Model-Based Diagnosis with Multiple Observations

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Motivation

Software fault localization – find the culprit!

```
1  void foo(bool b)
2  {
3      int x = 0;
4
5      x++;
6      if (b)
7          x++;
8      else
9          x++;
10
11     assert(x != 2);
12 }
```

`b = true`:

$\Delta = \{\{3\},\{5\},\{6\},\{7\}\}$

`b = false`:

$\Delta = \{\{3\},\{5\},\{6\},\{9\}\}$

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both traces:

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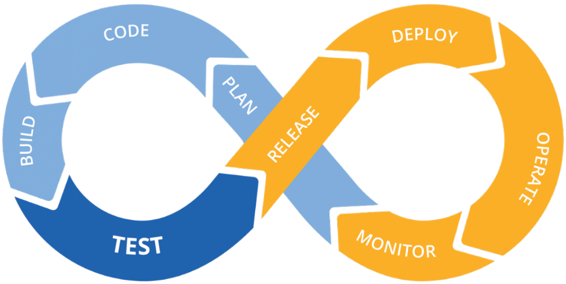
Meanwhile in real life...

Travis CI

Jenkins



continuous integration **(lots of traces!)**

Model-based diagnosis

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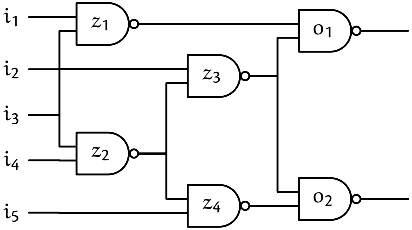

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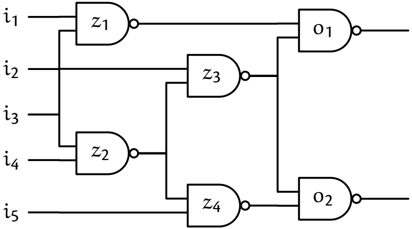

$$\begin{aligned} \mathsf{Comps} &\triangleq \{z_1, z_2, z_3, z_4, o_1, o_2\} \\ \mathsf{SD} &\triangleq \textstyle\bigwedge_{c \in \mathsf{Comps}} (\mathsf{Ab}(c) \vee F_c) \end{aligned}$$

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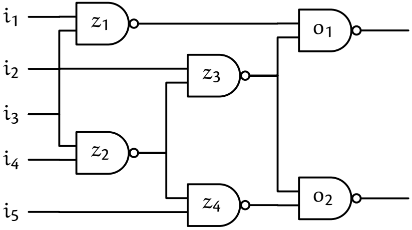

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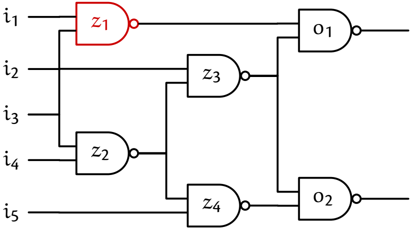

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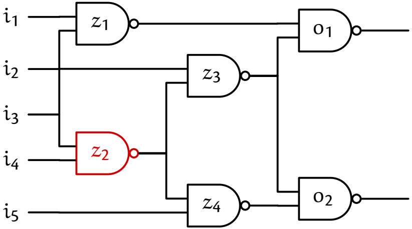

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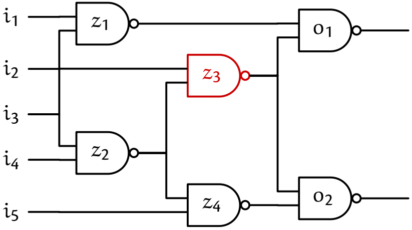

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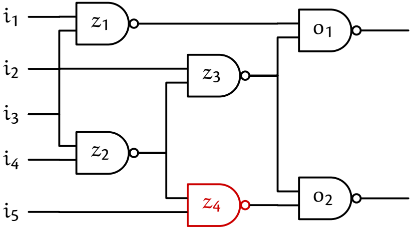

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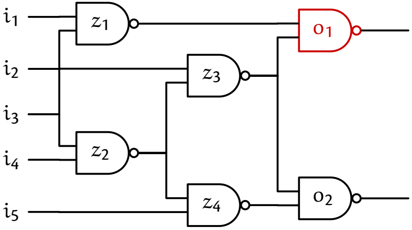

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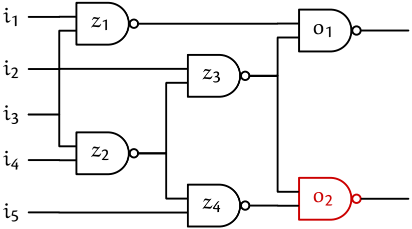

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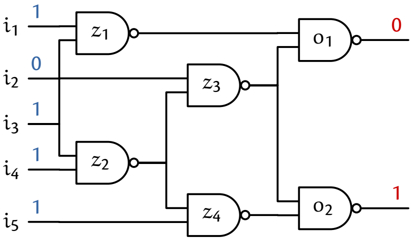

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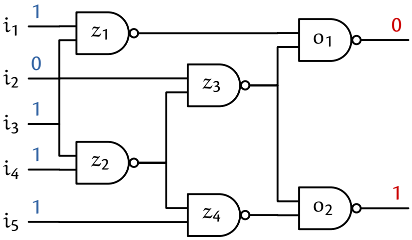
$$\text{Obs} = \{\langle i_1, i_2, i_3, i_4, i_5 \rangle = \langle 1, 0, 1, 1, 1 \rangle, \quad \langle o_1, o_2 \rangle = \langle 0, 1 \rangle\}$$

Model-based diagnosis



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$$\mathsf{SD} \wedge \mathsf{Obs} \wedge \textstyle\bigwedge_{c \in \mathsf{Comps}} \neg \mathsf{Ab}(c) \models \bot$$

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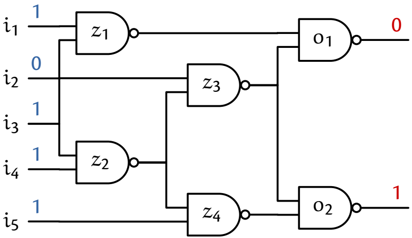

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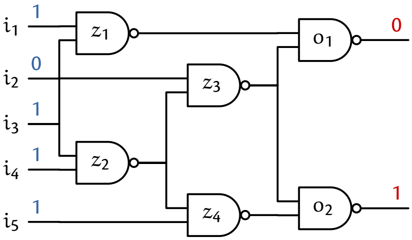

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$$\text{SD} \wedge \text{Obs} \wedge \bigwedge_{c \in \text{Comps}} \neg \text{Ab}(c) \models \bot$$

find $\Delta \subseteq \text{Comps}$ s.t.

$$\text{SD} \wedge \text{Obs} \wedge \bigwedge_{c \in \Delta} \text{Ab}(c) \wedge \bigwedge_{c \in \text{Comps} \setminus \Delta} \neg \text{Ab}(c) \not\models \bot$$

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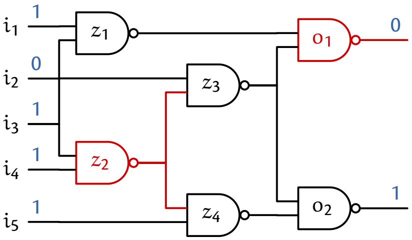

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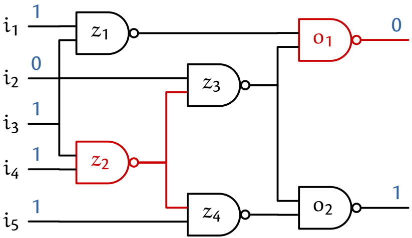
$$\Delta = \{z_2, o_1\}$$

Model-based diagnosis



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$$\text{SD} \wedge \text{Obs} \wedge \textstyle\bigwedge_{c \in \text{Comps}} \neg\text{Ab}(c) \models \perp$$

find $\Delta \subseteq \text{Comps}$ s.t.

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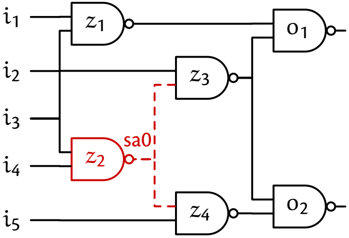
$\Delta = \{z_2, o_1\}$ — **minimize Δ, e.g. with MaxSAT**

Multiple observations?

MBD with multiple observations



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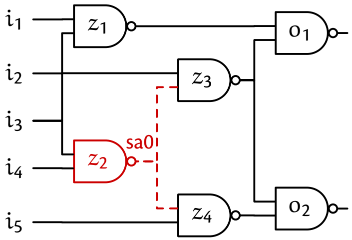
$$

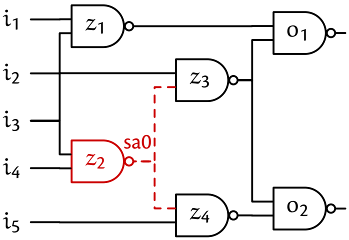
MBD with multiple observations



$$
\begin{aligned}
\mathrm{Comps} &\triangleq \{z_1, z_2, z_3, z_4, o_1, o_2\} \\
\mathrm{SD} &\triangleq \textstyle\bigwedge_{c \in \mathrm{Comps}} (\mathrm{Ab}(c) \vee F_c) \\
F_{z_1} &\triangleq \mathrm{CNF}(z_1 \leftrightarrow \neg(i_1 \wedge i_3)) \\
F_{z_2} &\triangleq \mathrm{CNF}(z_2 \leftrightarrow 0) \\
F_{z_3} &\triangleq \mathrm{CNF}(z_3 \leftrightarrow \neg(i_2 \wedge z_2)) \\
F_{z_4} &\triangleq \mathrm{CNF}(z_4 \leftrightarrow \neg(z_2 \wedge i_5)) \\
F_{o_1} &\triangleq \mathrm{CNF}(o_1 \leftrightarrow \neg(z_1 \wedge z_3)) \\
F_{o_2} &\triangleq \mathrm{CNF}(o_2 \leftrightarrow \neg(z_3 \wedge z_4))
\end{aligned}
$$

Observation	$\langle i_1, i_2, i_3, i_4, i_5, o_1, o_2 \rangle$	Diagnoses
Obs_1	$\langle 0,1,1,0,1,1,1 \rangle$	$D_1 = \{\{z_2\},\{z_3\},\{z_1,z_4\},\{z_1,o_2\},\{z_4,o_1\},\{o_1,o_2\}\}$
Obs_2	$\langle 1,1,1,0,1,1,1 \rangle$	$D_2 = \{\{z_2\},\{z_3\},\{z_4\},\{o_2\}\}$
Obs_3	$\langle 1,0,0,0,1,0,1 \rangle$	$D_3 = \{\{z_2\},\{z_4\},\{o_2\},\{z_3,o_1\}\}$

MBD with multiple observations



$$
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F_{z_3} &\triangleq \mathrm{CNF}(z_3 \leftrightarrow \neg(i_2 \wedge z_2)) \\
F_{z_4} &\triangleq \mathrm{CNF}(z_4 \leftrightarrow \neg(z_2 \wedge i_5)) \\
F_{o_1} &\triangleq \mathrm{CNF}(o_1 \leftrightarrow \neg(z_1 \wedge z_3)) \\
F_{o_2} &\triangleq \mathrm{CNF}(o_2 \leftrightarrow \neg(z_3 \wedge z_4))
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$$

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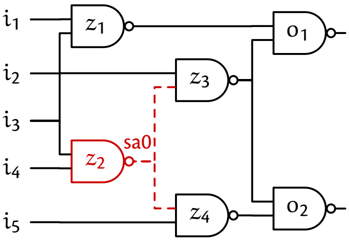
Obs_2	$\langle 1,1,1,0,1,1,1 \rangle$	$D_2 = \{\{z_2\},\{z_3\},\{z_4\},\{o_2\}\}$
Obs_3	$\langle 1,0,0,0,1,0,1 \rangle$	$D_3 = \{\{z_2\},\{z_4\},\{o_2\},\{z_3,o_1\}\}$

state-of-the-art approaches enumerate 96 *aggregated* diagnoses while

MBD with multiple observations



$$\begin{aligned}
\text{Comps} &\triangleq \{z_1, z_2, z_3, z_4, o_1, o_2\} \\
\text{SD} &\triangleq \bigwedge_{c \in \text{Comps}} (\text{Ab}(c) \vee F_c) \\
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F_{z_4} &\triangleq \text{CNF}(z_4 \leftrightarrow \neg(z_2 \wedge i_5)) \\
F_{o_1} &\triangleq \text{CNF}(o_1 \leftrightarrow \neg(z_1 \wedge z_3)) \\
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\end{aligned}$$

Observation	$\langle i_1, i_2, i_3, i_4, i_5, o_1, o_2 \rangle$	Diagnoses
Obs_1	$\langle 0,1,1,0,1,1,1 \rangle$	$D_1 = \{\{z_2\},\{z_3\},\{z_1,z_4\},\{z_1,o_2\},\{z_4,o_1\},\{o_1,o_2\}\}$
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Obs_3	$\langle 1,0,0,0,1,0,1 \rangle$	$D_3 = \{\{z_2\},\{z_4\},\{o_2\},\{z_3,o_1\}\}$

state-of-the-art approaches enumerate 96 *aggregated* diagnoses while

$\mathbb{D} = \{\{z_2\},\{z_1,z_4\},\{z_1,o_2\},\{z_3,o_1\},\{z_3,o_2\},\{z_4,o_1\},\{z_3,z_4\},\{o_1,o_2\}\}$, i.e. $|\mathbb{D}| = 8$

DiagCombine[1]:

[1] S. Lamraoui and S. Nakajima. *A formula-based approach for automatic fault localization of imperative programs*. In ICFEM, pp. 251–266, 2014.

DiagCombine[1]:

1. *enumerate* **all diagnoses** **for each observation**

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DiagCombine[1]:

1. *enumerate* **all diagnoses** **for each observation**
2. *compute* **all "combinations"**

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DiagCombine[1]:

1. *enumerate* **all diagnoses for each observation**
2. *compute* **all "combinations"**

(exponentially) many redundant diagnoses

[1] S. Lamraoui and S. Nakajima. *A formula-based approach for automatic fault localization of imperative programs.* In ICFEM, pp. 251–266, 2014.

Example of DiagCombine

$$D_1 \qquad \{\ \{0\},\ \{2\}\ \}$$

$$D_2 \qquad \{\ \{0\},\ \{1,2\}\ \}$$

$$\mathbb{D} \qquad \{ \qquad \}$$

Example of DiagCombine

$$D_1 \qquad \{\ \{0\},\ \{2\}\ \}$$

$$D_2 \qquad \{\ \{0\},\ \{1,2\}\ \}$$

$$\mathbb{D} \qquad \{\ \{0\},\ \qquad \}$$

Example of DiagCombine

$$\mathrm{D}_1 \qquad \{\ \{0\},\ \{2\}\ \}$$

$$\mathrm{D}_2 \qquad \{\ \{0\},\ \{1, 2\}\ \}$$

$$\mathbb{D} \qquad \{\ \{0\},\ \{0, 1, 2\},\ \qquad \}$$

Example of DiagCombine

$$D_1 \quad \{\ \{0\},\ \{2\}\ \}$$

$$D_2 \quad \{\ \{0\},\ \{1,2\}\ \}$$

$$\mathbb{D} \quad \{\ \{0\},\ \{0,1,2\},\ \{0,2\},\ \}$$

Example of DiagCombine

$$D_1 \qquad \{\ \{0\},\ \{2\}\ \}$$

$$D_2 \qquad \{\ \{0\},\ \{1,2\}\ \}$$

$$\mathbb{D} \qquad \{\ \{0\},\ \{0,1,2\},\ \{0,2\},\ \{1,2\}\ \}$$

Example of DiagCombine

$$D_1 \qquad \{\ \{0\},\ \{2\}\ \}$$

$$D_2 \qquad \{\ \{0\},\ \{1,2\}\ \}$$

redundant diagnoses!

$$\mathbb{D} \qquad \{\ \{0\},\ \cancel{\{0,1,2\}},\ \cancel{\{0,2\}},\ \{1,2\}\ \}$$

Improved DiagCombine

(a) $\exists_{\Delta} \forall_{D_i} \qquad \Delta \in D_i \;\Rightarrow\; \Delta \in \mathbb{D}$

Improved DiagCombine

$$\textbf{(a)} \quad \exists_{\Delta} \forall_{D_i} \qquad \Delta \in D_i \Rightarrow \Delta \in \mathbb{D}$$

$$\textbf{(b)} \quad \exists_{\Delta} \forall_{D_i} \exists_{\Delta_i \in D_i} \; \Delta_i \subseteq \Delta \Rightarrow \Delta \in \mathbb{D}$$

Improved DiagCombine

$$\textbf{(a)} \quad \exists_{\Delta}\, \forall_{D_i} \qquad \Delta \in D_i \;\Rightarrow\; \Delta \in \mathbb{D}$$

$$\textbf{(b)} \quad \exists_{\Delta}\, \forall_{D_i}\, \exists_{\Delta_i \in D_i} \quad \Delta_i \subseteq \Delta \;\Rightarrow\; \Delta \in \mathbb{D}$$

$$D_1 \qquad \{\ \{0\},\ \{2\}\ \}$$

$$D_2 \qquad \{\ \{0\},\ \{1,2\}\ \}$$

$$\mathbb{D} \qquad \{ \qquad \}$$

$$\text{(a)} \quad \exists_{\Delta} \forall_{D_i} \qquad \Delta \in D_i \Rightarrow \Delta \in \mathbb{D}$$

$$\textbf{(b)} \quad \exists_{\Delta} \forall_{D_i} \exists_{\Delta_i \in D_i} \ \Delta_i \subseteq \Delta \Rightarrow \Delta \in \mathbb{D}$$

$D_1 \qquad \{ \{0\}, \{2\} \}$

$D_2 \qquad \{ \{0\}, \{1, 2\} \}$

$\mathbb{D} \qquad \{ \{0\}, \qquad \}$

Improved DiagCombine

$$\textbf{(a)} \quad \exists_{\Delta} \forall_{D_i} \qquad \Delta \in D_i \Rightarrow \Delta \in \mathbb{D}$$

$$\textbf{(b)} \quad \exists_{\Delta} \forall_{D_i} \exists_{\Delta_i \in D_i} \quad \Delta_i \subseteq \Delta \Rightarrow \Delta \in \mathbb{D}$$

$$D_1 \qquad \{ \quad \{2\} \}$$

$$D_2 \qquad \{ \quad \{1, 2\} \}$$

$$\mathbb{D} \qquad \{ \{0\}, \quad \{1, 2\} \}$$

$$\textbf{(a)} \quad \exists_{\Delta} \forall_{D_i} \qquad \Delta \in D_i \Rightarrow \Delta \in \mathbb{D}$$

$$\textbf{(b)} \quad \exists_{\Delta} \forall_{D_i} \exists_{\Delta_i \in D_i} \; \Delta_i \subseteq \Delta \Rightarrow \Delta \in \mathbb{D}$$

$$D_1 \qquad \{ \qquad \{2\} \; \}$$

$$D_2 \qquad \{ \qquad \qquad \}$$

$$\mathbb{D} \qquad \{ \{0\}, \cancel{\{0,1,2\}}, \cancel{\{0,2\}}, \{1,2\} \}$$

(a) and **(b)** **not always apply!**

⬇

no silver bullet

Implicit hitting set dualization

Implicit hitting set dualization

input : $SD, Obs_1, \ldots, Obs_m$
output : $\mathbb{D} = \{\Delta_1, \Delta_2 \ldots\}, \mathbb{U} = \{\mathcal{U}_1, \mathcal{U}_2 \ldots\}$

```
(H_1, ..., H_m, S) ← Encode(SD, Obs_1, ..., Obs_m)
(D, U) ← (∅, ∅)
while true:
    (st, Δ) ← MinHS(U, D)                  # find a min HS of U s.t. D
    if not st:
        break
    foreach i ∈ {1, ..., m}:
        (st, κ) ← SAT(H_i ∪ (S \ Δ))
        if not st:
            𝒰 ← Reduce(κ)                  # 𝒰 is MUS of H_i ∪ (S \ Δ)
            U ← U ∪ {𝒰}
            ReportExpl(𝒰)                   # report min explanation
            break
    else:                                   # if the loop was not broken
        D ← D ∪ {Δ}                         # block diagnosis Δ
        ReportDiag(Δ)                       # report min diagnosis
    foreach i ∈ {1, ..., m}:
        if not SAT(H_i ∪ D):                # no more diagnoses exist
            return
return
```

Implicit hitting set dualization

input : $\mathsf{SD}, \mathsf{Obs}_1, \ldots, \mathsf{Obs}_m$
output : $\mathbb{D} = \{\Delta_1, \Delta_2 \ldots\}$, $\mathbb{U} = \{\mathcal{U}_1, \mathcal{U}_2 \ldots\}$

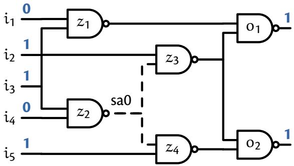
$(\mathcal{H}_1, \ldots, \mathcal{H}_m, \mathcal{S}) \leftarrow \mathsf{Encode}(\mathsf{SD}, \mathsf{Obs}_1, \ldots, \mathsf{Obs}_m)$
$(\mathbb{D}, \mathbb{U}) \leftarrow (\emptyset, \emptyset)$

while true:
    $(st, \Delta) \leftarrow \mathtt{MinHS}(\mathbb{U}, \mathbb{D})$ *# find a min HS of $\mathbb{U}$ s.t. $\mathbb{D}$*
    if not *st*:
        break
    foreach $i \in \{1, \ldots, m\}$:
        $(st, \kappa) \leftarrow \mathtt{SAT}(\mathcal{H}_i \cup (\mathcal{S} \setminus \Delta))$
        if not *st*:
            $\mathcal{U} \leftarrow \mathtt{Reduce}(\kappa)$ *# $\mathcal{U}$ is MUS of $\mathcal{H}_i \cup (\mathcal{S} \setminus \Delta)$*
            $\mathbb{U} \leftarrow \mathbb{U} \cup \{\mathcal{U}\}$
            $\mathtt{ReportExpl}(\mathcal{U})$ *# report min explanation*
            break
    else: *# if the loop was not broken*
        $\mathbb{D} \leftarrow \mathbb{D} \cup \{\Delta\}$ *# block diagnosis Δ*
        $\mathtt{ReportDiag}(\Delta)$ *# report min diagnosis*
    foreach $i \in \{1, \ldots, m\}$:
        if not $\mathtt{SAT}(\mathcal{H}_i \cup \mathbb{D})$: *# no more diagnoses exist*
            return
return

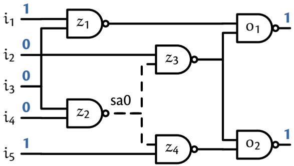
Implicit hitting set dualization

```
input  : SD, Obs_1, ..., Obs_m
output : 𝔻 = {Δ_1, Δ_2 ...}, 𝕌 = {𝒰_1, 𝒰_2 ...}

(ℋ_1, ..., ℋ_m, 𝒮) ← Encode(SD, Obs_1, ..., Obs_m)
(𝔻, 𝕌) ← (∅, ∅)

while true:
    (st, Δ) ← MinHS(𝕌, 𝔻)                          # find a min HS of 𝕌 s.t. 𝔻
    if not st:
        break
    foreach i ∈ {1, ..., m}:
        (st, κ) ← SAT(ℋ_i ∪ (𝒮 \ Δ))
        if not st:
            𝒰 ← Reduce(κ)                           # 𝒰 is MUS of ℋ_i ∪ (𝒮 \ Δ)
            𝕌 ← 𝕌 ∪ {𝒰}
            ReportExpl(𝒰)                           # report min explanation
            break
    else:                                           # if the loop was not broken
        𝔻 ← 𝔻 ∪ {Δ}                                 # block diagnosis Δ
        ReportDiag(Δ)                               # report min diagnosis
    foreach i ∈ {1, ..., m}:
        if not SAT(ℋ_i ∪ 𝔻):                        # no more diagnoses exist
            return
return
```

HSD – example



i1 0
i2 1
i3 1
i4 0
i5 1
z1
z2
z3
z4
sa0
o1 1
o2 1



i1 1
i2 0
i3 0
i4 0
i5 1
z1
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z3
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o1 1
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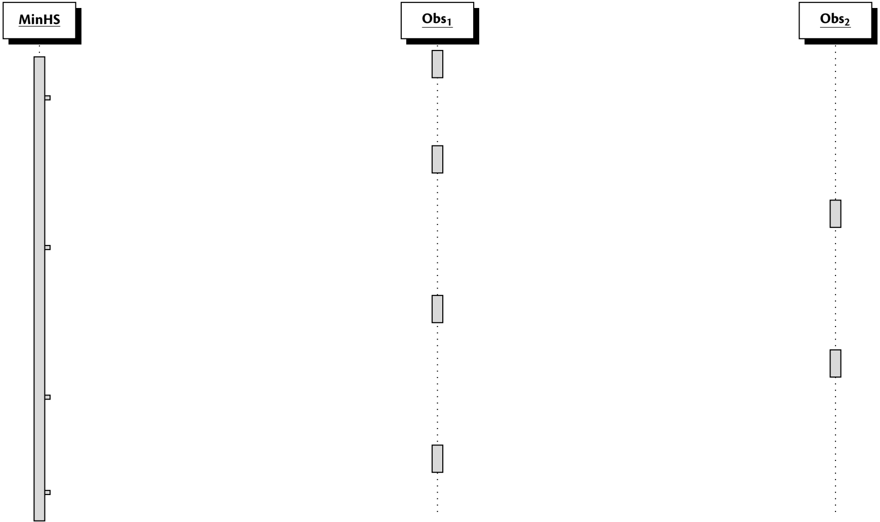
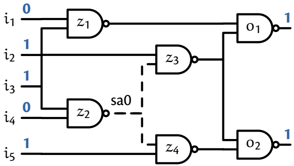
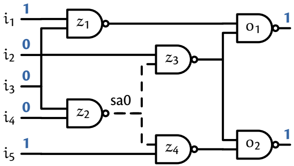


MinHS
Obs1
Obs2

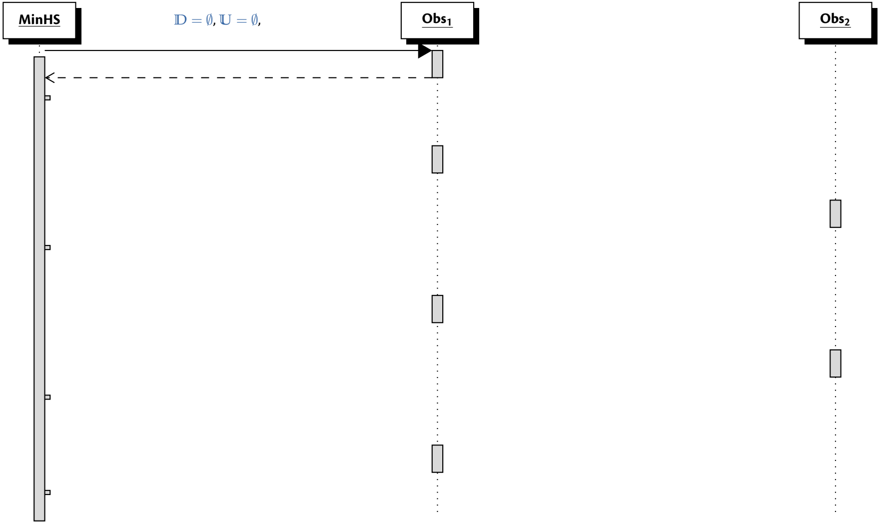
HSD – example



i_1 0
i_2 1
i_3 1
i_4 0
i_5 1
z_1
z_2
z_3
z_4
sa0
o_1 1
o_2 1

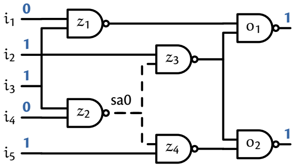


i_1 1
i_2 0
i_3 0
i_4 0
i_5 1
z_1
z_2
z_3
z_4
sa0
o_1 1
o_2 1

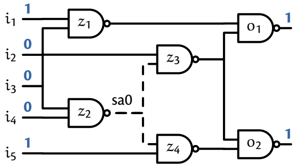


MinHS
$\mathbb{D} = \emptyset, \mathbb{U} = \emptyset,$
Obs_1
Obs_2

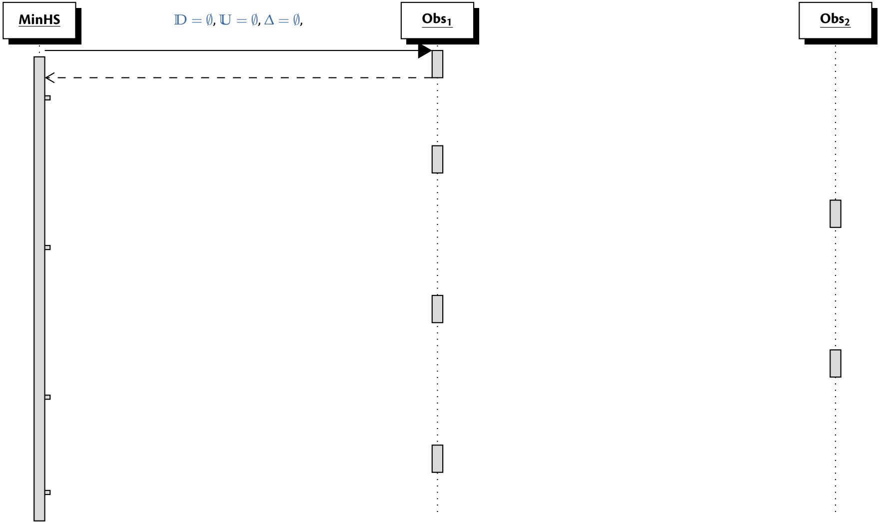
HSD – example



i_1 0
i_2 1
i_3 1
i_4 0
i_5 1
z_1
z_2
z_3
z_4
sa0
o_1 1
o_2 1

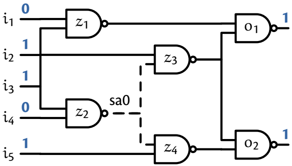


i_1 1
i_2 0
i_3 0
i_4 0
i_5 1
z_1
z_2
z_3
z_4
sa0
o_1 1
o_2 1

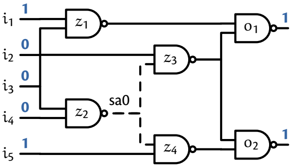


MinHS
$\mathbb{D} = \emptyset, \mathbb{U} = \emptyset, \Delta = \emptyset,$
$\mathbf{Obs_1}$
$\mathbf{Obs_2}$

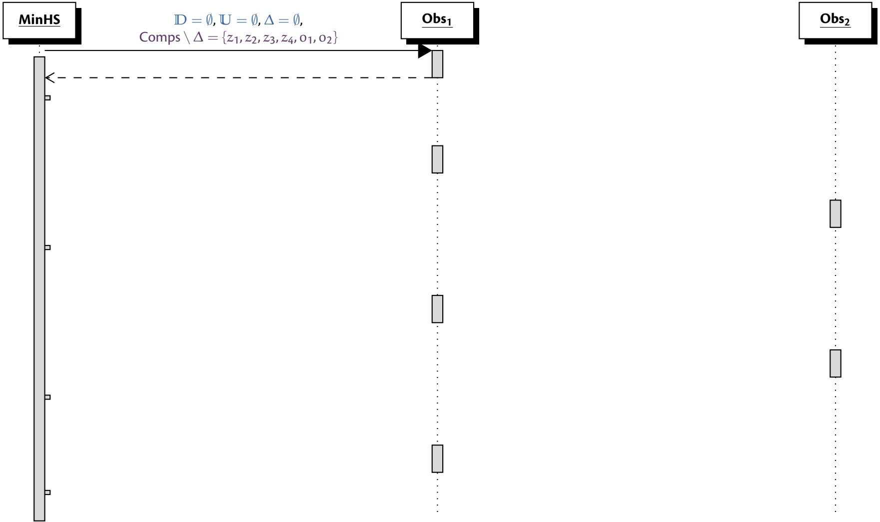
HSD – example



i_1 0
i_2 1
i_3 1
i_4 0
i_5 1
z_1
z_2
z_3
z_4
sa0
o_1 1
o_2 1

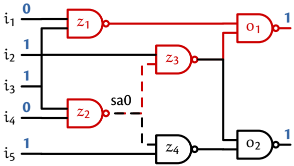


i_1 1
i_2 0
i_3 0
i_4 0
i_5 1
z_1
z_2
z_3
z_4
sa0
o_1 1
o_2 1

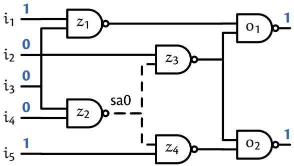


MinHS
$\mathbb{D} = \emptyset, \mathbb{U} = \emptyset, \Delta = \emptyset,$
Comps $\setminus \Delta = \{z_1, z_2, z_3, z_4, o_1, o_2\}$
Obs_1
Obs_2

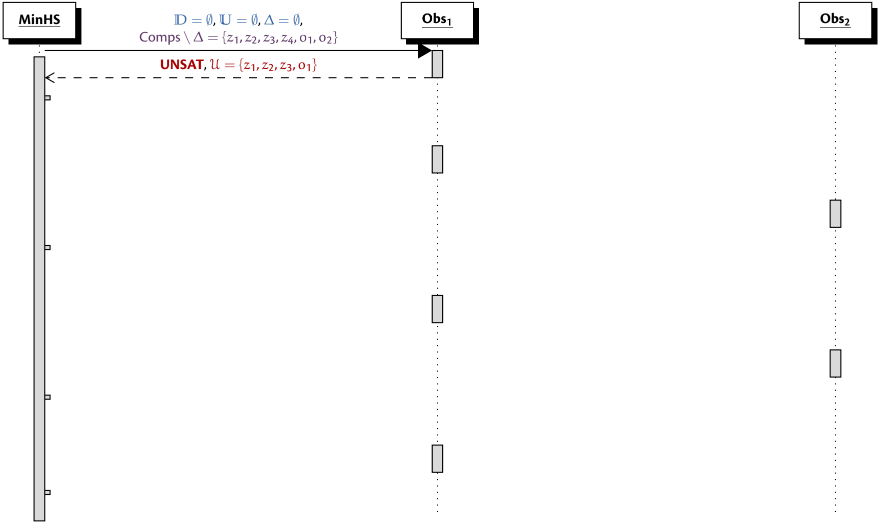
HSD – example



i_1 0
i_2 1
i_3 1
i_4 0
i_5 1
z_1
z_2
z_3
z_4
sa0
o_1 1
o_2 1

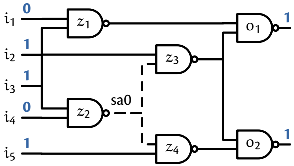


i_1 1
i_2 0
i_3 0
i_4 0
i_5 1
z_1
z_2
z_3
z_4
sa0
o_1 1
o_2 1

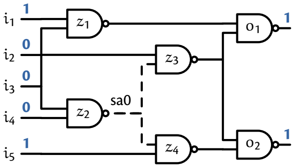


MinHS
Obs$_1$
Obs$_2$
$\mathbb{D} = \emptyset, \mathbb{U} = \emptyset, \Delta = \emptyset,$
Comps $\setminus \Delta = \{z_1, z_2, z_3, z_4, o_1, o_2\}$
UNSAT, $\mathcal{U} = \{z_1, z_2, z_3, o_1\}$

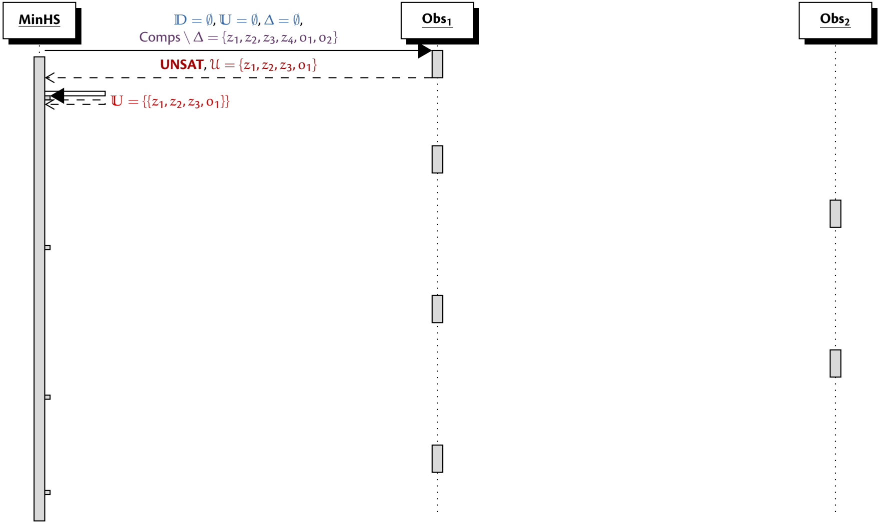
HSD – example



i_1 0
i_2 1
i_3 1
i_4 0
i_5 1
z_1
z_2
z_3
z_4
sa0
o_1 1
o_2 1

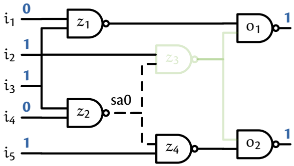


i_1 1
i_2 0
i_3 0
i_4 0
i_5 1
z_1
z_2
z_3
z_4
sa0
o_1 1
o_2 1

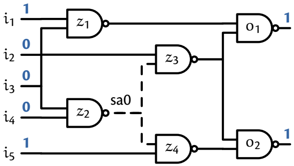


MinHS
Obs$_1$
Obs$_2$
$\mathbb{D} = \emptyset, \mathbb{U} = \emptyset, \Delta = \emptyset,$
$\text{Comps} \setminus \Delta = \{z_1, z_2, z_3, z_4, o_1, o_2\}$
UNSAT, $\mathcal{U} = \{z_1, z_2, z_3, o_1\}$
$\mathbb{U} = \{\{z_1, z_2, z_3, o_1\}\}$

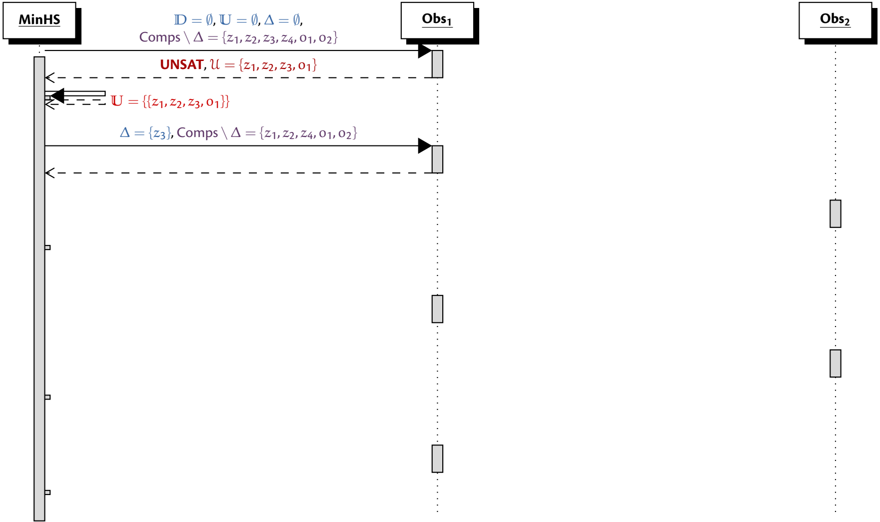
HSD – example



i_1 0
i_2 1
i_3 1
i_4 0
i_5 1
z_1
z_2
z_3
z_4
sa0
o_1 1
o_2 1

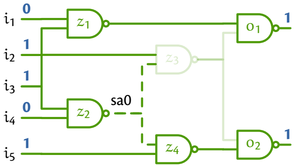


i_1 1
i_2 0
i_3 0
i_4 0
i_5 1
z_1
z_2
z_3
z_4
sa0
o_1 1
o_2 1

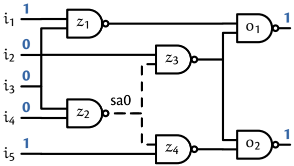


MinHS
Obs_1
Obs_2
$\mathbb{D} = \emptyset, \mathbb{U} = \emptyset, \Delta = \emptyset,$
$\text{Comps} \setminus \Delta = \{z_1, z_2, z_3, z_4, o_1, o_2\}$
UNSAT, $\mathcal{U} = \{z_1, z_2, z_3, o_1\}$
$\mathbb{U} = \{\{z_1, z_2, z_3, o_1\}\}$
$\Delta = \{z_3\}, \text{Comps} \setminus \Delta = \{z_1, z_2, z_4, o_1, o_2\}$

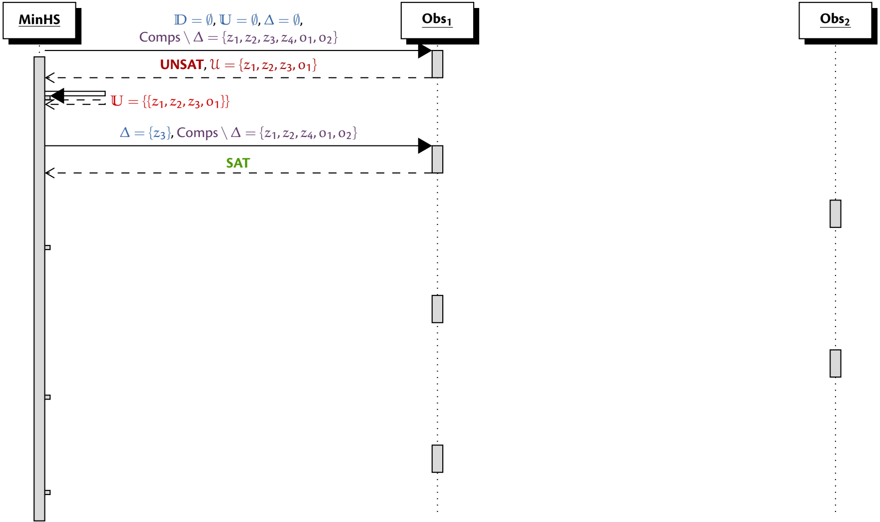
HSD – example



i_1 0
i_2 1
i_3 1
i_4 0
i_5 1
z_1
z_2
z_3
z_4
sa0
o_1 1
o_2 1

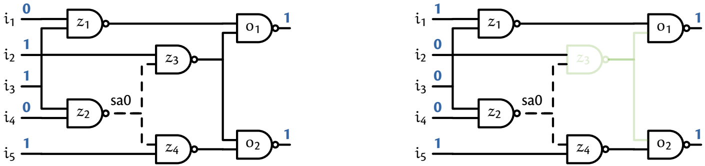


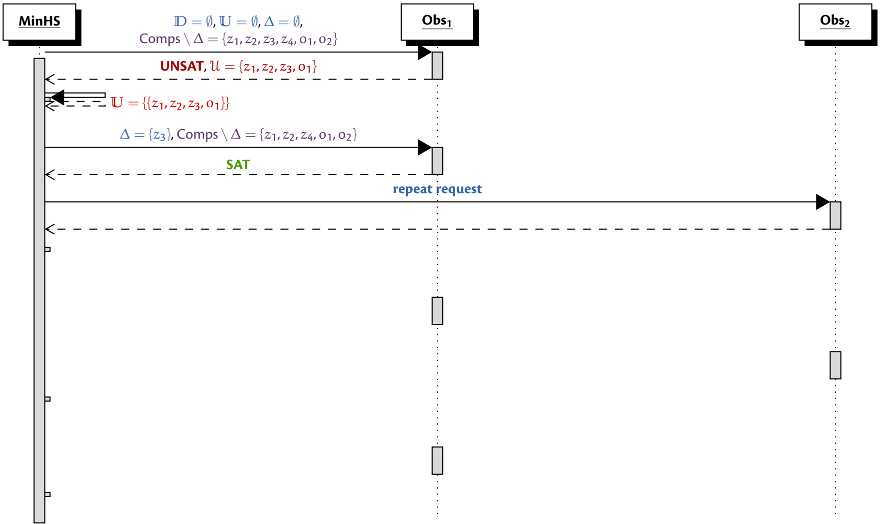
i_1 1
i_2 0
i_3 0
i_4 0
i_5 1
z_1
z_2
z_3
z_4
sa0
o_1 1
o_2 1



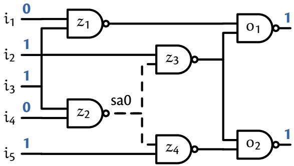
MinHS
Obs$_1$
Obs$_2$
$\mathbb{D} = \emptyset, \mathbb{U} = \emptyset, \Delta = \emptyset,$
$\text{Comps} \setminus \Delta = \{z_1, z_2, z_3, z_4, o_1, o_2\}$
UNSAT, $\mathcal{U} = \{z_1, z_2, z_3, o_1\}$
$\mathbb{U} = \{\{z_1, z_2, z_3, o_1\}\}$
$\Delta = \{z_3\}, \text{Comps} \setminus \Delta = \{z_1, z_2, z_4, o_1, o_2\}$
SAT

HSD – example

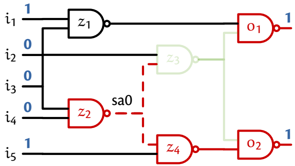

i_1 0
i_2 1
i_3 1
i_4 0
i_5 1
z_1
z_2
z_3
z_4
sa0
o_1 1
o_2 1
i_1 1
i_2 0
i_3 0
i_4 0
i_5 1
z_1
z_2
z_3
z_4
sa0
o_1 1
o_2 1


MinHS
Obs$_1$
Obs$_2$
$\mathbb{D} = \emptyset, \mathbb{U} = \emptyset, \Delta = \emptyset,$
Comps $\setminus \Delta = \{z_1, z_2, z_3, z_4, o_1, o_2\}$
UNSAT, $\mathcal{U} = \{z_1, z_2, z_3, o_1\}$
$\mathbb{U} = \{\{z_1, z_2, z_3, o_1\}\}$
$\Delta = \{z_3\}$, Comps $\setminus \Delta = \{z_1, z_2, z_4, o_1, o_2\}$
SAT
repeat request

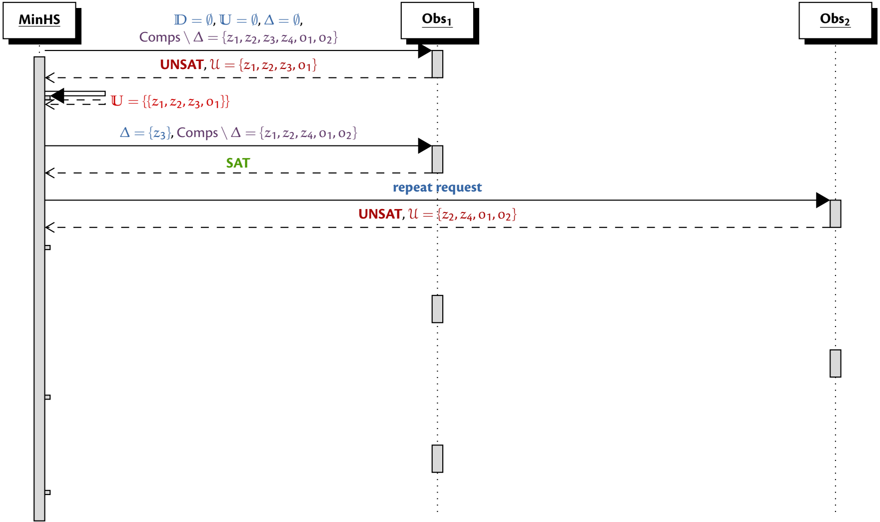
HSD – example



i_1 0
i_2 1
i_3 1
i_4 0
i_5 1
z_1
z_2
z_3
z_4
sa0
o_1 1
o_2 1

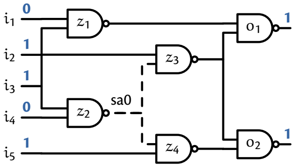


i_1 1
i_2 0
i_3 0
i_4 0
i_5 1
z_1
z_2
z_3
z_4
sa0
o_1 1
o_2 1

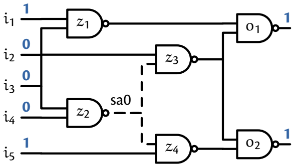


MinHS
Obs$_1$
Obs$_2$
$\mathbb{D} = \emptyset, \mathbb{U} = \emptyset, \Delta = \emptyset,$
Comps $\setminus \Delta = \{z_1, z_2, z_3, z_4, o_1, o_2\}$
UNSAT, $\mathcal{U} = \{z_1, z_2, z_3, o_1\}$
$\mathbb{U} = \{\{z_1, z_2, z_3, o_1\}\}$
$\Delta = \{z_3\}$, Comps $\setminus \Delta = \{z_1, z_2, z_4, o_1, o_2\}$
SAT
repeat request
UNSAT, $\mathcal{U} = \{z_2, z_4, o_1, o_2\}$

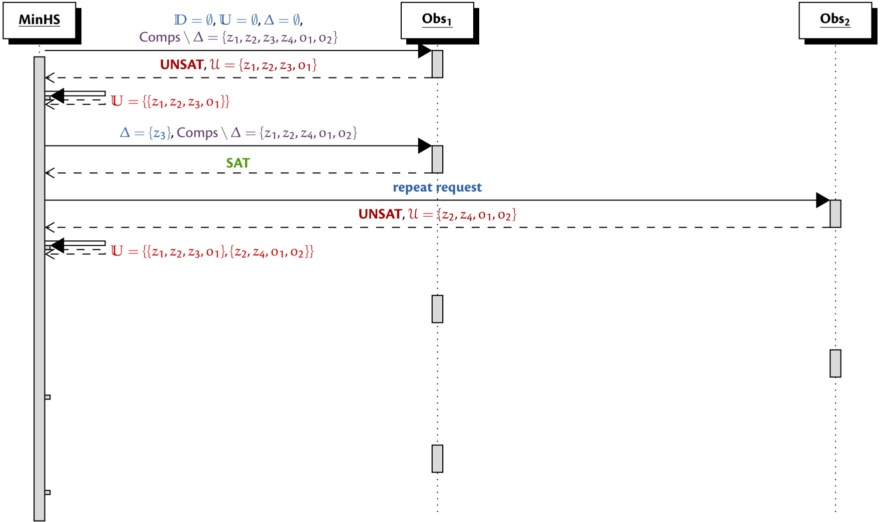
HSD – example



i1 0
i2 1
i3 1
i4 0
i5 1
z1
z2
z3
z4
sa0
o1 1
o2 1

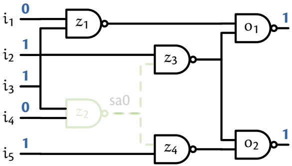


i1 1
i2 0
i3 0
i4 0
i5 1
z1
z2
z3
z4
sa0
o1 1
o2 1

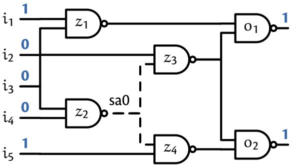


MinHS
Obs1
Obs2
$\mathbb{D} = \emptyset, \mathbb{U} = \emptyset, \Delta = \emptyset,$
$\text{Comps} \setminus \Delta = \{z_1, z_2, z_3, z_4, o_1, o_2\}$
UNSAT, $\mathcal{U} = \{z_1, z_2, z_3, o_1\}$
$\mathbb{U} = \{\{z_1, z_2, z_3, o_1\}\}$
$\Delta = \{z_3\}, \text{Comps} \setminus \Delta = \{z_1, z_2, z_4, o_1, o_2\}$
SAT
repeat request
UNSAT, $\mathcal{U} = \{z_2, z_4, o_1, o_2\}$
$\mathbb{U} = \{\{z_1, z_2, z_3, o_1\}, \{z_2, z_4, o_1, o_2\}\}$

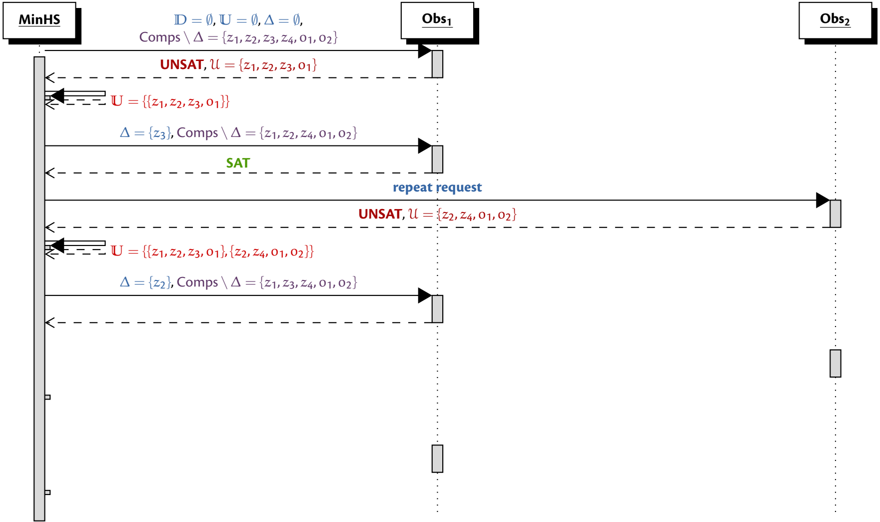
HSD – example



i1 0
i2 1
i3 1
i4 0
i5 1
z1
z2
z3
z4
sa0
o1 1
o2 1

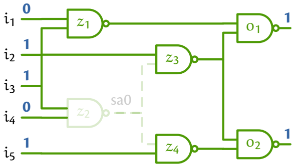


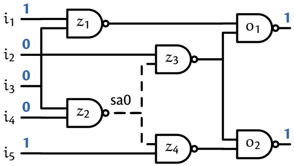
i1 1
i2 0
i3 0
i4 0
i5 1
z1
z2
z3
z4
sa0
o1 1
o2 1

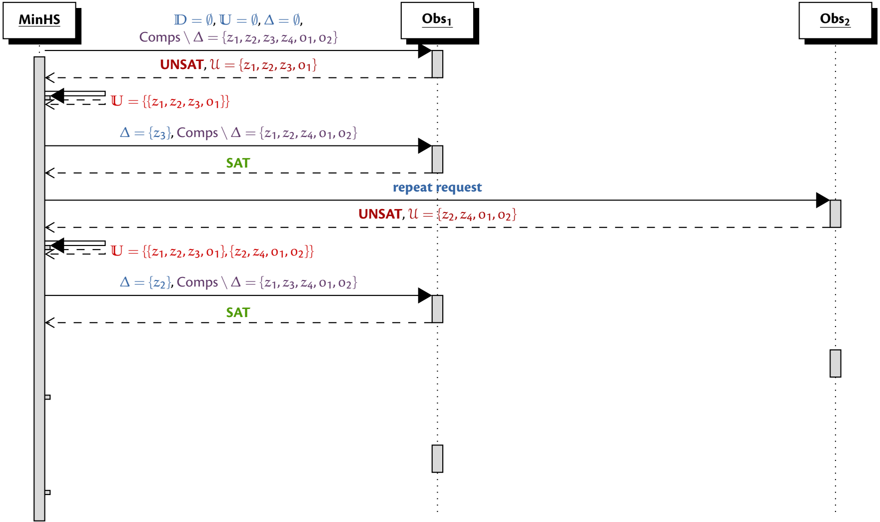


MinHS
Obs$_1$
Obs$_2$
$\mathbb{D} = \emptyset, \mathbb{U} = \emptyset, \Delta = \emptyset,$
$\text{Comps} \setminus \Delta = \{z_1, z_2, z_3, z_4, o_1, o_2\}$
UNSAT, $\mathcal{U} = \{z_1, z_2, z_3, o_1\}$
$\mathbb{U} = \{\{z_1, z_2, z_3, o_1\}\}$
$\Delta = \{z_3\}, \text{Comps} \setminus \Delta = \{z_1, z_2, z_4, o_1, o_2\}$
SAT
repeat request
UNSAT, $\mathcal{U} = \{z_2, z_4, o_1, o_2\}$
$\mathbb{U} = \{\{z_1, z_2, z_3, o_1\}, \{z_2, z_4, o_1, o_2\}\}$
$\Delta = \{z_2\}, \text{Comps} \setminus \Delta = \{z_1, z_3, z_4, o_1, o_2\}$

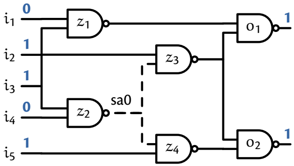
HSD – example


i_1 0
i_2 1
i_3 1
i_4 0
i_5 1
z_1
z_2
z_3
z_4
sa0
o_1 1
o_2 1

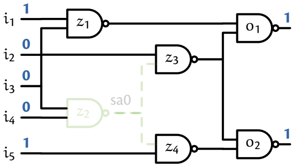

i_1 1
i_2 0
i_3 0
i_4 0
i_5 1
z_1
z_2
z_3
z_4
sa0
o_1 1
o_2 1


MinHS
Obs_1
Obs_2
$\mathbb{D} = \emptyset, \mathbb{U} = \emptyset, \Delta = \emptyset,$
$\text{Comps} \setminus \Delta = \{z_1, z_2, z_3, z_4, o_1, o_2\}$
UNSAT, $\mathcal{U} = \{z_1, z_2, z_3, o_1\}$
$\mathbb{U} = \{\{z_1, z_2, z_3, o_1\}\}$
$\Delta = \{z_3\}, \text{Comps} \setminus \Delta = \{z_1, z_2, z_4, o_1, o_2\}$
SAT
repeat request
UNSAT, $\mathcal{U} = \{z_2, z_4, o_1, o_2\}$
$\mathbb{U} = \{\{z_1, z_2, z_3, o_1\}, \{z_2, z_4, o_1, o_2\}\}$
$\Delta = \{z_2\}, \text{Comps} \setminus \Delta = \{z_1, z_3, z_4, o_1, o_2\}$
SAT

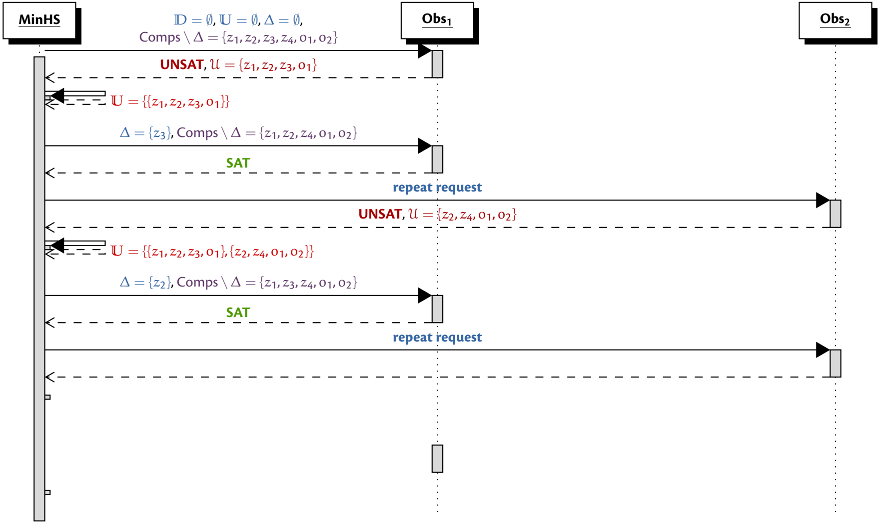
HSD – example



i_1 0
i_2 1
i_3 1
i_4 0
i_5 1
z_1
z_2
z_3
z_4
sa0
o_1 1
o_2 1

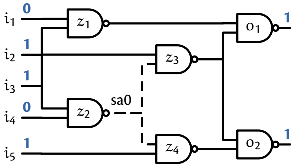


i_1 1
i_2 0
i_3 0
i_4 0
i_5 1
z_1
z_2
z_3
z_4
sa0
o_1 1
o_2 1

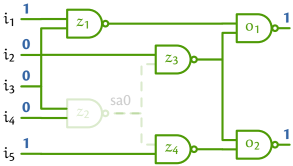


MinHS
Obs$_1$
Obs$_2$
$\mathbb{D} = \emptyset, \mathbb{U} = \emptyset, \Delta = \emptyset,$
Comps $\setminus \Delta = \{z_1, z_2, z_3, z_4, o_1, o_2\}$
UNSAT, $\mathcal{U} = \{z_1, z_2, z_3, o_1\}$
$\mathbb{U} = \{\{z_1, z_2, z_3, o_1\}\}$
$\Delta = \{z_3\}$, Comps $\setminus \Delta = \{z_1, z_2, z_4, o_1, o_2\}$
SAT
repeat request
UNSAT, $\mathcal{U} = \{z_2, z_4, o_1, o_2\}$
$\mathbb{U} = \{\{z_1, z_2, z_3, o_1\}, \{z_2, z_4, o_1, o_2\}\}$
$\Delta = \{z_2\}$, Comps $\setminus \Delta = \{z_1, z_3, z_4, o_1, o_2\}$
SAT
repeat request

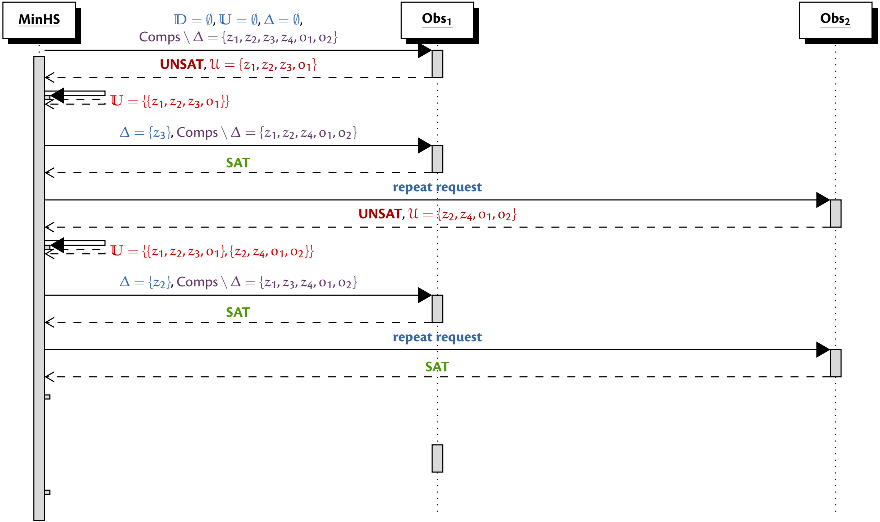
HSD – example



i_1 0
i_2 1
i_3 1
i_4 0
i_5 1
z_1
z_2
z_3
z_4
sa0
o_1 1
o_2 1

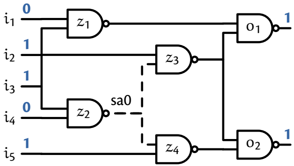


i_1 1
i_2 0
i_3 0
i_4 0
i_5 1
z_1
z_2
z_3
z_4
sa0
o_1 1
o_2 1

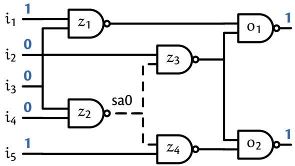


MinHS
Obs$_1$
Obs$_2$
$\mathbb{D} = \emptyset, \mathbb{U} = \emptyset, \Delta = \emptyset,$
$\text{Comps} \setminus \Delta = \{z_1, z_2, z_3, z_4, o_1, o_2\}$
UNSAT, $\mathcal{U} = \{z_1, z_2, z_3, o_1\}$
$\mathbb{U} = \{\{z_1, z_2, z_3, o_1\}\}$
$\Delta = \{z_3\}, \text{Comps} \setminus \Delta = \{z_1, z_2, z_4, o_1, o_2\}$
SAT
repeat request
UNSAT, $\mathcal{U} = \{z_2, z_4, o_1, o_2\}$
$\mathbb{U} = \{\{z_1, z_2, z_3, o_1\}, \{z_2, z_4, o_1, o_2\}\}$
$\Delta = \{z_2\}, \text{Comps} \setminus \Delta = \{z_1, z_3, z_4, o_1, o_2\}$
SAT
repeat request
SAT

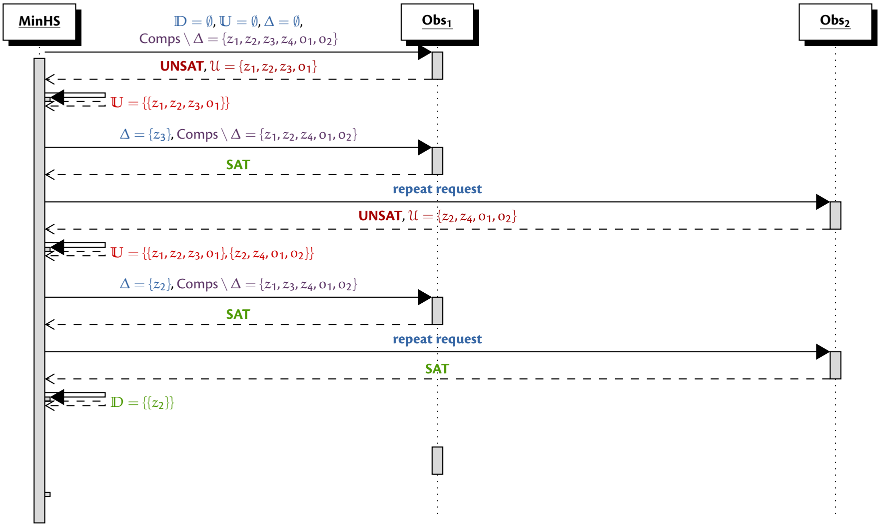
HSD – example



i_1 0
i_2 1
i_3 1
i_4 0
i_5 1
z_1
z_2
z_3
z_4
sa0
o_1 1
o_2 1

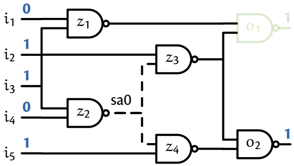


i_1 1
i_2 0
i_3 0
i_4 0
i_5 1
z_1
z_2
z_3
z_4
sa0
o_1 1
o_2 1

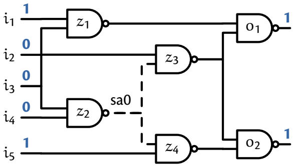


MinHS
Obs$_1$
Obs$_2$
$\mathbb{D} = \emptyset, \mathbb{U} = \emptyset, \Delta = \emptyset,$
$\mathsf{Comps} \setminus \Delta = \{z_1, z_2, z_3, z_4, o_1, o_2\}$
UNSAT, $\mathcal{U} = \{z_1, z_2, z_3, o_1\}$
$\mathbb{U} = \{\{z_1, z_2, z_3, o_1\}\}$
$\Delta = \{z_3\}, \mathsf{Comps} \setminus \Delta = \{z_1, z_2, z_4, o_1, o_2\}$
SAT
repeat request
UNSAT, $\mathcal{U} = \{z_2, z_4, o_1, o_2\}$
$\mathbb{U} = \{\{z_1, z_2, z_3, o_1\}, \{z_2, z_4, o_1, o_2\}\}$
$\Delta = \{z_2\}, \mathsf{Comps} \setminus \Delta = \{z_1, z_3, z_4, o_1, o_2\}$
SAT
repeat request
SAT
$\mathbb{D} = \{\{z_2\}\}$

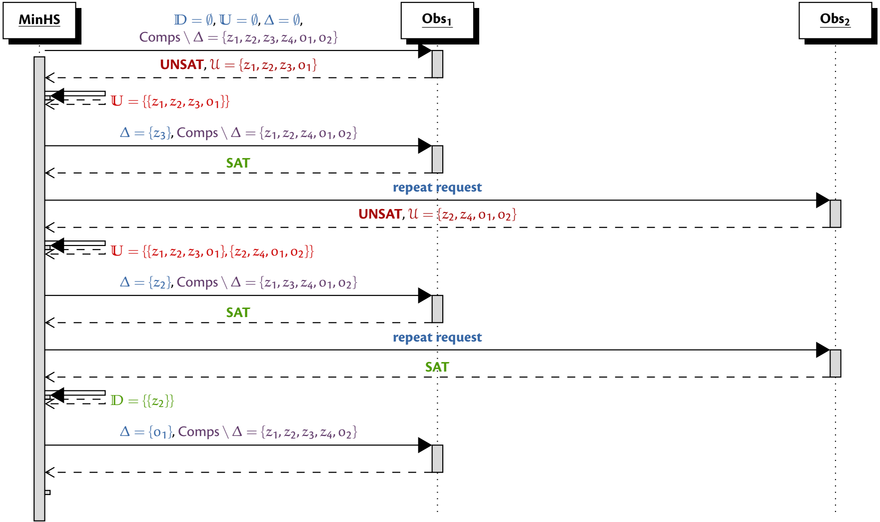
HSD – example



i_1 0
i_2 1
i_3 1
i_4 0
i_5 1
z_1
z_2
z_3
z_4
sa0
o_1 1
o_2 1

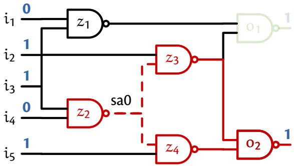


i_1 1
i_2 0
i_3 0
i_4 0
i_5 1
z_1
z_2
z_3
z_4
sa0
o_1 1
o_2 1

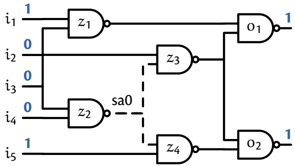


MinHS
Obs$_1$
Obs$_2$
$\mathbb{D} = \emptyset, \mathbb{U} = \emptyset, \Delta = \emptyset,$
$\text{Comps} \setminus \Delta = \{z_1, z_2, z_3, z_4, o_1, o_2\}$
UNSAT, $\mathcal{U} = \{z_1, z_2, z_3, o_1\}$
$\mathbb{U} = \{\{z_1, z_2, z_3, o_1\}\}$
$\Delta = \{z_3\}, \text{Comps} \setminus \Delta = \{z_1, z_2, z_4, o_1, o_2\}$
SAT
repeat request
UNSAT, $\mathcal{U} = \{z_2, z_4, o_1, o_2\}$
$\mathbb{U} = \{\{z_1, z_2, z_3, o_1\}, \{z_2, z_4, o_1, o_2\}\}$
$\Delta = \{z_2\}, \text{Comps} \setminus \Delta = \{z_1, z_3, z_4, o_1, o_2\}$
SAT
repeat request
SAT
$\mathbb{D} = \{\{z_2\}\}$
$\Delta = \{o_1\}, \text{Comps} \setminus \Delta = \{z_1, z_2, z_3, z_4, o_2\}$

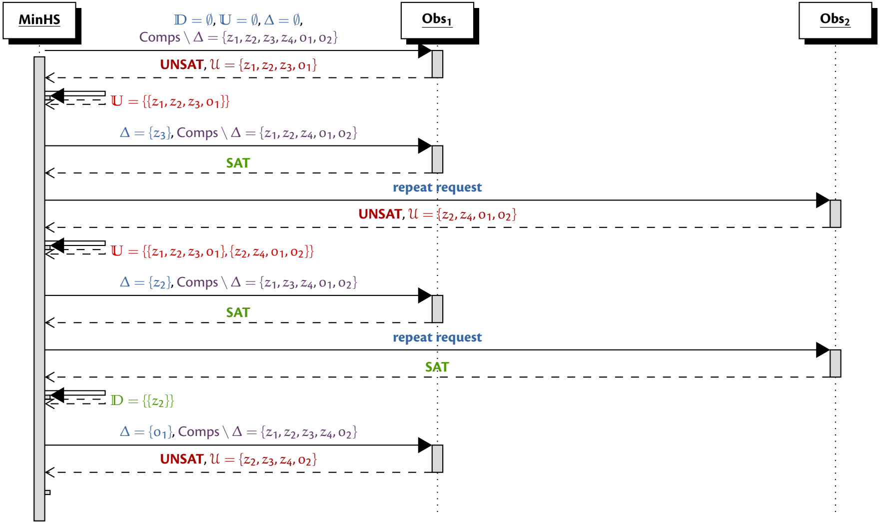
HSD – example



i_1 0
i_2 1
i_3 1
i_4 0
i_5 1
z_1
z_2
z_3
z_4
sa0
o_1 1
o_2 1



i_1 1
i_2 0
i_3 0
i_4 0
i_5 1
z_1
z_2
z_3
z_4
sa0
o_1 1
o_2 1



MinHS
Obs$_1$
Obs$_2$
$\mathbb{D} = \emptyset, \mathbb{U} = \emptyset, \Delta = \emptyset,$
$\text{Comps} \setminus \Delta = \{z_1, z_2, z_3, z_4, o_1, o_2\}$
UNSAT, $\mathcal{U} = \{z_1, z_2, z_3, o_1\}$
$\mathbb{U} = \{\{z_1, z_2, z_3, o_1\}\}$
$\Delta = \{z_3\}, \text{Comps} \setminus \Delta = \{z_1, z_2, z_4, o_1, o_2\}$
SAT
repeat request
UNSAT, $\mathcal{U} = \{z_2, z_4, o_1, o_2\}$
$\mathbb{U} = \{\{z_1, z_2, z_3, o_1\}, \{z_2, z_4, o_1, o_2\}\}$
$\Delta = \{z_2\}, \text{Comps} \setminus \Delta = \{z_1, z_3, z_4, o_1, o_2\}$
SAT
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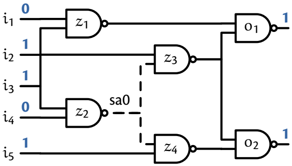
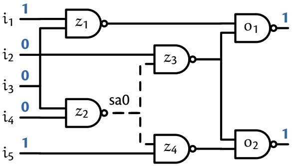
HSD – example



i_1 0
i_2 1
i_3 1
i_4 0
i_5 1
z_1
z_2
z_3
z_4
sa0
o_1 1
o_2 1



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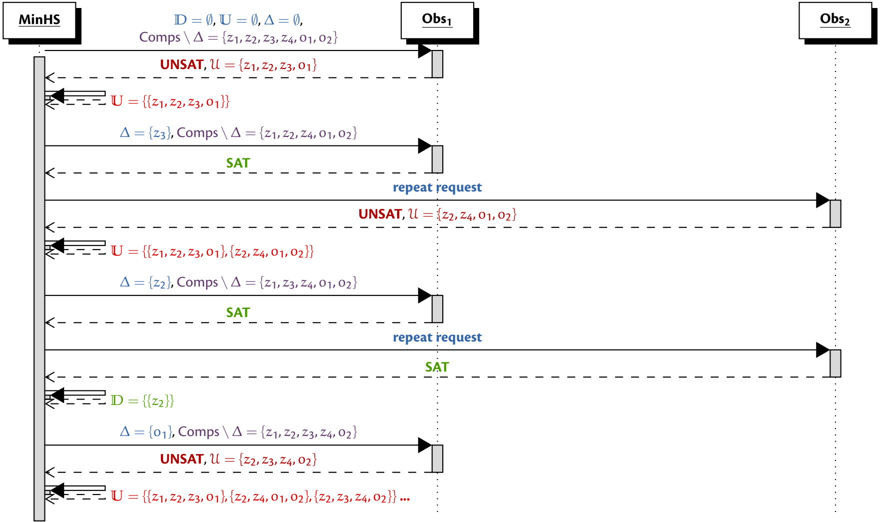

MinHS
Obs$_1$
Obs$_2$
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Comps $\setminus \Delta = \{z_1, z_2, z_3, z_4, o_1, o_2\}$
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Experimental results

Experimental evaluation[2]

- **ISCAS85 circuits** + **single stuck-at faults**

[2] https://github.com/alexeyignatiev/mbd-mobs

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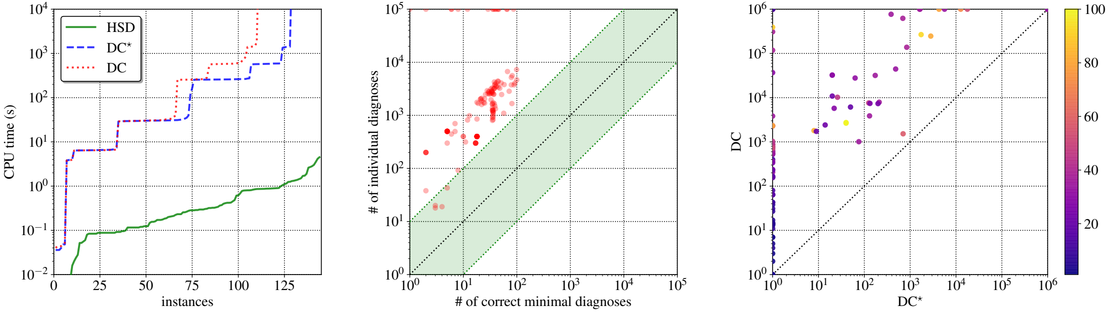

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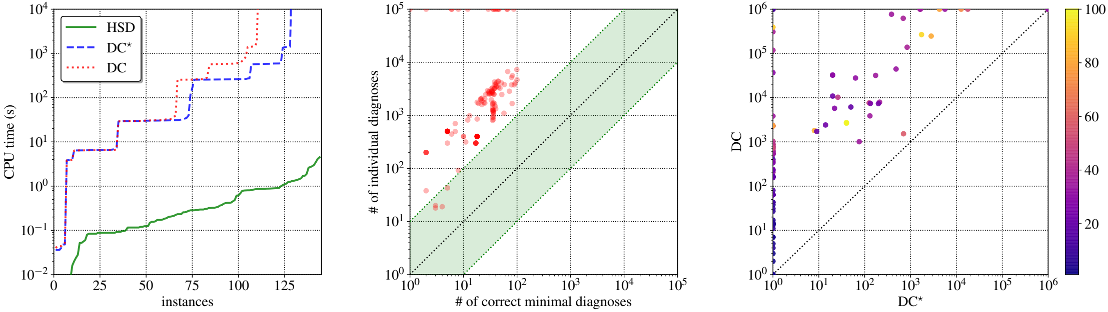

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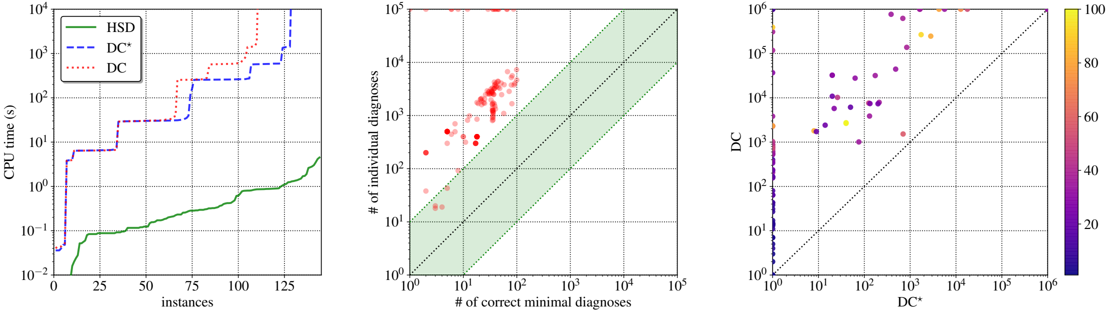

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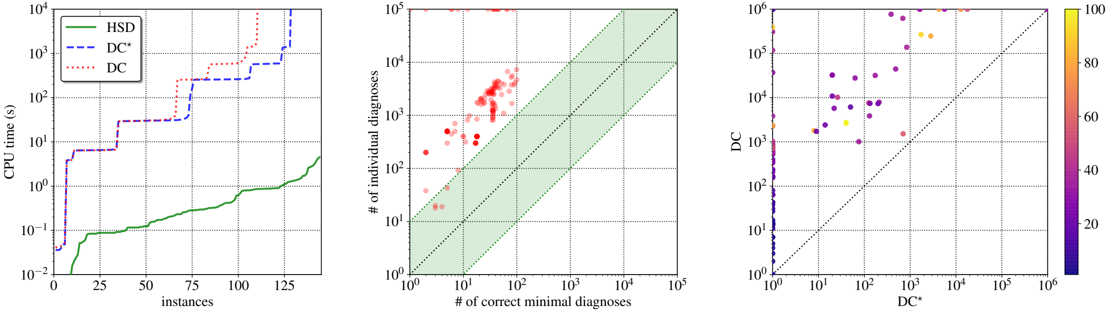

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DC vs. **DC*** — 1–6 orders of magnitude less "garbage"

(but still a lot!)

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    - **machine learning models?**
    - etc...

Questions?