Competence Centers for Excellent Technologies

Combinatorial Methods for Modelling Composed Software Systems

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March 13, 2017

Outline of the Talk

Composed SUTs
- Motivation for Combinatorial Methods
- Nested Test Suites from Nested Models

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Modelling Composed SUTs
- The Case of Automotive Industry
- The Case of Linux Kernel API

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- The Case of Automotive Industry
- The Case of Linux Kernel API

Extending Bounds of Usability of CT
- Nested CA Construction
- Construction of Large CAs

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Composed SUT

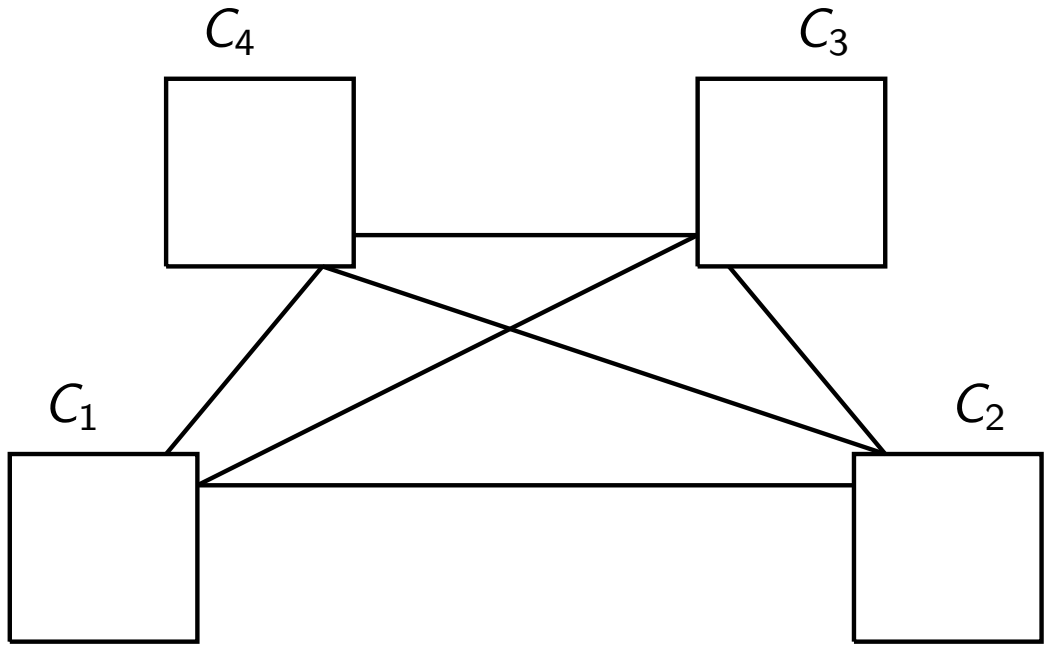
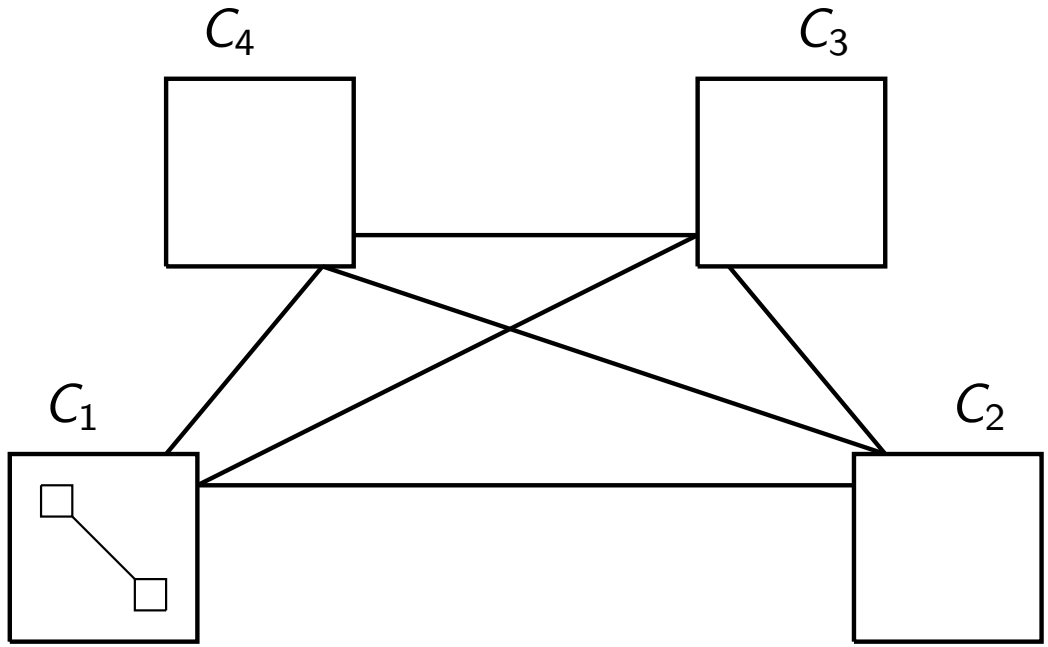


Figure: Composed SUT, with components C_1, C_2, C_3, C_4

$\mathcal{C}_1$	$\mathcal{C}_2$	$\mathcal{C}_3$	$\mathcal{C}_4$

Table: Corresponding IPM: 4 parameters

Composed SUT



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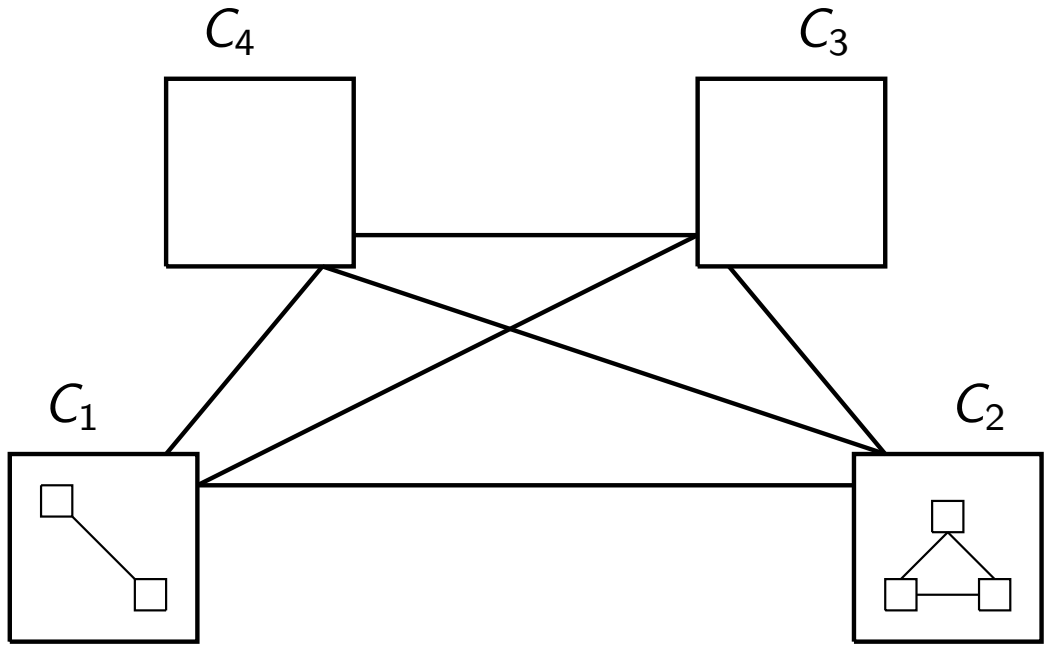

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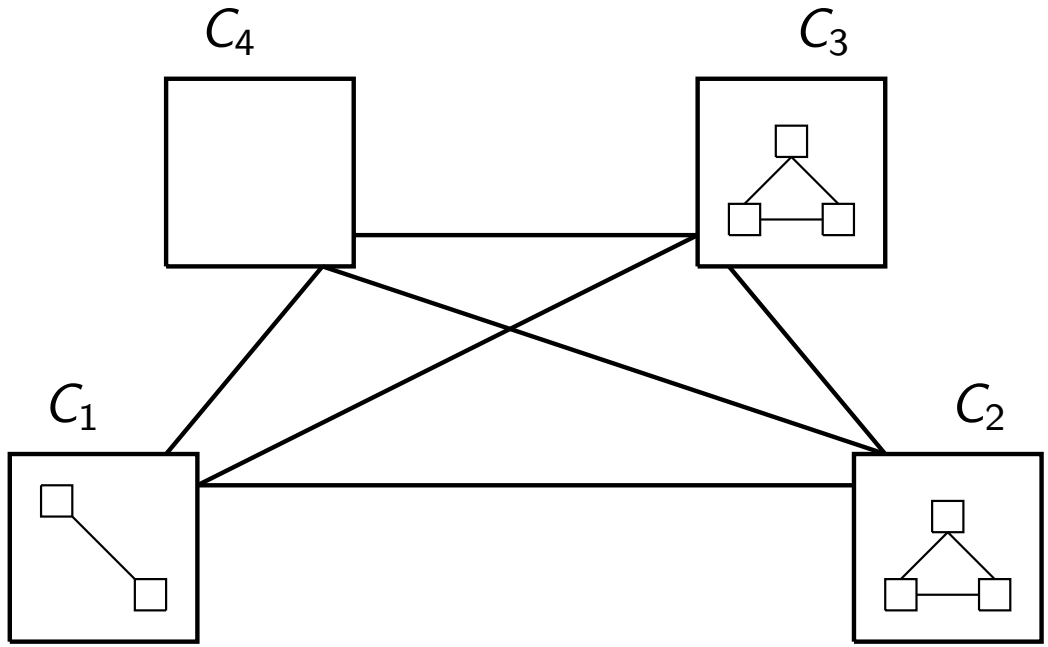

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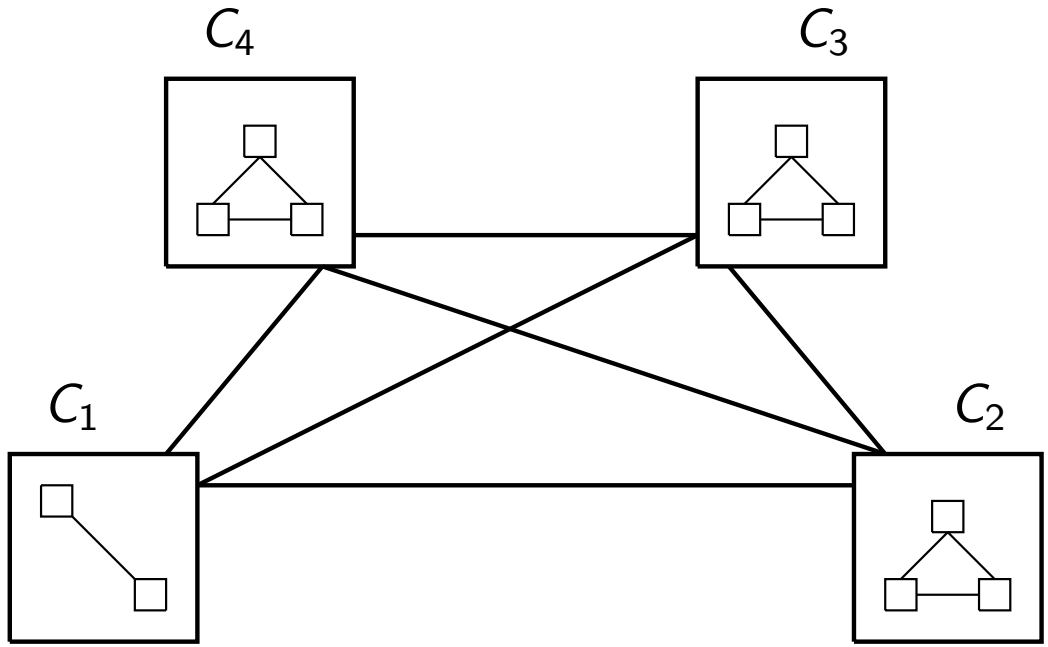

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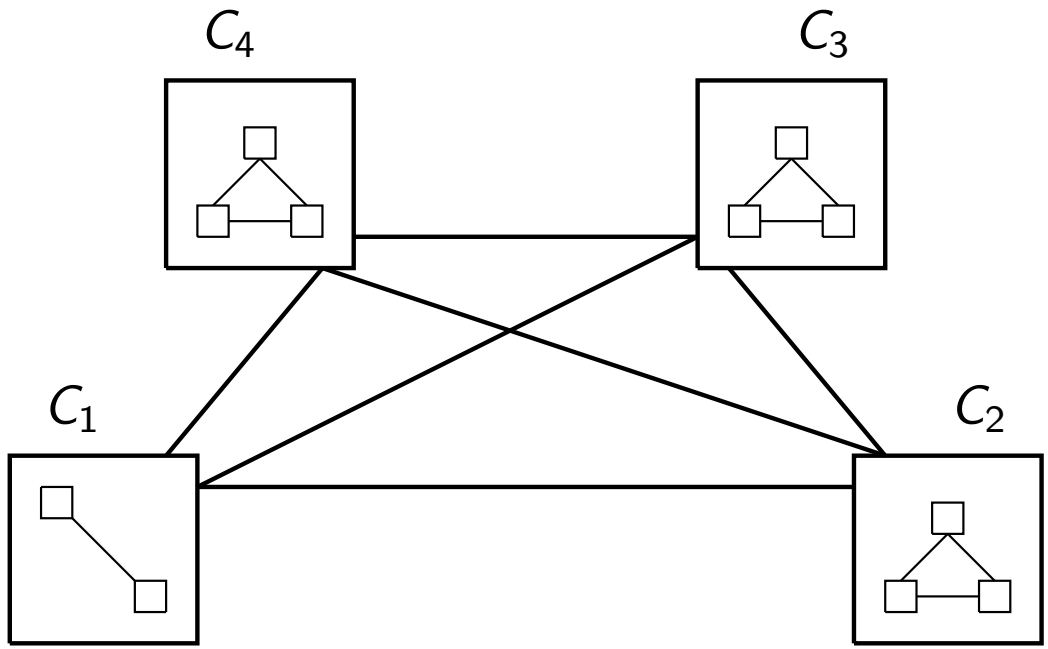

Figure: Composed SUT, with components C_1, C_2, C_3, C_4

C_1		C_2			C_3			C_4		
a_1	a_2	b_1	b_2	b_3	c_1	c_2	c_3	d_1	d_2	d_3

Table: Corresponding IPM: 4 vs. 11 parameters

Motivation for Combinatorial Methods

Modular Software Everywhere!

Modern software design relies on modular software architecture

- Software is structured in **components**
- These components interact with each other
- Unit testing: Components are tested individually
- Integration testing: Targets interactions between different components

Our Contribution

- Combinatorial modelling methodology that adapts to this modular approach of software design
- Combinatorial constructions to merge test suites of the components to a test suite for the whole SUT
- Formalized the concept of t-way coverage inheritance

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Nested Test Suites from Nested Models

Methodology

1. Given a composed SUT with components $C_1, \ldots, C_k$
2. IPM of composed SUT is comprised of many different **sub-IPMs**
3. sub-IPMs have test suites $S_1, \ldots, S_k$
4. Test suites may or may not form a t-way CA
5. Combine the **test suites** to obtain a nested test suite for the SUT

t-way Coverage Inheritance Property

If the test suites are CAs of strength t, then the resulting nested test suite $\mathcal{R}$ is again a CA of strength t

- Formal statement (**proof**) and more general properties (see paper)

SBA Research

Nested Test Suites for Composed SUTs

Algorithmic Procedure

1. Select test suites $S_1, \ldots, S_k$ (seeds) and desired interaction strength t between the component $C_1, \ldots, C_k$
2. Compute meta array $\mathcal{M} := MCA(N; t, k, (|S_1|, \ldots, |S_k|))$ [a]
3. For each test suite S_i identify the tests with the values occurring in column i of $\mathcal{M}$, via a **bijective mapping**
4. Replace each value in $\mathcal{M}$ according to the mappings defined in Step 3

[a] $|S_i|$ denotes the number of test cases in the test suite $|S_i|$

Other Approaches

- Concept of subrelations (Cohen et al, 1997)
- Submodels and (informal) coverage preservation (Czerwonka, 2006)
- Concept Sub-attributes (Krishnan et al, 2007)

Composed SUT: Modern Car

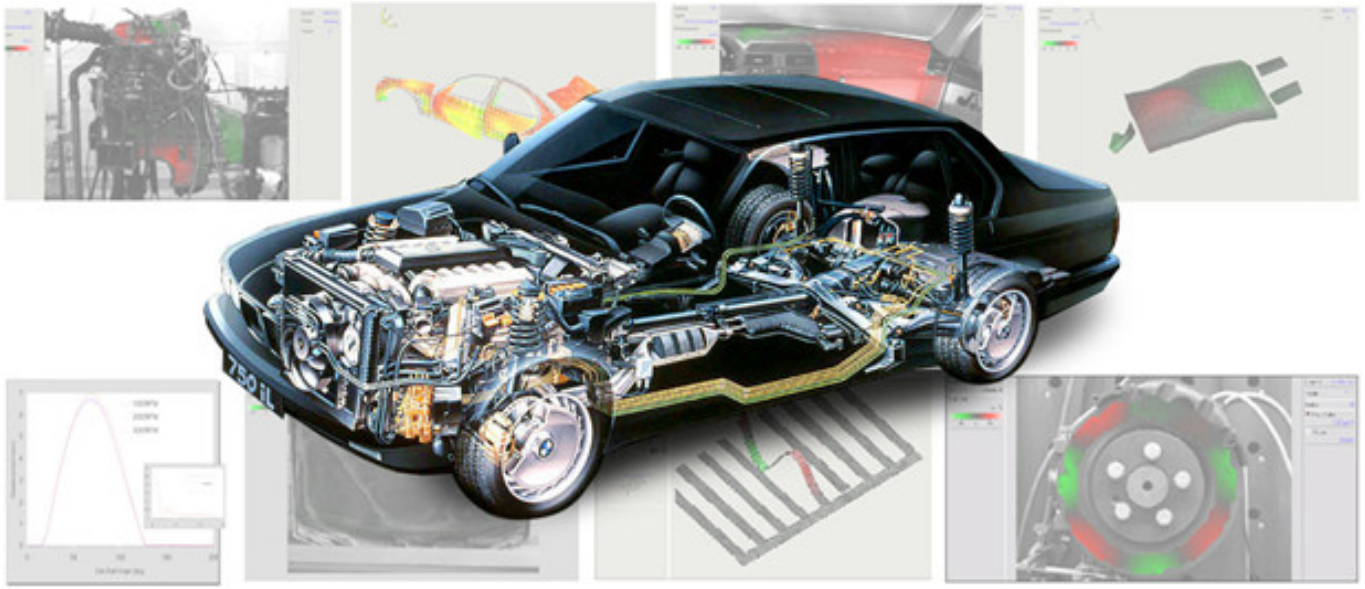
Components of the Car

C_1: Wheels modelled with two parameters

C_2: Engine modelled with three parameters

C_3: Infotainment modelled with three parameters

C_4: Communication modelled with three parameters



IPM of a component: Wheels

```
Name: IPM-Wheels

producer (enum): Giti (0), Mitas (1), Pirelli (2)
type  (boolean): winter (0), summer (1)
```

A	
a_1	a_2
0	0
0	1
1	0
1	1
2	0
2	1

Wheels	
producer	type
Giti	winter
Giti	summer
Mitas	winter
Mitas	summer
Pirelli	winter
Pirelli	summer

IPM of a component: Engine

```
Name: IPM-Engine

fuel       (boolean): diesel (0), gas (1)
drive_mode (boolean): eco (0), sport (1)
filter     (boolean): present (0), missing (1)
```

B		
b_1	b_2	b_3
0	0	1
0	1	0
1	0	0
1	1	1

Engine		
fuel	drive_mode	filter
diesel	eco	missing
diesel	sport	present
gas	eco	present
gas	sport	missing

IPM of a component: Infotainment system

```
Name: IPM-Infotainment

streaming      (boolean): true (0), false (1)
audio          (boolean): speaker (0), bluetooth (1)
remote_control (boolean): connected (0), disconnected (1)
```

C		
c_1	c_2	c_3
0	0	1
1	1	1
1	0	0
0	1	0

Infotainment		
streaming	audio	remote
true	speaker	disconnected
false	bluetooth	disconnected
false	speaker	connected
true	bluetooth	connected

IPM of a component: Communication

```
Name: IPM-Communication

ip_version (boolean): ipv4 (0), ipv6 (1)
connection (boolean): lte (0), wifi (1)
speed      (boolean): good (0), bad (1)
```

D		
d_1	d_2	d_3
0	0	1
0	1	0
1	0	0
1	1	1

Communication		
ip_version	connection	speed
ipv4	lte	bad
ipv4	wifi	good
ipv6	lte	good
ipv6	wifi	bad

Plug-In of Seeds into Meta Array $\mathcal{M}$

A	
a_1	a_2
0	0
0	1
1	0
1	1
2	0
2	1

B		
b_1	b_2	b_3
0	0	1
0	1	0
1	0	0
1	1	1

C		
c_1	c_2	c_3
0	0	1
1	1	1
1	0	0
0	1	0

D		
d_1	d_2	d_3
0	0	1
0	1	0
1	0	0
1	1	1

	$\mathcal{M}$			
#	M_1	M_2	M_3	M_4
1	0	0	1	1
2	0	1	2	2
3	0	2	3	3
4	0	3	0	0
5	1	0	2	3
6	1	1	3	0
7	1	2	0	1
8	1	3	1	2
9	2	0	3	2
10	2	1	0	3
11	2	2	1	0
12	2	3	2	1
13	3	0	0	2
14	3	1	1	3
15	3	2	2	0
16	3	3	3	1
17	4	0	0	0
18	4	1	1	1
19	4	2	2	2
20	4	3	3	3
21	5	0	0	0
22	5	1	1	1
23	5	2	2	2
24	5	3	3	3

Plug-In of Seeds into Meta Array $\mathcal{M}$

A	
a_1	a_2
0	0
0	1
1	0
1	1
2	0
2	1

B		
b_1	b_2	b_3
0	0	1
0	1	0
1	0	0
1	1	1

C		
c_1	c_2	c_3
0	0	1
1	1	1
1	0	0
0	1	0

D		
d_1	d_2	d_3
0	0	1
0	1	0
1	0	0
1	1	1

	$\mathcal{M}$			
#	M_1	M_2	M_3	M_4
1	0	0	1	1
2	0	1	2	2
3	0	2	3	3
4	0	3	0	0
5	1	0	2	3
6	1	1	3	0
7	1	2	0	1
8	1	3	1	2
9	2	0	3	2
10	2	1	0	3
11	2	2	1	0
12	2	3	2	1
13	3	0	0	2
14	3	1	1	3
15	3	2	2	0
16	3	3	3	1
17	4	0	0	0
18	4	1	1	1
19	4	2	2	2
20	4	3	3	3
21	5	0	0	0
22	5	1	1	1
23	5	2	2	2
24	5	3	3	3

Plug-In of Seeds into Meta Array $\mathcal{M}$

A	
a_1	a_2
0	0
0	1
1	0
1	1
2	0
2	1

B		
b_1	b_2	b_3
0	0	1
0	1	0
1	0	0
1	1	1

C		
c_1	c_2	c_3
0	0	1
1	1	1
1	0	0
0	1	0

D		
d_1	d_2	d_3
0	0	1
0	1	0
1	0	0
1	1	1

	$\mathcal{M}$			
#	M_1	M_2	M_3	M_4
1	0	0	1	1
2	0	1	2	2
3	0	2	3	3
4	0	3	0	0
5	1	0	2	3
6	1	1	3	0
7	1	2	0	1
8	1	3	1	2
9	2	0	3	2
10	2	1	0	3
11	2	2	1	0
12	2	3	2	1
13	3	0	0	2
14	3	1	1	3
15	3	2	2	0
16	3	3	3	1
17	4	0	0	0
18	4	1	1	1
19	4	2	2	2
20	4	3	3	3
21	5	0	0	0
22	5	1	1	1
23	5	2	2	2
24	5	3	3	3

Plug-In of Seeds into Meta Array $\mathcal{M}$

A	
a_1	a_2
0	0
0	1
1	0
1	1
2	0
2	1

B		
b_1	b_2	b_3
0	0	1
0	1	0
1	0	0
1	1	1

C		
c_1	c_2	c_3
0	0	1
1	1	1
1	0	0
0	1	0

D		
d_1	d_2	d_3
0	0	1
0	1	0
1	0	0
1	1	1

	$\mathcal{M}$			
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1	0	0	1	1
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3	0	2	3	3
4	0	3	0	0
5	1	0	2	3
6	1	1	3	0
7	1	2	0	1
8	1	3	1	2
9	2	0	3	2
10	2	1	0	3
11	2	2	1	0
12	2	3	2	1
13	3	0	0	2
14	3	1	1	3
15	3	2	2	0
16	3	3	3	1
17	4	0	0	0
18	4	1	1	1
19	4	2	2	2
20	4	3	3	3
21	5	0	0	0
22	5	1	1	1
23	5	2	2	2
24	5	3	3	3

Plug-In of Seeds into Meta Array $\mathcal{M}$

A	
a_1	a_2
0	0
0	1
1	0
1	1
2	0
2	1

B		
b_1	b_2	b_3
0	0	1
0	1	0
1	0	0
1	1	1

C		
c_1	c_2	c_3
0	0	1
1	1	1
1	0	0
0	1	0

D		
d_1	d_2	d_3
0	0	1
0	1	0
1	0	0
1	1	1

	$\mathcal{M}$			
#	M_1	M_2	M_3	M_4
1	0	0	1	1
2	0	1	2	2
3	0	2	3	3
4	0	3	0	0
5	1	0	2	3
6	1	1	3	0
7	1	2	0	1
8	1	3	1	2
9	2	0	3	2
10	2	1	0	3
11	2	2	1	0
12	2	3	2	1
13	3	0	0	2
14	3	1	1	3
15	3	2	2	0
16	3	3	3	1
17	4	0	0	0
18	4	1	1	1
19	4	2	2	2
20	4	3	3	3
21	5	0	0	0
22	5	1	1	1
23	5	2	2	2
24	5	3	3	3

Plug-In of Seeds into Meta Array $\mathcal{M}$

A	
a_1	a_2
0	0
0	1
1	0
1	1
2	0
2	1

B		
b_1	b_2	b_3
0	0	1
0	1	0
1	0	0
1	1	1

C		
c_1	c_2	c_3
0	0	1
1	1	1
1	0	0
0	1	0

D		
d_1	d_2	d_3
0	0	1
0	1	0
1	0	0
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1	0	0	1	1
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3	0	2	3	3
4	0	3	0	0
5	1	0	2	3
6	1	1	3	0
7	1	2	0	1
8	1	3	1	2
9	2	0	3	2
10	2	1	0	3
11	2	2	1	0
12	2	3	2	1
13	3	0	0	2
14	3	1	1	3
15	3	2	2	0
16	3	3	3	1
17	4	0	0	0
18	4	1	1	1
19	4	2	2	2
20	4	3	3	3
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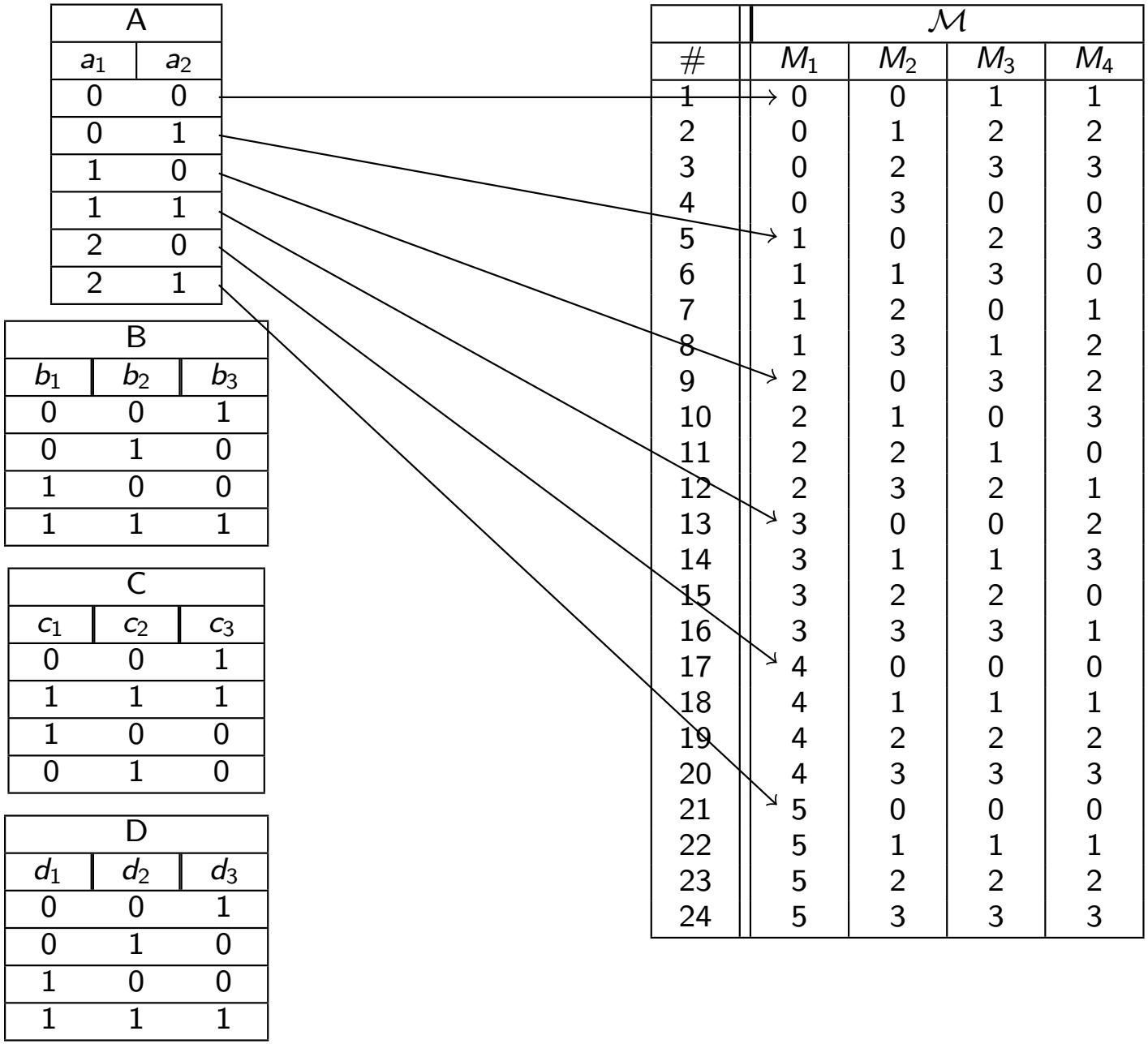

A	
a_1	a_2
0	0
0	1
1	0
1	1
2	0
2	1

B		
b_1	b_2	b_3
0	0	1
0	1	0
1	0	0
1	1	1

C		
c_1	c_2	c_3
0	0	1
1	1	1
1	0	0
0	1	0

D		
d_1	d_2	d_3
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7	1	2	0	1
8	1	3	1	2
9	2	0	3	2
10	2	1	0	3
11	2	2	1	0
12	2	3	2	1
13	3	0	0	2
14	3	1	1	3
15	3	2	2	0
16	3	3	3	1
17	4	0	0	0
18	4	1	1	1
19	4	2	2	2
20	4	3	3	3
21	5	0	0	0
22	5	1	1	1
23	5	2	2	2
24	5	3	3	3

Plug-In of Seeds into Meta Array $\mathcal{M}$

A	
a_1	a_2
0	0
0	1
1	0
1	1
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2	1

B		
b_1	b_2	b_3
0	0	1
0	1	0
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1	1	1

C		
c_1	c_2	c_3
0	0	1
1	1	1
1	0	0
0	1	0

D		
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	$\mathcal{M}$			
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5	1	0	2	3
6	1	1	3	0
7	1	2	0	1
8	1	3	1	2
9	2	0	3	2
10	2	1	0	3
11	2	2	1	0
12	2	3	2	1
13	3	0	0	2
14	3	1	1	3
15	3	2	2	0
16	3	3	3	1
17	4	0	0	0
18	4	1	1	1
19	4	2	2	2
20	4	3	3	3
21	5	0	0	0
22	5	1	1	1
23	5	2	2	2
24	5	3	3	3

Plug-In of Seeds into Meta Array $\mathcal{M}$

A	
a_1	a_2
0	0
0	1
1	0
1	1
2	0
2	1

B		
b_1	b_2	b_3
0	0	1
0	1	0
1	0	0
1	1	1

C		
c_1	c_2	c_3
0	0	1
1	1	1
1	0	0
0	1	0

D		
d_1	d_2	d_3
0	0	1
0	1	0
1	0	0
1	1	1

	$\mathcal{M}$			
#	M_1	M_2	M_3	M_4
1	0	0	1	1
2	0	1	2	2
3	0	2	3	3
4	0	3	0	0
5	1	0	2	3
6	1	1	3	0
7	1	2	0	1
8	1	3	1	2
9	2	0	3	2
10	2	1	0	3
11	2	2	1	0
12	2	3	2	1
13	3	0	0	2
14	3	1	1	3
15	3	2	2	0
16	3	3	3	1
17	4	0	0	0
18	4	1	1	1
19	4	2	2	2
20	4	3	3	3
21	5	0	0	0
22	5	1	1	1
23	5	2	2	2
24	5	3	3	3

Plug-In of Seeds into Meta Array $\mathcal{M}$

A	
a_1	a_2
0	0
0	1
1	0
1	1
2	0
2	1

B		
b_1	b_2	b_3
0	0	1
0	1	0
1	0	0
1	1	1

C		
c_1	c_2	c_3
0	0	1
1	1	1
1	0	0
0	1	0

D		
d_1	d_2	d_3
0	0	1
0	1	0
1	0	0
1	1	1

	$\mathcal{M}$			
#	M_1	M_2	M_3	M_4
1	0	0	1	1
2	0	1	2	2
3	0	2	3	3
4	0	3	0	0
5	1	0	2	3
6	1	1	3	0
7	1	2	0	1
8	1	3	1	2
9	2	0	3	2
10	2	1	0	3
11	2	2	1	0
12	2	3	2	1
13	3	0	0	2
14	3	1	1	3
15	3	2	2	0
16	3	3	3	1
17	4	0	0	0
18	4	1	1	1
19	4	2	2	2
20	4	3	3	3
21	5	0	0	0
22	5	1	1	1
23	5	2	2	2
24	5	3	3	3

Plug-In of Seeds into Meta Array $\mathcal{M}$

A	
a_1	a_2
0	0
0	1
1	0
1	1
2	0
2	1

B		
b_1	b_2	b_3
0	0	1
0	1	0
1	0	0
1	1	1

C		
c_1	c_2	c_3
0	0	1
1	1	1
1	0	0
0	1	0

D		
d_1	d_2	d_3
0	0	1
0	1	0
1	0	0
1	1	1

	$\mathcal{M}$			
#	M_1	M_2	M_3	M_4
1	0	0	1	1
2	0	1	2	2
3	0	2	3	3
4	0	3	0	0
5	1	0	2	3
6	1	1	3	0
7	1	2	0	1
8	1	3	1	2
9	2	0	3	2
10	2	1	0	3
11	2	2	1	0
12	2	3	2	1
13	3	0	0	2
14	3	1	1	3
15	3	2	2	0
16	3	3	3	1
17	4	0	0	0
18	4	1	1	1
19	4	2	2	2
20	4	3	3	3
21	5	0	0	0
22	5	1	1	1
23	5	2	2	2
24	5	3	3	3

Plug-In of Seeds into Meta Array $\mathcal{M}$

A	
a_1	a_2
0	0
0	1
1	0
1	1
2	0
2	1

B		
b_1	b_2	b_3
0	0	1
0	1	0
1	0	0
1	1	1

C		
c_1	c_2	c_3
0	0	1
1	1	1
1	0	0
0	1	0

D		
d_1	d_2	d_3
0	0	1
0	1	0
1	0	0
1	1	1

	$\mathcal{M}$			
#	M_1	M_2	M_3	M_4
1	0	0	1	1
2	0	1	2	2
3	0	2	3	3
4	0	3	0	0
5	1	0	2	3
6	1	1	3	0
7	1	2	0	1
8	1	3	1	2
9	2	0	3	2
10	2	1	0	3
11	2	2	1	0
12	2	3	2	1
13	3	0	0	2
14	3	1	1	3
15	3	2	2	0
16	3	3	3	1
17	4	0	0	0
18	4	1	1	1
19	4	2	2	2
20	4	3	3	3
21	5	0	0	0
22	5	1	1	1
23	5	2	2	2
24	5	3	3	3

Plug-In of Seeds into Meta Array $\mathcal{M}$

A	
a_1	a_2
0	0
0	1
1	0
1	1
2	0
2	1

B		
b_1	b_2	b_3
0	0	1
0	1	0
1	0	0
1	1	1

C		
c_1	c_2	c_3
0	0	1
1	1	1
1	0	0
0	1	0

D		
d_1	d_2	d_3
0	0	1
0	1	0
1	0	0
1	1	1

	$\mathcal{M}$			
#	M_1	M_2	M_3	M_4
1	0	0	1	1
2	0	1	2	2
3	0	2	3	3
4	0	3	0	0
5	1	0	2	3
6	1	1	3	0
7	1	2	0	1
8	1	3	1	2
9	2	0	3	2
10	2	1	0	3
11	2	2	1	0
12	2	3	2	1
13	3	0	0	2
14	3	1	1	3
15	3	2	2	0
16	3	3	3	1
17	4	0	0	0
18	4	1	1	1
19	4	2	2	2
20	4	3	3	3
21	5	0	0	0
22	5	1	1	1
23	5	2	2	2
24	5	3	3	3

Plug-In of Seeds into Meta Array $\mathcal{M}$

A	
a_1	a_2
0	0
0	1
1	0
1	1
2	0
2	1

B		
b_1	b_2	b_3
0	0	1
0	1	0
1	0	0
1	1	1

C		
c_1	c_2	c_3
0	0	1
1	1	1
1	0	0
0	1	0

D		
d_1	d_2	d_3
0	0	1
0	1	0
1	0	0
1	1	1

	$\mathcal{M}$			
#	M_1	M_2	M_3	M_4
1	0	0	1	1
2	0	1	2	2
3	0	2	3	3
4	0	3	0	0
5	1	0	2	3
6	1	1	3	0
7	1	2	0	1
8	1	3	1	2
9	2	0	3	2
10	2	1	0	3
11	2	2	1	0
12	2	3	2	1
13	3	0	0	2
14	3	1	1	3
15	3	2	2	0
16	3	3	3	1
17	4	0	0	0
18	4	1	1	1
19	4	2	2	2
20	4	3	3	3
21	5	0	0	0
22	5	1	1	1
23	5	2	2	2
24	5	3	3	3

Plug-In of Seeds into Meta Array $\mathcal{M}$

A	
a_1	a_2
0	0
0	1
1	0
1	1
2	0
2	1

B		
b_1	b_2	b_3
0	0	1
0	1	0
1	0	0
1	1	1

C		
c_1	c_2	c_3
0	0	1
1	1	1
1	0	0
0	1	0

D		
d_1	d_2	d_3
0	0	1
0	1	0
1	0	0
1	1	1

	$\mathcal{M}$			
#	M_1	M_2	M_3	M_4
1	0	0	1	1
2	0	1	2	2
3	0	2	3	3
4	0	3	0	0
5	1	0	2	3
6	1	1	3	0
7	1	2	0	1
8	1	3	1	2
9	2	0	3	2
10	2	1	0	3
11	2	2	1	0
12	2	3	2	1
13	3	0	0	2
14	3	1	1	3
15	3	2	2	0
16	3	3	3	1
17	4	0	0	0
18	4	1	1	1
19	4	2	2	2
20	4	3	3	3
21	5	0	0	0
22	5	1	1	1
23	5	2	2	2
24	5	3	3	3

Plug-In of Seeds into Meta Array $\mathcal{M}$

A	
a_1	a_2
0	0
0	1
1	0
1	1
2	0
2	1

B		
b_1	b_2	b_3
0	0	1
0	1	0
1	0	0
1	1	1

C		
c_1	c_2	c_3
0	0	1
1	1	1
1	0	0
0	1	0

D		
d_1	d_2	d_3
0	0	1
0	1	0
1	0	0
1	1	1

	$\mathcal{M}$			
#	M_1	M_2	M_3	M_4
1	0	0	1	1
2	0	1	2	2
3	0	2	3	3
4	0	3	0	0
5	1	0	2	3
6	1	1	3	0
7	1	2	0	1
8	1	3	1	2
9	2	0	3	2
10	2	1	0	3
11	2	2	1	0
12	2	3	2	1
13	3	0	0	2
14	3	1	1	3
15	3	2	2	0
16	3	3	3	1
17	4	0	0	0
18	4	1	1	1
19	4	2	2	2
20	4	3	3	3
21	5	0	0	0
22	5	1	1	1
23	5	2	2	2
24	5	3	3	3

Plug-In of Seeds into Meta Array $\mathcal{M}$

A	
a_1	a_2
0	0
0	1
1	0
1	1
2	0
2	1

B		
b_1	b_2	b_3
0	0	1
0	1	0
1	0	0
1	1	1

C		
c_1	c_2	c_3
0	0	1
1	1	1
1	0	0
0	1	0

D		
d_1	d_2	d_3
0	0	1
0	1	0
1	0	0
1	1	1

	$\mathcal{M}$			
#	M_1	M_2	M_3	M_4
1	0	0	1	1
2	0	1	2	2
3	0	2	3	3
4	0	3	0	0
5	1	0	2	3
6	1	1	3	0
7	1	2	0	1
8	1	3	1	2
9	2	0	3	2
10	2	1	0	3
11	2	2	1	0
12	2	3	2	1
13	3	0	0	2
14	3	1	1	3
15	3	2	2	0
16	3	3	3	1
17	4	0	0	0
18	4	1	1	1
19	4	2	2	2
20	4	3	3	3
21	5	0	0	0
22	5	1	1	1
23	5	2	2	2
24	5	3	3	3

Plug-In of Seeds into Meta Array $\mathcal{M}$

A	
a_1	a_2
0	0
0	1
1	0
1	1
2	0
2	1

B		
b_1	b_2	b_3
0	0	1
0	1	0
1	0	0
1	1	1

C		
c_1	c_2	c_3
0	0	1
1	1	1
1	0	0
0	1	0

D		
d_1	d_2	d_3
0	0	1
0	1	0
1	0	0
1	1	1

	$\mathcal{M}$			
#	M_1	M_2	M_3	M_4
1	0	0	1	1
2	0	1	2	2
3	0	2	3	3
4	0	3	0	0
5	1	0	2	3
6	1	1	3	0
7	1	2	0	1
8	1	3	1	2
9	2	0	3	2
10	2	1	0	3
11	2	2	1	0
12	2	3	2	1
13	3	0	0	2
14	3	1	1	3
15	3	2	2	0
16	3	3	3	1
17	4	0	0	0
18	4	1	1	1
19	4	2	2	2
20	4	3	3	3
21	5	0	0	0
22	5	1	1	1
23	5	2	2	2
24	5	3	3	3

Plug-In of Seeds into Meta Array $\mathcal{M}$

A	
a_1	a_2
0	0
0	1
1	0
1	1
2	0
2	1

B		
b_1	b_2	b_3
0	0	1
0	1	0
1	0	0
1	1	1

C		
c_1	c_2	c_3
0	0	1
1	1	1
1	0	0
0	1	0

D		
d_1	d_2	d_3
0	0	1
0	1	0
1	0	0
1	1	1

	$\mathcal{M}$			
#	M_1	M_2	M_3	M_4
1	0	0	1	1
2	0	1	2	2
3	0	2	3	3
4	0	3	0	0
5	1	0	2	3
6	1	1	3	0
7	1	2	0	1
8	1	3	1	2
9	2	0	3	2
10	2	1	0	3
11	2	2	1	0
12	2	3	2	1
13	3	0	0	2
14	3	1	1	3
15	3	2	2	0
16	3	3	3	1
17	4	0	0	0
18	4	1	1	1
19	4	2	2	2
20	4	3	3	3
21	5	0	0	0
22	5	1	1	1
23	5	2	2	2
24	5	3	3	3

Plug-In of Seeds into Meta Array $\mathcal{M}$

A	
a_1	a_2
0	0
0	1
1	0
1	1
2	0
2	1

B		
b_1	b_2	b_3
0	0	1
0	1	0
1	0	0
1	1	1

C		
c_1	c_2	c_3
0	0	1
1	1	1
1	0	0
0	1	0

D		
d_1	d_2	d_3
0	0	1
0	1	0
1	0	0
1	1	1

	$\mathcal{M}$			
#	M_1	M_2	M_3	M_4
1	0	0	1	1
2	0	1	2	2
3	0	2	3	3
4	0	3	0	0
5	1	0	2	3
6	1	1	3	0
7	1	2	0	1
8	1	3	1	2
9	2	0	3	2
10	2	1	0	3
11	2	2	1	0
12	2	3	2	1
13	3	0	0	2
14	3	1	1	3
15	3	2	2	0
16	3	3	3	1
17	4	0	0	0
18	4	1	1	1
19	4	2	2	2
20	4	3	3	3
21	5	0	0	0
22	5	1	1	1
23	5	2	2	2
24	5	3	3	3

Plug-In of Seeds into Meta Array $\mathcal{M}$

A	
a_1	a_2
0	0
0	1
1	0
1	1
2	0
2	1

B		
b_1	b_2	b_3
0	0	1
0	1	0
1	0	0
1	1	1

C		
c_1	c_2	c_3
0	0	1
1	1	1
1	0	0
0	1	0

D		
d_1	d_2	d_3
0	0	1
0	1	0
1	0	0
1	1	1

	$\mathcal{M}$			
#	M_1	M_2	M_3	M_4
1	0	0	1	1
2	0	1	2	2
3	0	2	3	3
4	0	3	0	0
5	1	0	2	3
6	1	1	3	0
7	1	2	0	1
8	1	3	1	2
9	2	0	3	2
10	2	1	0	3
11	2	2	1	0
12	2	3	2	1
13	3	0	0	2
14	3	1	1	3
15	3	2	2	0
16	3	3	3	1
17	4	0	0	0
18	4	1	1	1
19	4	2	2	2
20	4	3	3	3
21	5	0	0	0
22	5	1	1	1
23	5	2	2	2
24	5	3	3	3

Resulting Array $\mathcal{R}$ where $|\mathcal{R}| = |\mathcal{M}|$

$\mathcal{R}$										
a_1	a_2	b_1	b_2	b_3	c_1	c_2	c_3	d_1	d_2	d_3
0	0	0	0	1	1	1	1	0	1	0
0	0	0	1	0	1	0	0	1	0	0
0	0	1	0	0	0	1	0	1	1	1
0	0	1	1	1	0	0	1	0	0	1
0	1	0	0	1	1	0	0	1	1	1
0	1	0	1	0	0	1	0	0	0	1
0	1	1	0	0	0	0	1	0	1	0
0	1	1	1	1	1	1	1	1	0	0
1	0	0	0	1	0	1	0	1	0	0
1	0	0	1	0	0	0	1	1	1	1
1	0	1	0	0	1	1	1	0	0	1
1	0	1	1	1	1	0	0	0	1	0
1	1	0	0	1	0	0	1	1	0	0
1	1	0	1	0	1	1	1	1	1	1
1	1	1	0	0	1	0	0	0	0	1
1	1	1	1	1	0	1	0	0	1	0
2	0	0	0	1	0	0	1	0	0	1
2	0	0	1	0	1	1	1	0	1	0
2	0	1	0	0	1	0	0	1	0	0
2	0	1	1	1	0	1	0	1	1	1
2	1	0	0	1	0	0	1	0	0	1
2	1	0	1	0	1	1	1	0	1	0
2	1	1	0	0	1	0	0	1	0	0
2	1	1	1	1	0	1	0	1	1	1

An $MCA(24; 2, 11, (3, 2^{10}))$

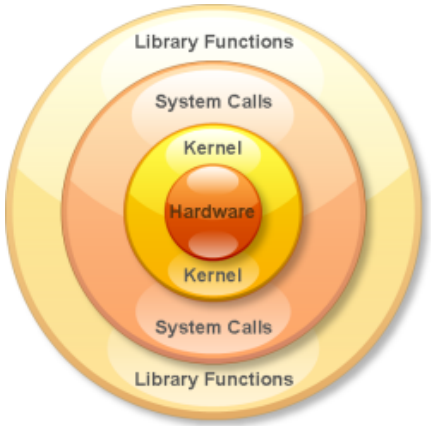
IPMs for Linux Kernel Systems Calls

SUTs: System Call API of Linux kernel

- Is the interface between the kernel and user space
- Is mostly used via wrappers in the standard library of the programming languages
- Is used to request, monitor and control system resources

Goal

Reliability and quality assurance of kernel software



SBA Research

Linux Kernel System Call API: chmod System Call

Example: chmod(pathname, mode)

- The `chmod()` system call changes the permissions of a file
- It has two arguments:
  1. **pathname**: Path to a file called
  2. **mode**: New file permissions specified in a bitmask
- Mode is created by **ORing** together zero or more of the following flags: `S_ISUID`, `S_ISGID`, `S_ISVTX`, `S_IRUSR`, `S_IWUSR`, `S_IXUSR`, `S_IRGRP`, `S_IWGRP`, `S_IXGRP`, `S_IROTH`, `S_IWOTH`, `S_IXOTH`
- Flags can be modelled as boolean parameters (TRUE / FALSE)

Towards Nested Models for the System Call chmod

Incorporating semantics – new Nested IPM

- The mode argument can be regarded as a component, having its own internal structure
- Model mode with four sub-attributes:

P_{user}: Captures semantically all permission masks for 'user': `S_IRUSR, S_IWUSR, S_IXUSR`

P_{grp}: Captures semantically all permission masks for 'group': `S_IRGRP, S_IWGRP, S_IXGRP`

P_{other}: Captures semantically all permission masks for 'other': `S_IROTH, S_IWOTH, S_IXOTH`

P_{sys}: Captures semantically the masks `S_ISUID, S_ISGID, S_ISVTX`

Nested Models for the System Call API chmod

How to choose tests for P_{user}, P_{grp}, P_{other}, P_{sys}?

Let P be a sub-attribute of chmod-IPM-NEST, having three binary parameters:

- Use full Cartesian product of the values of three binary parameters to produce all possible triples to form a seed array, leading to eight test cases
- Use a 2-way test suite for three binary parameters as a seed array, leading to four test cases
- Use a non-empty proper subset of the Cartesian product as legacy test suite; Reasons for making this choice include the reuse of an existing test suite

Depending on the testing requirements, different choices can be made P_{user}, P_{grp}, P_{other}, P_{sys}

Nested Models for the System Call API chmod

```
Name: ipm-P_sys

is_uid (boolean): true (0), false (1)
is_gid (boolean): true (0), false (1)
is_vtx (boolean): true (0), false (1)
```

A_1		
a_1	a_2	a_3
0	0	0
1	0	1
0	1	1

Figure: Tests selected by expert knowledge.

Nested Models for the System Call API chmod

```
Name: ipm-P_usr

u_r (boolean): true (0), false (1)
u_w (boolean): true (0), false (1)
u_x (boolean): true (0), false (1)
```

B_1		
b_1	b_2	b_3
0	0	0
1	1	1

Figure: Tests selected by expert knowledge.

Nested Models for the System Call API chmod

```
Name: ipm-P_grp

g_r (boolean): true (0), false (1)
g_w (boolean): true (0), false (1)
g_x (boolean): true (0), false (1)
```

C_1		
c_1	c_2	c_3
0	0	0
1	1	1

Figure: Tests selected by expert knowledge.

Nested Models for the System Call API chmod

```
Name: ipm-P_oth

o_r (boolean): true (0), false (1)
o_w (boolean): true (0), false (1)
o_x (boolean): true (0), false (1)
```

D_1		
d_1	d_2	d_3
0	0	0
1	1	1

Figure: Tests selected by expert knowledge.

Plug-In of Seeds into Meta Array

A_1		
a_1	a_2	a_3
0	0	0
1	0	1
0	1	1

B_1		
b_1	b_2	b_3
0	0	0
1	1	1

C_1		
c_1	c_2	c_3
0	0	0
1	1	1

D_1		
d_1	d_2	d_3
0	0	0
1	1	1

	$\mathcal{M}$			
#	M_1	M_2	M_3	M_4
1	0	0	1	1
2	0	1	0	0
3	1	0	0	1
4	1	1	1	0
5	2	0	0	0
6	2	1	1	1

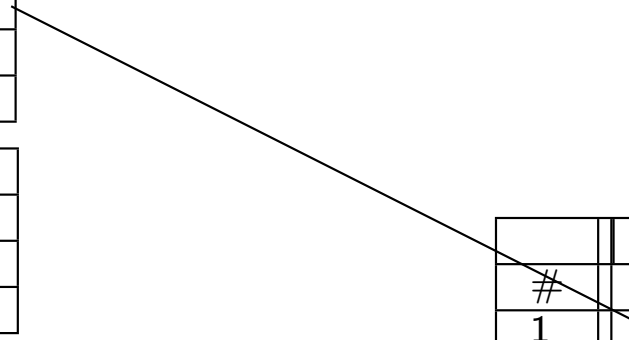
Plug-In of Seeds into Meta Array

A_1		
a_1	a_2	a_3
0	0	0
1	0	1
0	1	1

B_1		
b_1	b_2	b_3
0	0	0
1	1	1

C_1		
c_1	c_2	c_3
0	0	0
1	1	1

D_1		
d_1	d_2	d_3
0	0	0
1	1	1



	$\mathcal{M}$			
#	M_1	M_2	M_3	M_4
1	0	0	1	1
2	0	1	0	0
3	1	0	0	1
4	1	1	1	0
5	2	0	0	0
6	2	1	1	1

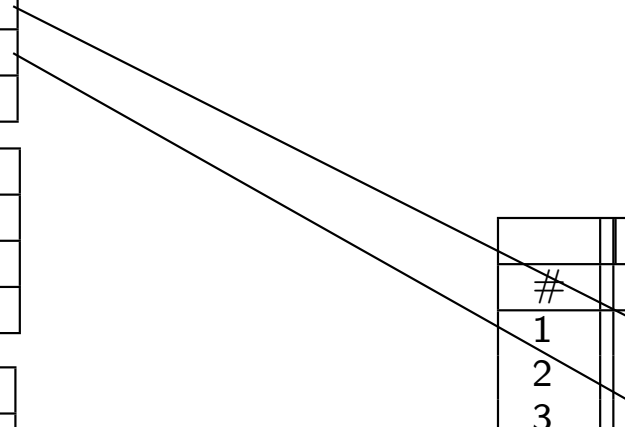
Plug-In of Seeds into Meta Array

A_1		
a_1	a_2	a_3
0	0	0
1	0	1
0	1	1

B_1		
b_1	b_2	b_3
0	0	0
1	1	1

C_1		
c_1	c_2	c_3
0	0	0
1	1	1

D_1		
d_1	d_2	d_3
0	0	0
1	1	1



	$\mathcal{M}$			
#	M_1	M_2	M_3	M_4
1	0	0	1	1
2	0	1	0	0
3	1	0	0	1
4	1	1	1	0
5	2	0	0	0
6	2	1	1	1

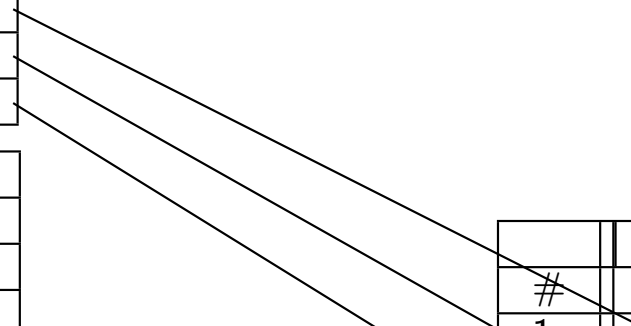
Plug-In of Seeds into Meta Array

A_1		
a_1	a_2	a_3
0	0	0
1	0	1
0	1	1

B_1		
b_1	b_2	b_3
0	0	0
1	1	1

C_1		
c_1	c_2	c_3
0	0	0
1	1	1

D_1		
d_1	d_2	d_3
0	0	0
1	1	1



	$\mathcal{M}$			
#	M_1	M_2	M_3	M_4
1	0	0	1	1
2	0	1	0	0
3	1	0	0	1
4	1	1	1	0
5	2	0	0	0
6	2	1	1	1

Plug-In of Seeds into Meta Array

A_1		
a_1	a_2	a_3
0	0	0
1	0	1
0	1	1

B_1		
b_1	b_2	b_3
0	0	0
1	1	1

C_1		
c_1	c_2	c_3
0	0	0
1	1	1

D_1		
d_1	d_2	d_3
0	0	0
1	1	1

	$\mathcal{M}$			
#	M_1	M_2	M_3	M_4
1	0	0	1	1
2	0	1	0	0
3	1	0	0	1
4	1	1	1	0
5	2	0	0	0
6	2	1	1	1

Plug-In of Seeds into Meta Array

A_1		
a_1	a_2	a_3
0	0	0
1	0	1
0	1	1

B_1		
b_1	b_2	b_3
0	0	0
1	1	1

C_1		
c_1	c_2	c_3
0	0	0
1	1	1

D_1		
d_1	d_2	d_3
0	0	0
1	1	1

	$\mathcal{M}$			
#	M_1	M_2	M_3	M_4
1	0	0	1	1
2	0	1	0	0
3	1	0	0	1
4	1	1	1	0
5	2	0	0	0
6	2	1	1	1

Plug-In of Seeds into Meta Array

A_1		
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0	0	0
1	0	1
0	1	1

B_1		
b_1	b_2	b_3
0	0	0
1	1	1

C_1		
c_1	c_2	c_3
0	0	0
1	1	1

D_1		
d_1	d_2	d_3
0	0	0
1	1	1

	$\mathcal{M}$			
#	M_1	M_2	M_3	M_4
1	0	0	1	1
2	0	1	0	0
3	1	0	0	1
4	1	1	1	0
5	2	0	0	0
6	2	1	1	1

Plug-In of Seeds into Meta Array

A_1		
a_1	a_2	a_3
0	0	0
1	0	1
0	1	1

B_1		
b_1	b_2	b_3
0	0	0
1	1	1

C_1		
c_1	c_2	c_3
0	0	0
1	1	1

D_1		
d_1	d_2	d_3
0	0	0
1	1	1

	$\mathcal{M}$			
#	M_1	M_2	M_3	M_4
1	0	0	1	1
2	0	1	0	0
3	1	0	0	1
4	1	1	1	0
5	2	0	0	0
6	2	1	1	1

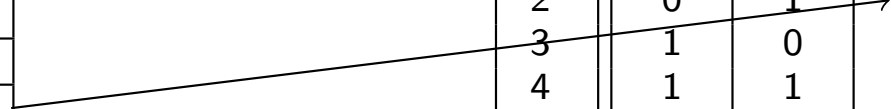
Plug-In of Seeds into Meta Array

A_1		
a_1	a_2	a_3
0	0	0
1	0	1
0	1	1

B_1		
b_1	b_2	b_3
0	0	0
1	1	1

C_1		
c_1	c_2	c_3
0	0	0
1	1	1

D_1		
d_1	d_2	d_3
0	0	0
1	1	1



	$\mathcal{M}$			
#	M_1	M_2	M_3	M_4
1	0	0	1	1
2	0	1	0	0
3	1	0	0	1
4	1	1	1	0
5	2	0	0	0
6	2	1	1	1

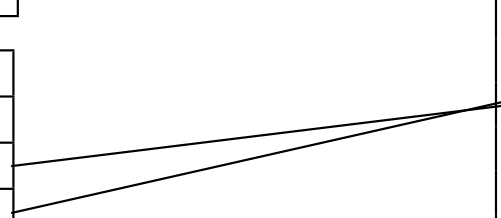
Plug-In of Seeds into Meta Array

A_1		
a_1	a_2	a_3
0	0	0
1	0	1
0	1	1

B_1		
b_1	b_2	b_3
0	0	0
1	1	1

C_1		
c_1	c_2	c_3
0	0	0
1	1	1

D_1		
d_1	d_2	d_3
0	0	0
1	1	1



	$\mathcal{M}$			
#	M_1	M_2	M_3	M_4
1	0	0	1	1
2	0	1	0	0
3	1	0	0	1
4	1	1	1	0
5	2	0	0	0
6	2	1	1	1

Plug-In of Seeds into Meta Array

A_1		
a_1	a_2	a_3
0	0	0
1	0	1
0	1	1

B_1		
b_1	b_2	b_3
0	0	0
1	1	1

C_1		
c_1	c_2	c_3
0	0	0
1	1	1

D_1		
d_1	d_2	d_3
0	0	0
1	1	1

	$\mathcal{M}$			
#	M_1	M_2	M_3	M_4
1	0	0	1	1
2	0	1	0	0
3	1	0	0	1
4	1	1	1	0
5	2	0	0	0
6	2	1	1	1

Plug-In of Seeds into Meta Array

A_1		
a_1	a_2	a_3
0	0	0
1	0	1
0	1	1

B_1		
b_1	b_2	b_3
0	0	0
1	1	1

C_1		
c_1	c_2	c_3
0	0	0
1	1	1

D_1		
d_1	d_2	d_3
0	0	0
1	1	1

	$\mathcal{M}$			
#	M_1	M_2	M_3	M_4
1	0	0	1	1
2	0	1	0	0
3	1	0	0	1
4	1	1	1	0
5	2	0	0	0
6	2	1	1	1

Plug-In of Seeds into Meta Array

A_1		
a_1	a_2	a_3
0	0	0
1	0	1
0	1	1

B_1		
b_1	b_2	b_3
0	0	0
1	1	1

C_1		
c_1	c_2	c_3
0	0	0
1	1	1

D_1		
d_1	d_2	d_3
0	0	0
1	1	1

	$\mathcal{M}$			
#	M_1	M_2	M_3	M_4
1	0	0	1	1
2	0	1	0	0
3	1	0	0	1
4	1	1	1	0
5	2	0	0	0
6	2	1	1	1

Result of Plug In

	$\mathcal{H}$											
#	a_1	a_2	a_3	b_1	b_2	b_3	c_1	c_2	c_3	d_1	d_2	d_3
1	0	0	0	0	0	0	1	1	1	1	1	1
2	0	0	0	1	1	1	0	0	0	0	0	0
3	1	0	1	0	0	0	0	0	0	1	1	1
4	1	0	1	1	1	1	1	1	1	0	0	0
5	0	1	1	0	0	0	0	0	0	0	0	0
6	0	1	1	1	1	1	1	1	1	1	1	1

Extending Bounds of Usability of CT

Observation

Analysis of CA generation tools shows that (most) of them rely on tuple counting

- May cause interruption of computation of large CAs

Possible Solution

- Use *'smaller'* CAs to build *'bigger'* CAs leveraging coverage inheritance
- In case an MCA is not directly constructible due to resource consumption and (constrained) computing environment:
  - employ a "Nested CA construction"

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Nested CA Construction

Construct an $MCA(N; t, g, (v_1, \ldots, v_g))$

1. Partition parameter configuration into classes $V_1, \ldots, V_k$
2. For each $i = 1, \ldots, k$ construct seed arrays $S_i = MCA(N_i; t, |V_i|, V_i)$
3. Construct a meta array $\mathcal{M} = MCA(N_m; t, k, (N_1, \ldots, N_k))$
4. Apply a plug-in construction to the **seed arrays** $(S_i)_{i=1}^k$ and the **meta array** $\mathcal{M}$

Example: Construct $CA(N; 3, 500, 2)$

1. Partition parameters into classes of 10 parameters each.
2. Compute a seed array $S = CA(12; 3, 5, 2)$.
3. Compute a meta array $\mathcal{M} = CA(10807; 3, 100, 12)$.
4. Apply a plug-in construction to the seed array S and the meta array $\mathcal{M}$.

The resulting array is a $CA(10807; 3, 500, 2)$

Construction of Large CAs

Remarks

- The constructed arrays are not optimal
- When available infrastructure fails to compute a CA
- We might still be able to construct a CA
  - Computing only the seeds
  - Applying a plug-in construction

Array	Computation Time	Size	Memory Available
$CA(N; 3, 1000, 2)$	o.o.M.	-	5 GB
$S = CA(6; 2, 6, 2)$	0sec	6	5 GB
$T = CA(20; 3, 5, 2)$	0 sec	20	5 GB
$\mathcal{M} = CA(1635; 3, 200, 6)$	$\sim$10 min	1635	5 GB
$\mathcal{R} = CA(1655; 3, 1000, 6)$	0 sec	1655	5 GB
$CA(N; 3, 2000, 3)$	o.o.M. (after $>$7 hrs)	-	10 GB
$S = CA(6; 2, 5, 2)$	0 sec	6	10 GB
$T = CA(20; 3, 5, 2)$	0 sec	20	10 GB
$\mathcal{M} = CA(1930; 3, 400, 6)$	$\sim$2.5 hrs	1930	10 GB
$\mathcal{R} = CA(1950; 3, 2000, 2)$	0 sec	1950	10 GB

"o.o.M.", the computation aborted with an out of memory error.

Summary

Highlights

1. Combinatorial methods for modelling composed software systems
   - automotives
   - Linux kernel system calls
2. Combinatorial constructions for building nested test suites (resp. CAs) from nested IPMs (resp. CAs):
   - use of t-way coverage inheritance
3. Extending bounds of usability of CT

Future Work

- Cyber-Physical Systems (CPS) Modelling
- Internet of Things (IoT)

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References

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Questions - Comments

Thank you for your Attention!

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