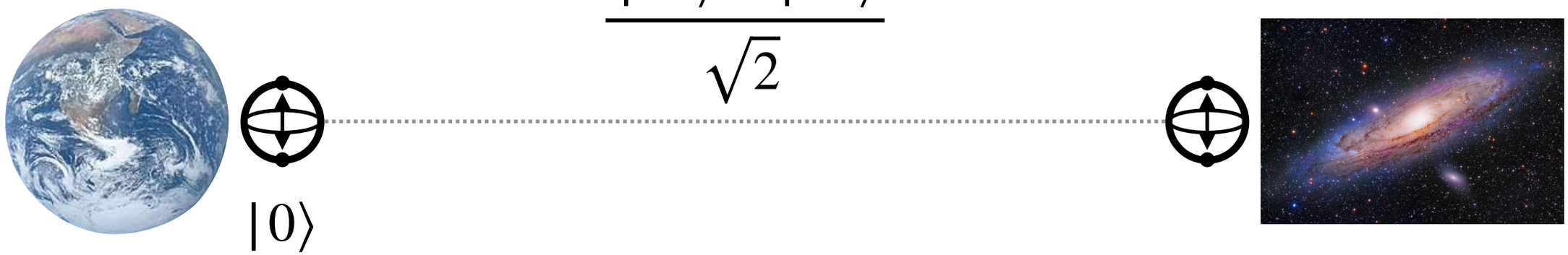

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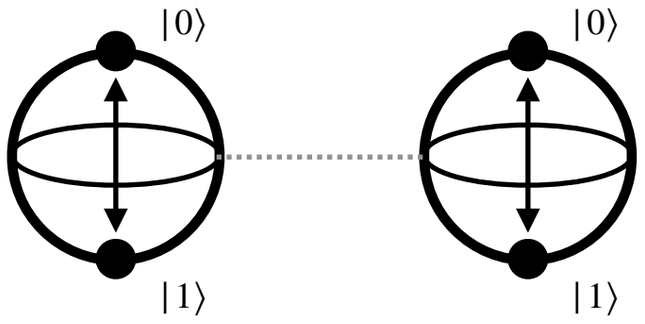
1. 두 큐비트 

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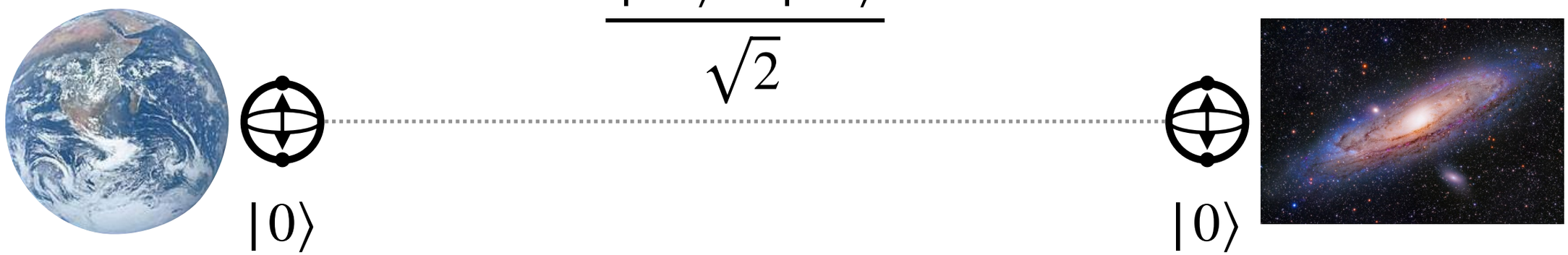

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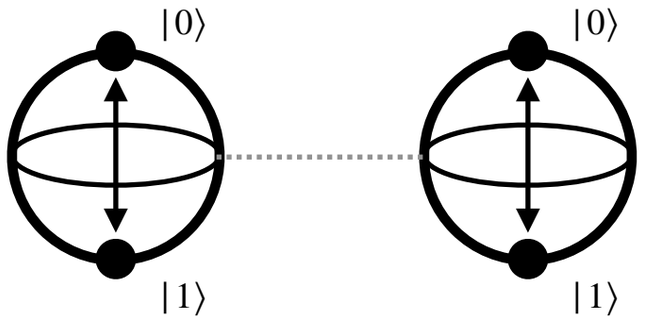
1. 두 큐비트 

를 $\frac{|00\rangle + |11\rangle}{\sqrt{2}}$ 상태로 준비

2. 두 큐비트를 서로 멀리 떨어지도록 이동

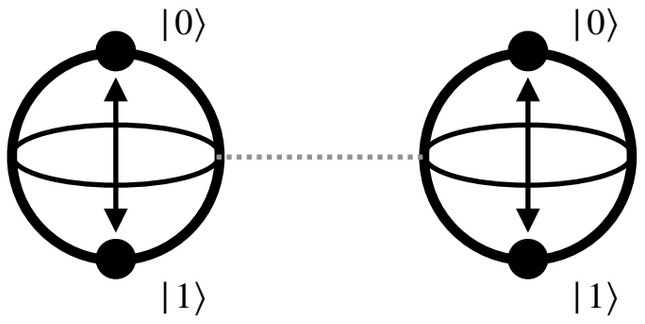
$|0\rangle$
$|1\rangle$

$\frac{|00\rangle + |11\rangle}{\sqrt{2}}$

$|0\rangle$

3. 측정

EPR 패러독스

1. 두 큐비트 

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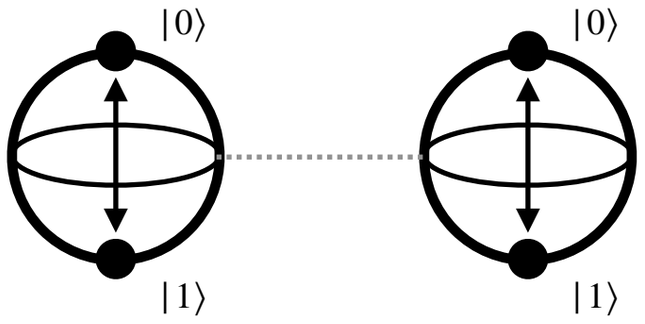
2. 두 큐비트를 서로 멀리 떨어지도록 이동

|0⟩
|1⟩

|0⟩
|1⟩

3. 측정

EPR 패러독스

1. 두 큐비트 

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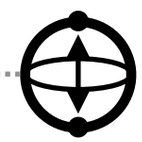
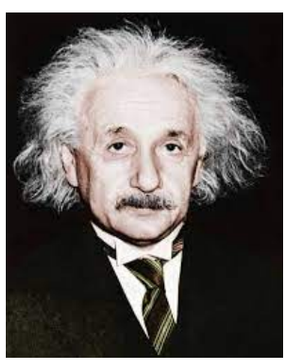
$|0\rangle$
$|1\rangle$



$|0\rangle$
$|1\rangle$

3. 측정

“Spooky action at a distance”



양자 게이트

$$\alpha_0|0\rangle + \alpha_1|1\rangle \quad \boxed{X} \quad \alpha_1|0\rangle + \alpha_0|1\rangle$$

- 큐비트 상태 = 벡터

$$|\psi\rangle = \alpha_0|0\rangle + \alpha_1|1\rangle = \alpha_0 \begin{bmatrix} 1 \\ 0 \end{bmatrix} + \alpha_1 \begin{bmatrix} 0 \\ 1 \end{bmatrix} = \begin{bmatrix} \alpha_0 \\ \alpha_1 \end{bmatrix}$$

- 게이트 연산 = 행렬 곱

$$\begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} \times \begin{bmatrix} \alpha_0 \\ \alpha_1 \end{bmatrix} = \begin{bmatrix} \alpha_1 \\ \alpha_0 \end{bmatrix}$$

양자 게이트

$$\alpha_0|0\rangle + \alpha_1|1\rangle \quad \boxed{Z} \quad \alpha_0|0\rangle - \alpha_1|1\rangle$$

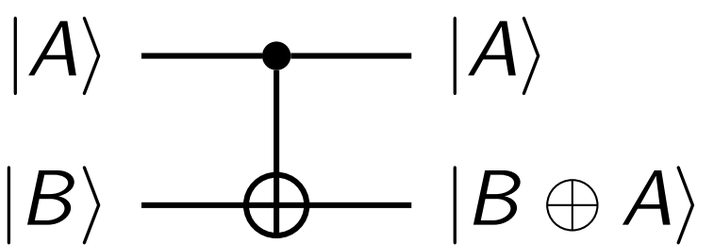
$$\begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}$$

$$\alpha_0|0\rangle + \alpha_1|1\rangle \quad \boxed{H} \quad \alpha_0\left(\frac{|0\rangle + |1\rangle}{\sqrt{2}}\right) + \alpha_1\left(\frac{|0\rangle - |1\rangle}{\sqrt{2}}\right)$$

$$\frac{1}{\sqrt{2}}\begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}$$

양자 게이트

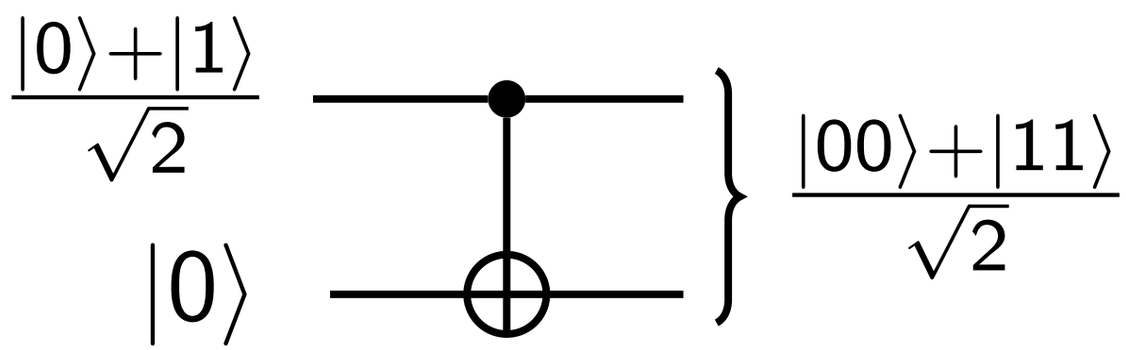
- CNOT (Controlled-Not) 게이트



$$\text{CNOT} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{bmatrix}$$

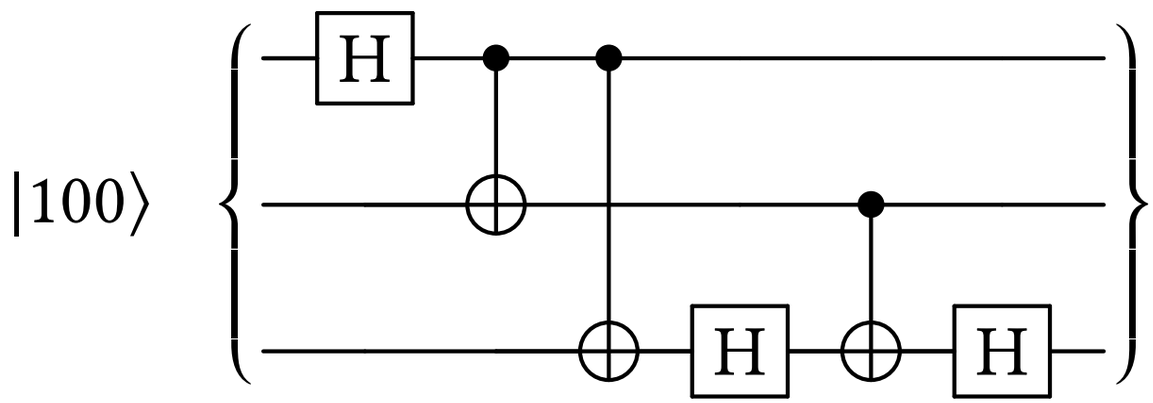
$$\begin{aligned} CNOT(\alpha_{00}|00\rangle + \alpha_{01}|01\rangle + \alpha_{10}|10\rangle + \alpha_{11}|11\rangle) \\ = \alpha_{00}|00\rangle + \alpha_{01}|01\rangle + \alpha_{10}|11\rangle + \alpha_{11}|10\rangle \end{aligned}$$

- CNOT: 얽힌 상태를 만드는데 사용



양자 회로

- 양자 게이트들의 조합



$$|GHZ\rangle = \frac{1}{\sqrt{2}}(|000\rangle + |111\rangle)$$

```
circ = QuantumCircuit(3)
circ.h(0)
circ.cx(0, 1)
circ.cx(0, 2)
circ.h(2)
circ.cx(1, 2)
circ.h(2)
```

Qiskit

양자 프로그래밍의 어려움

- 전혀 다른 계산 모델

양자 회로 자동 합성 (OOPSLA 2023)

입출력 명세

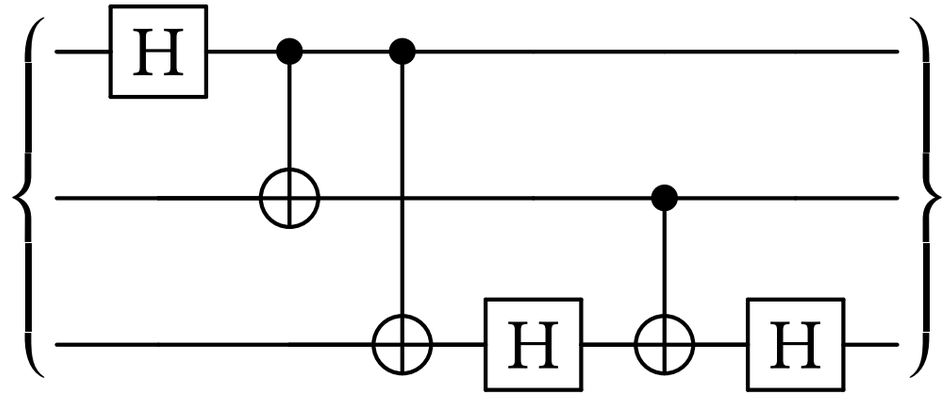
$$|100\rangle \mapsto \frac{1}{\sqrt{2}}(|000\rangle + |111\rangle)$$

컴포넌트 게이트

$$H, CNOT$$

양자 회로 합성기

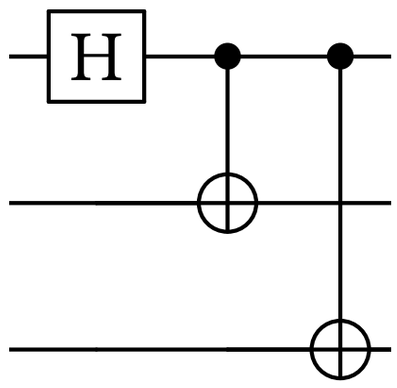
$|100\rangle$

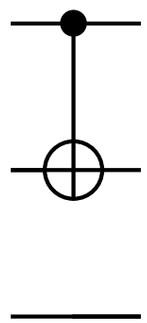


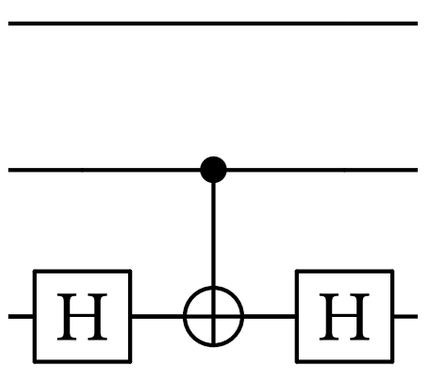
$$|GHZ\rangle = \frac{1}{\sqrt{2}}(|000\rangle + |111\rangle)$$

아이디어: 모듈 레벨 양자 회로 합성

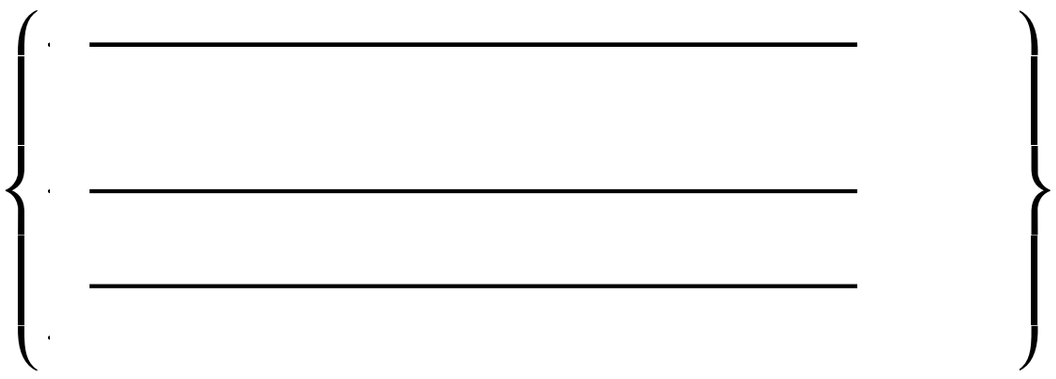
1. 모듈 = 게이트 조합 (up to some fixed length)

$M_1 =$ 

$M_2 =$ 

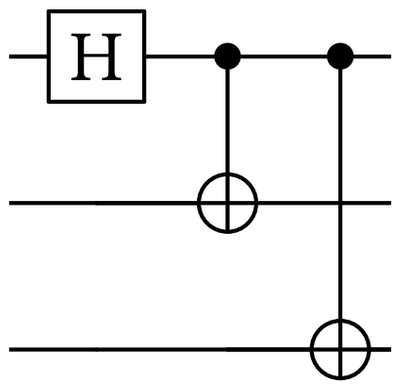
$M_3 =$ 

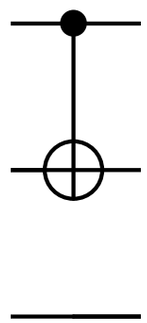
2. 명세와의 특성 차이를 줄이는 방향으로 모듈 쌓기

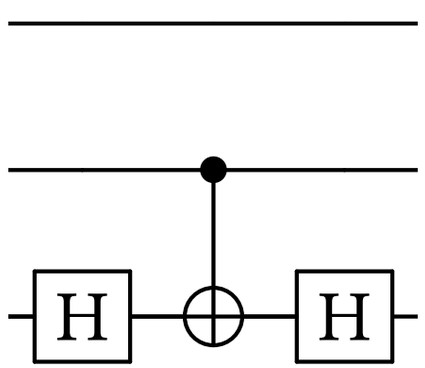
$|100\rangle$  $|GHZ\rangle = \frac{1}{\sqrt{2}}(|000\rangle + |111\rangle)$

아이디어: 모듈 레벨 양자 회로 합성

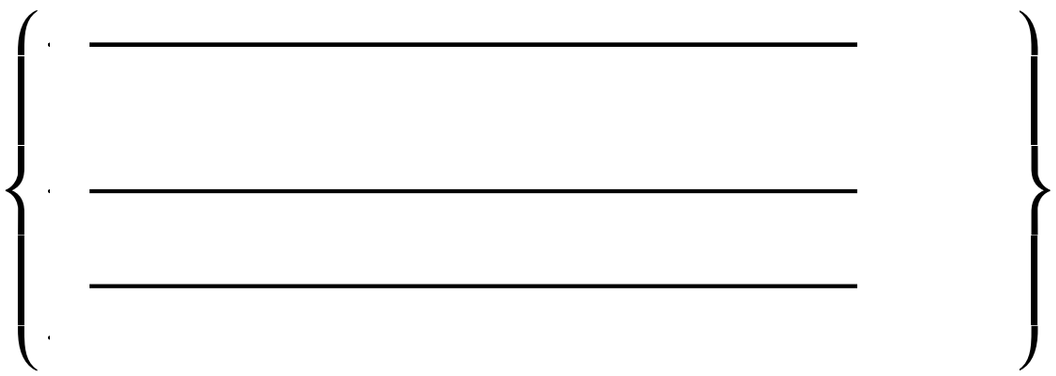
1. 모듈 = 게이트 조합 (up to some fixed length)

$M_1 =$ 

$M_2 =$ 

$M_3 =$ 

2. 명세와의 특성 차이를 줄이는 방향으로 모듈 쌓기

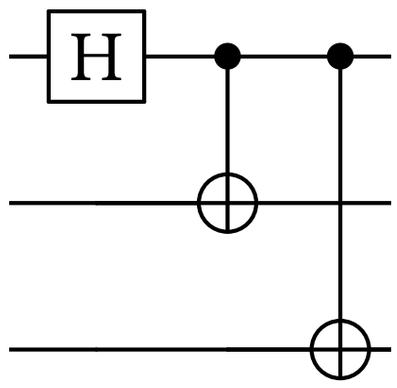
$|100\rangle$  $|GHZ\rangle = \frac{1}{\sqrt{2}}(|000\rangle + |111\rangle)$

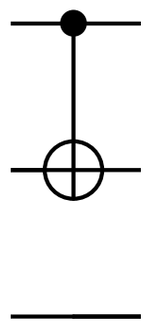
$|100\rangle \longleftrightarrow \frac{1}{\sqrt{2}}(|000\rangle + |111\rangle)$

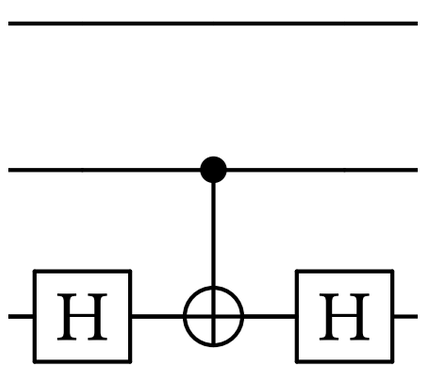
'얽힘' 차이

아이디어: 모듈 레벨 양자 회로 합성

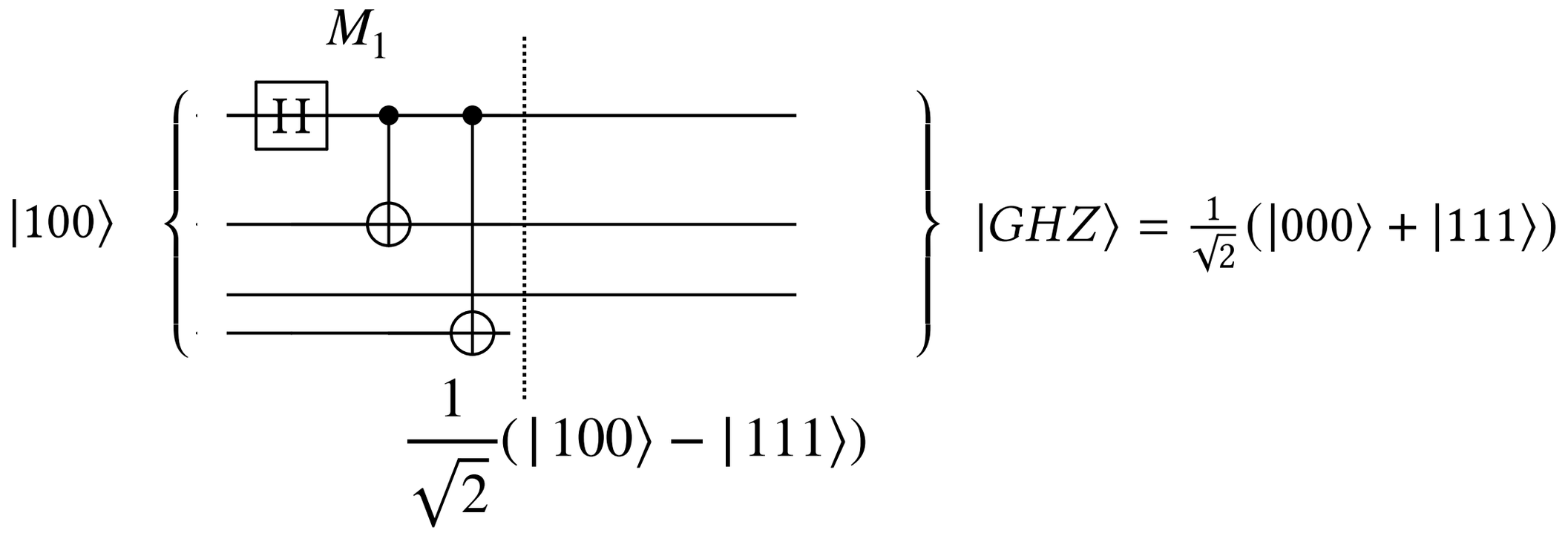
1. 모듈 = 게이트 조합 (up to some fixed length)

$M_1 =$ 

$M_2 =$ 

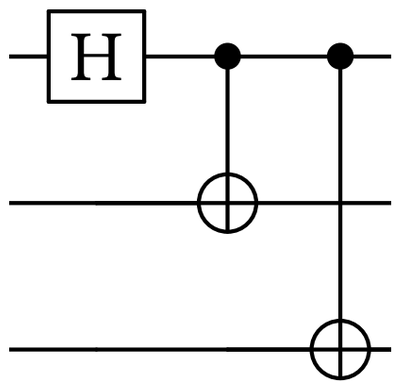
$M_3 =$ 

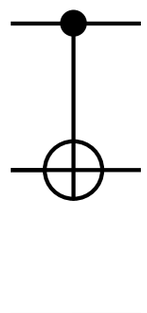
2. 명세와의 특성 차이를 줄이는 방향으로 모듈 쌓기

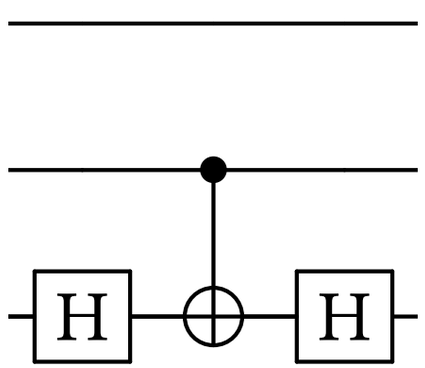


아이디어: 모듈 레벨 양자 회로 합성

1. 모듈 = 게이트 조합 (up to some fixed length)

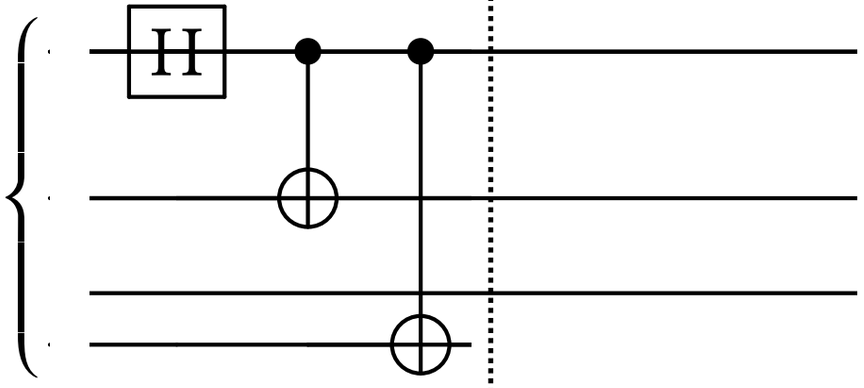
$M_1 =$ 

$M_2 =$ 

$M_3 =$ 

2. 명세와의 특성 차이를 줄이는 방향으로 모듈 쌓기

M_1

$|100\rangle$ 

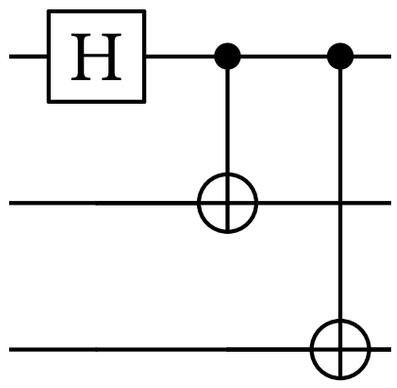
$|GHZ\rangle = \frac{1}{\sqrt{2}}(|000\rangle + |111\rangle)$

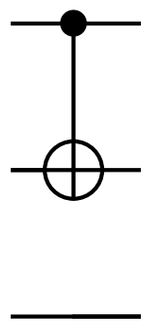
$\frac{1}{\sqrt{2}}(|100\rangle - |111\rangle)$ ⟷ $\frac{1}{\sqrt{2}}(|000\rangle + |111\rangle)$

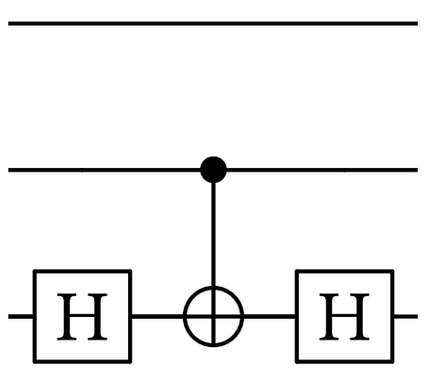
‘위상’ 차이

아이디어: 모듈 레벨 양자 회로 합성

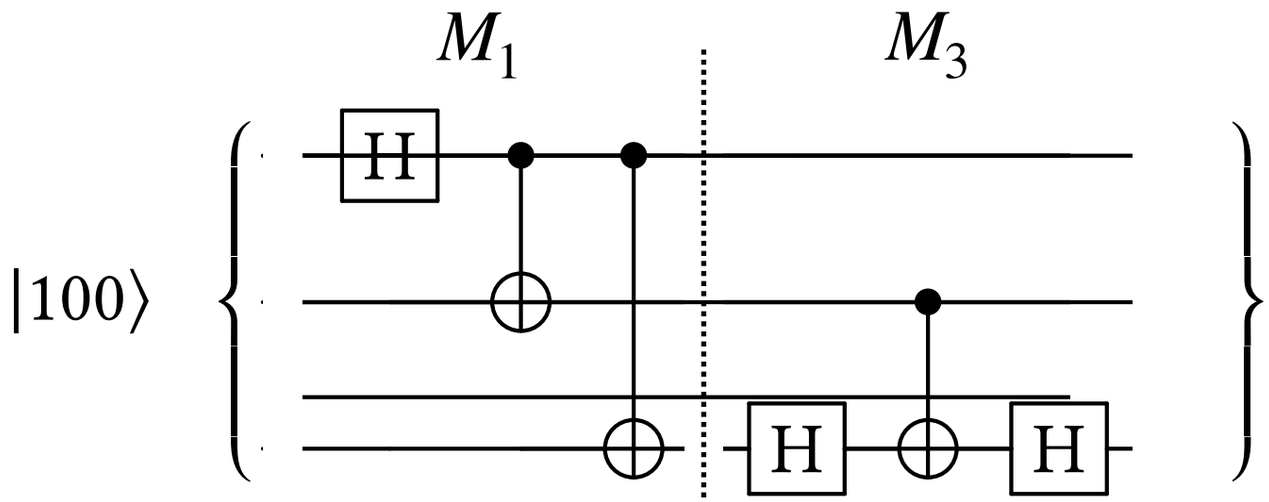
1. 모듈 = 게이트 조합 (up to some fixed length)

$M_1 =$ 

$M_2 =$ 

$M_3 =$ 

2. 명세와의 특성 차이를 줄이는 방향으로 모듈 쌓기



$|100\rangle$

$|GHZ\rangle = \frac{1}{\sqrt{2}}(|000\rangle + |111\rangle)$

$\frac{1}{\sqrt{2}}(|100\rangle - |111\rangle)$ ‘위상’ 차이 $\frac{1}{\sqrt{2}}(|000\rangle + |111\rangle)$

합성 알고리즘의 안전성 (Soundness)

"특정 가정하에서 모듈 기반 합성 알고리즘이 항상 정답을 찾아냄"

THEOREM 4.17. *Let* $E = \{(|in\rangle, |out\rangle)\}$ *be an example and* $C^* = M_1; \cdots; M_k$ *(*$M_i \in \mathcal{M}$ *and attribute of each* M_i *is not* IDENTITY*) be the solution circuit to be synthesized such that* $C^*(|in\rangle) = |out\rangle$*. Suppose* C^* *is monotonically decreasing (by input* $|in\rangle$*). Then, for any prefix* $C = M_1; \cdots; M_{l-1}$ $(l \leq k)$ *of* C^**,*

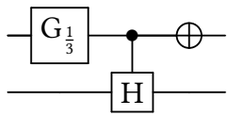
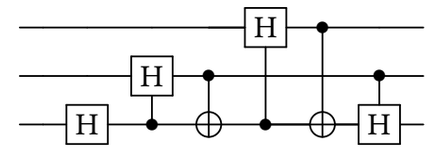
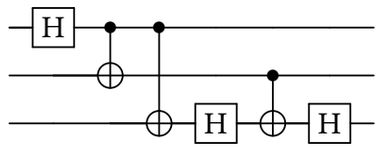
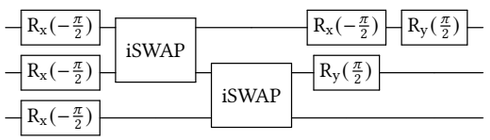
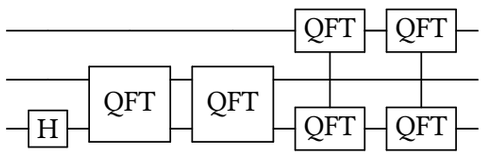
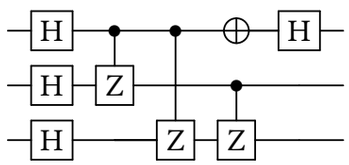
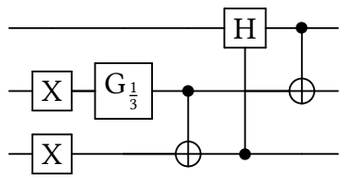
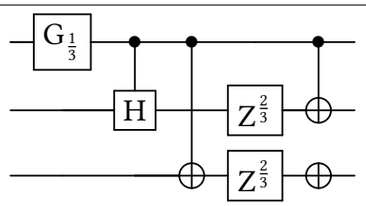
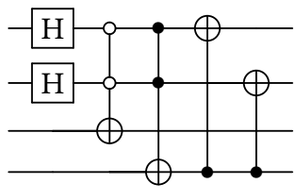
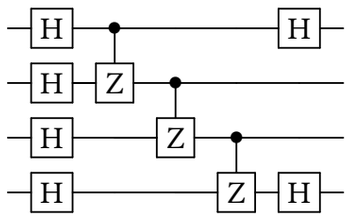
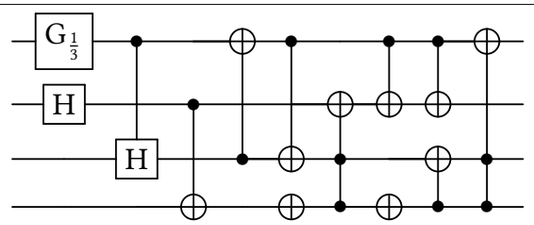
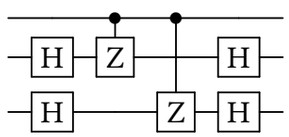
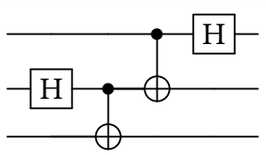
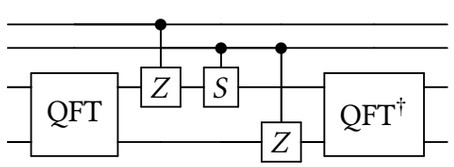
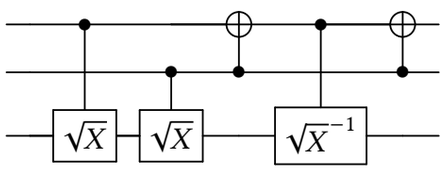
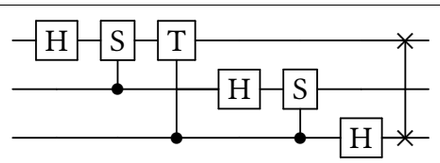
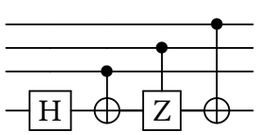
$$\text{is\_gap\_filled}(C, M_l, (|in\rangle, |out\rangle)) = \mathit{True}.$$

PROOF. Let $|\psi\rangle = C\,|in\rangle = M_{l-1} \cdots M_1\,|in\rangle$ be the output vector of C. By definition $M_k \cdots M_l\,|\psi\rangle = |out\rangle$ and thus

$$Att_{|\psi\rangle}(M_k M_{k-1} \cdots M_l) = |out\rangle \ominus |\psi\rangle = \text{gap\_att}_{|in\rangle,|out\rangle}(C).$$

Since C^* (and so C) is decreasing, by Lemma 4.16 $Att_{|\psi\rangle}(M_k M_{k-1} \cdots M_l) = Att_{|\psi\rangle}(M_l)$. Therefore, $\text{gap\_att}_{|in\rangle,|out\rangle}(C) = Att_{|\psi\rangle}(M_l)$, which is satisfying the criterion. □

벤치마크

Type	ID	Circuit	ID	Circuit
State Preparation	three_superpose		M_valued	
	GHZ_from_100		GHZ_by_iSWAP	
	GHZ_by_QFT		GHZ_Game	
	W_orthog		W_phased	
	W_four		cluster	
	bit_measure			
Multi IO	flip		teleportation	
	draper		toffoli_by_$\sqrt{X}$	
	QFT		indexed_bell	

게이트 레벨 합성 알고리즘

모듈 레벨 합성 알고리즘

ID	Base_{no_prune}	Base	Ours_{no_prune}	Ours	Spd-up
three_superpose	0.14	0.12	0.12	0.09	1x
M_valued	1764.75	1126.79	666.25	3.89	290x
GHZ_from_100	106.81	48.16	⊥	0.47	102x
GHZ_by_iSWAP	⊥	⊥	690.67	2.19	-
GHZ_by_QFT	116.90	101.65	101.17	39.26	3x
GHZ_Game	⊥	2305.71	4.51	0.57	4058x
W_orthog	2927.20	2075.06	248.23	2.43	854x
W_phased	⊥	⊥	258.56	5.43	-
W_four	⊥	⊥	2851.10	254.88	-
cluster	⊥	⊥	3560.38	8.91	-
bit_measure	⊥	⊥	⊥	⊥	-
flip	18.56	3.95	0.76	0.83	5x
teleportation	2.02	1.30	1.35	1.35	1x
indexed_bell	14.67	11.66	1.60	1.52	8x
toffoli_by_$\sqrt{X}$	956.29	716.28	306.10	264.66	3x
QFT	⊥	⊥	⊥	220.87	-
draper	⊥	⊥	933.47	737.99	-
Avg. (excluding ⊥/-)	656.37	639.07	687.45	96.58	20x

기회

- 양자 SW + X
  - 양자 SW 합성
  - 양자 SW 최적화
  - 양자 SW 정적 분석
  - 양자 SW 동적 분석
  - 양자 SW 정형 검증
  - 양자 SW 자동 수정
- 3無
  - 관심, 적용사례, 컴퓨터

감사합니다!