

- **Problem:** we have $\neg$, $\wedge$, and $\vee$, so given the specification

x_{n-1}	$\cdots$	x_1	x_0	r
0	$\cdots$	0	0	1
0	$\cdots$	0	1	0
0	$\cdots$	1	0	1
0	$\cdots$	1	1	0
$\vdots$		$\vdots$	$\vdots$	$\vdots$
1	$\cdots$	1	1	0

for some Boolean function

$$r = f(x_0, x_1, \dots, x_{n-1}),$$

design a Boolean expression e which can compute it.

- **Solution:** ?

- ▶ **Agenda:** **combinatorial logic** design, where, crucially,
 - ▶ the output is a function of the input only,
 - ▶ computation is viewed as being continuous,via coverage of
 1. special-purpose design patterns,
 2. special-purpose building blocks, and
 3. general-purpose derivation.

Part 1: special-purpose design patterns

► Pattern #1: **reuse** (or **sharing**).

- Imagine, for example, that we are given a 2-input, 1-bit AND gate.
- If, within some larger circuit, we compute

$$r = x \wedge y$$

and then, somewhere else,

$$r' = x \wedge y$$

then we can replace the two AND gates with one: clearly

$$r = r',$$

so we can share one definition between two usage points.

- Formally, this optimisation is type of **Common Sub-expression Elimination (CSE)**.

Part 1: special-purpose design patterns

► **Pattern #1:** *“don’t (re)compute a value you’ve computed already”.*

- Imagine, for example, that we are given a 2-input, 1-bit AND gate.
- If, within some larger circuit, we compute

$$r = x \wedge y$$

and then, somewhere else,

$$r' = x \wedge y$$

then we can replace the two AND gates with one: clearly

$$r = r',$$

so we can share one definition between two usage points.

- Formally, this optimisation is type of **Common Sub-expression Elimination (CSE)**.

Part 1: special-purpose design patterns

► Pattern #2: **decomposition** (or **divide-and-conquer**).

- Given an n -input, m -output Boolean function

$$f : \mathbb{B}^n \rightarrow \mathbb{B}^m$$

we can ensure

$$f(x) \equiv f_0(x) \parallel f_1(x) \parallel \dots \parallel f_{m-1}(x)$$

for appropriate f_i .

- Those f_i are such that

$$\begin{array}{rcl} f_0 & : & \mathbb{B}^n \rightarrow \mathbb{B} \\ f_1 & : & \mathbb{B}^n \rightarrow \mathbb{B} \\ & \vdots & \\ f_{m-1} & : & \mathbb{B}^n \rightarrow \mathbb{B} \end{array}$$

i.e., f_i uses x to compute the i -th output f would.

Part 1: special-purpose design patterns

- ▶ **Pattern #2:** “describe a large, complex function in terms of smaller, simple functions”.

- ▶ Given an n -input, m -output Boolean function

$$f : \mathbb{B}^n \rightarrow \mathbb{B}^m$$

we can ensure

$$f(x) \equiv f_0(x) \parallel f_1(x) \parallel \dots \parallel f_{m-1}(x)$$

for appropriate f_i .

- ▶ Those f_i are such that

$$\begin{array}{ccc} f_0 & : & \mathbb{B}^n \rightarrow \mathbb{B} \\ f_1 & : & \mathbb{B}^n \rightarrow \mathbb{B} \\ & \vdots & \\ f_{m-1} & : & \mathbb{B}^n \rightarrow \mathbb{B} \end{array}$$

i.e., f_i uses x to compute the i -th output f would.

Part 1: special-purpose design patterns

► Pattern #3: independent replication.

- Imagine, for example, that we are given a 2-input, 1-bit AND gate.
- A 2-input, m -bit AND gate is simply replication of 2-input, 1-bit AND gates, i.e.,

$$r = x \wedge y$$

is computed via

$$r_i = x_i \wedge y_i$$

for $0 \leq i < m$.

- For $n = 4$, as an example, this means

$$\begin{aligned} r_0 &= x_0 \wedge y_0 \\ r_1 &= x_1 \wedge y_1 \\ r_2 &= x_2 \wedge y_2 \\ r_3 &= x_3 \wedge y_3 \end{aligned}$$

Part 1: special-purpose design patterns

- ▶ **Pattern #3:** *“repeat the same structure multiple times; the outcomes are separate”*.

- ▶ Imagine, for example, that we are given a 2-input, 1-bit AND gate.
- ▶ A 2-input, m -bit AND gate is simply replication of 2-input, 1-bit AND gates, i.e.,

$$r = x \wedge y$$

is computed via

$$r_i = x_i \wedge y_i$$

for $0 \leq i < m$.

- ▶ For $n = 4$, as an example, this means

$$\begin{aligned} r_0 &= x_0 \wedge y_0 \\ r_1 &= x_1 \wedge y_1 \\ r_2 &= x_2 \wedge y_2 \\ r_3 &= x_3 \wedge y_3 \end{aligned}$$

Part 1: special-purpose design patterns

► Pattern #4: **dependent replication**.

- Imagine, for example, that we are given a 2-input, 1-bit AND gate.
- An n -input, 1-bit AND gate is simply replication of 2-input, 1-bit AND gates, i.e.,

$$r = \bigwedge_{i=0}^{n-1} x_i$$

is computed via

$$r = x_0 \wedge (x_1 \wedge \cdots (x_{n-1}))$$

which is often termed a **reduction** with respect to AND.

- For $n = 4$, as an example, this means

$$\begin{aligned} r &= x_0 \wedge (x_1 \wedge x_2 \wedge (x_3)) \\ &= x_0 \wedge x_1 \wedge x_2 \wedge x_3 \\ &= (x_0 \wedge x_1) \wedge (x_2 \wedge x_3) \end{aligned}$$

Part 1: special-purpose design patterns

► **Pattern #4:** “repeat the same structure multiple times; the outcomes are combined”.

- Imagine, for example, that we are given a 2-input, 1-bit AND gate.
- An n -input, 1-bit AND gate is simply replication of 2-input, 1-bit AND gates, i.e.,

$$r = \bigwedge_{i=0}^{n-1} x_i$$

is computed via

$$r = x_0 \wedge (x_1 \wedge \cdots (x_{n-1}))$$

which is often termed a **reduction** with respect to AND.

- For $n = 4$, as an example, this means

$$\begin{aligned} r &= x_0 \wedge (x_1 \wedge x_2 \wedge (x_3)) \\ &= x_0 \wedge x_1 \wedge x_2 \wedge x_3 \\ &= (x_0 \wedge x_1) \wedge (x_2 \wedge x_3) \end{aligned}$$

Part 2: special-purpose building blocks (1)

Choice

► **Concept: selection (or choice).**

1. a **multiplexer**

- has m inputs,
 - has 1 output,
 - uses a $(\lceil \log_2(m) \rceil)$ -bit control signal input to choose which input is connected to the output,
- while

2. a **demultiplexer**

- has 1 input,
- has m outputs,
- uses a $(\lceil \log_2(m) \rceil)$ -bit control signal input to choose which output is connected to the input,

noting that

- the input(s) and output(s) are n -bit, but clearly must match up,
- the connection made is continuous, since both components are combinatorial.

Part 2: special-purpose building blocks (2)

Choice

► Concept: by analogy,

1. the C switch statement

Listing

```
1 switch( c ) {  
2     case 0 : r = w; break;  
3     case 1 : r = x; break;  
4     case 2 : r = y; break;  
5     case 3 : r = z; break;  
6 }
```

acts similarly to a 4-input multiplexer,

2. the C switch statement

Listing

```
1 switch( c ) {  
2     case 0 : r0 = x; break;  
3     case 1 : r1 = x; break;  
4     case 2 : r2 = x; break;  
5     case 3 : r3 = x; break;  
6 }
```

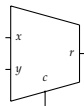
acts similarly to a 4-output demultiplexer.

Part 2: special-purpose building blocks (3)

Choice

Definition

The behaviour of a **2-input, 1-bit multiplexer** component



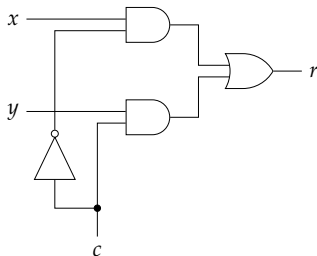
is described by the truth table

c	x	y	r
0	0	?	0
0	1	?	1
1	?	0	0
1	?	1	1

which can be used to derive the following implementation:

$$r = (\neg c \wedge x) \vee (c \wedge y)$$

Circuit

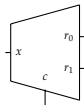


Part 2: special-purpose building blocks (4)

Choice

Definition

The behaviour of a **2-output, 1-bit demultiplexer** component



is described by the truth table

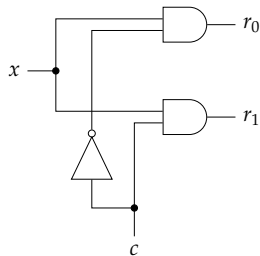
c	x	r_1	r_0
0	0	?	0
0	1	?	1
1	0	0	?
1	1	1	?

which can be used to derive the following implementation:

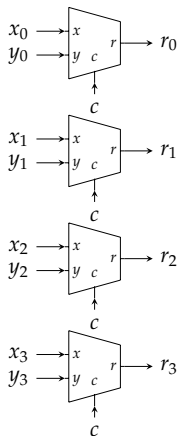
$$r_0 = \neg c \wedge x$$

$$r_1 = c \wedge x$$

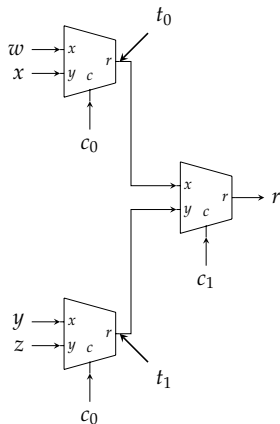
Circuit



Circuit (2-input, 4-bit multiplexer via independent replication)



Circuit (4-input, 1-bit multiplexer via dependent replication)



Part 2: special-purpose building blocks (7)

Addition

► **Concept: addition.**

1. a **half-adder**

- has 2 inputs: x and y ,
 - computes the 2-bit result $x + y$,
 - has 2 outputs: a sum s , and a carry-out co (which are the LSB and MSB of result),
- while

2. a **full-adder**

- has 3 inputs: x and y plus a carry-in ci ,
- computes the 2-bit result $x + y + ci$,
- has 2 outputs: a sum s , and a carry-out co (which are the LSB and MSB of result),

where all inputs and outputs are 1-bit.

Part 2: special-purpose building blocks (8)

Addition

Definition

The behaviour of a **half-adder** component



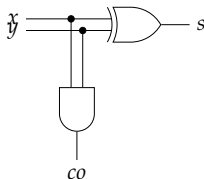
is described by the truth table

x	y	co	s
0	0	0	0
0	1	0	1
1	0	0	1
1	1	1	0

which can be used to derive the following implementation:

$$\begin{aligned} co &= x \wedge y \\ s &= x \oplus y \end{aligned}$$

Circuit



Part 2: special-purpose building blocks (9)

Addition

Definition

The behaviour of a **full-adder** component



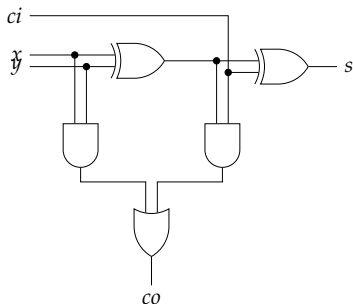
is described by the truth table

ci	x	y	co	s
0	0	0	0	0
0	0	1	0	1
0	1	0	0	1
0	1	1	1	0
1	0	0	0	1
1	0	1	1	0
1	1	0	1	0
1	1	1	1	1

which can be used to derive the following implementation:

$$\begin{aligned}co &= (x \wedge y) \vee (x \wedge ci) \vee (y \wedge ci) \\ &= (x \wedge y) \vee ((x \oplus y) \wedge ci) \\ s &= x \oplus y \oplus ci\end{aligned}$$

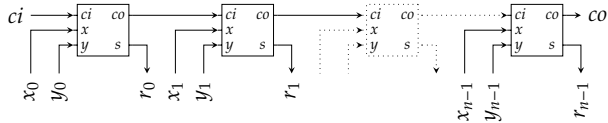
Circuit



Part 2: special-purpose building blocks (10)

Addition

Circuit (n -bit addition)



Part 2: special-purpose building blocks (11)

Comparison

► **Concept: comparison.**

1. an **equality comparator**

- has 2 inputs x and y ,
- computes the 1 output as

$$r = \begin{cases} 1 & \text{if } x = y \\ 0 & \text{otherwise} \end{cases}$$

while

2. a **less-than comparator**

- has 2 inputs x and y ,
- computes the 1 output as

$$r = \begin{cases} 1 & \text{if } x < y \\ 0 & \text{otherwise} \end{cases}$$

where all inputs and outputs are 1-bit.

Part 2: special-purpose building blocks (12)

Comparison

Definition

The behaviour of an **equality comparator** component



is described by the truth table

x	y	r
0	0	1
0	1	0
1	0	0
1	1	1

which can be used to derive the following implementation:

$$r = \neg(x \oplus y)$$

Circuit



Part 2: special-purpose building blocks (13)

Comparison

Definition

The behaviour of a **less-than comparator** component



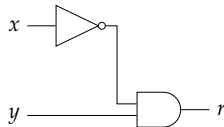
is described by the truth table

x	y	r
0	0	0
0	1	1
1	0	0
1	1	0

which can be used to derive the following implementation:

$$r = \neg x \wedge y$$

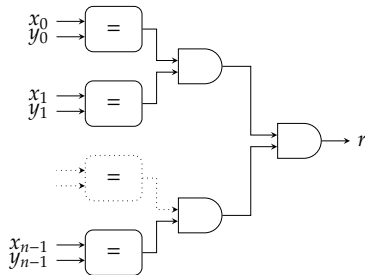
Circuit



Part 2: special-purpose building blocks (14)

Comparison

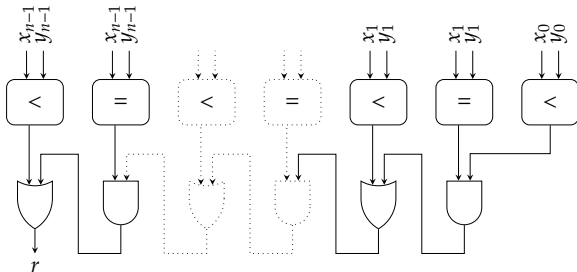
Circuit (n -bit equality comparison)



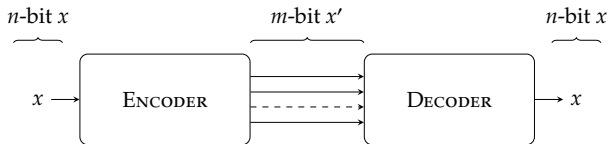
Part 2: special-purpose building blocks (15)

Comparison

Circuit (n -bit less-than comparison)



- **Concept:** translation, via **encoders** and **decoders**, i.e.,



or, more formally,

1. an n -to- m encoder translates an n -bit input into some m -bit code word, and
2. an m -to- n decoder translates an m -bit code word back into the same n -bit output

where if only one output (resp. input) is allowed to be 1 at a time, we call it a **one-of-many** encoder (resp. decoder).

► **Example:**

1. to encode, take 4 inputs, say x_i for $0 \leq i < 4$, and produce a unsigned integer x' that determines which $x_i = 1$,
2. to decode, take x' and set the correct $x_i = 1$
where for all $j \neq i$, $x'_j = 0$.

Part 2: special-purpose building blocks (17)

Control

Definition (example encoder)

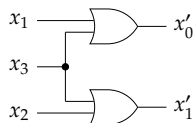
The example encoder is described by the truth table

x_3	x_2	x_1	x_0	x'_1	x'_0
0	0	0	1	0	0
0	0	1	0	0	1
0	1	0	0	1	0
1	0	0	0	1	1

which can be used to derive the following implementation:

$$\begin{aligned}x'_0 &= x_1 \vee x_3 \\x'_1 &= x_2 \vee x_3\end{aligned}$$

Circuit (example encoder)



Part 2: special-purpose building blocks (18)

Control

Definition (example decoder)

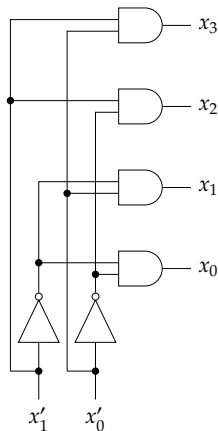
The example decoder is described by the truth table

x'_1	x'_0	x_3	x_2	x_1	x_0
0	0	0	0	0	1
0	1	0	0	1	0
1	0	0	1	0	0
1	1	1	0	0	0

which can be used to derive the following implementation:

$$\begin{aligned}x_0 &= \neg x'_0 \wedge \neg x'_1 \\x_1 &= x'_0 \wedge \neg x'_1 \\x_2 &= \neg x'_0 \wedge x'_1 \\x_3 &= x'_0 \wedge x'_1\end{aligned}$$

Circuit (example decoder)



Part 3: general-purpose derivation (1)

Method #1

Algorithm

Input: A truth table for some Boolean function f , with n inputs and 1 output

Output: A Boolean expression e that implements f

First let I_j be a synonym for the j -th input, for $0 \leq j < n$, and O be a synonym for the output.

1. Find a set T such that $i \in T$ iff. $O = 1$ in the i -th row of the truth table.
2. For each $i \in T$, form a term t_i by AND'ing together all the inputs while following two rules:

2.1 if $I_j = 1$ in the i -th row, then we use

$$I_j$$

as is, but

2.2 if $I_j = 0$ in the i -th row, then we use

$$\neg I_j.$$

3. An expression implementing the function is then formed by OR'ing together all the terms, i.e.,

$$e = \bigvee_{i \in T} t_i,$$

which is in SoP form.

Part 3: general-purpose derivation (2)

Method #1

Example

Consider the example of deriving an expression for XOR, i.e.,

$$r = f(x, y) = x \oplus y,$$

a function described by the following truth table:

x	y	r
0	0	0
0	1	1
1	0	1
1	1	0

Part 3: general-purpose derivation (2)

Method #1

Example

Consider the example of deriving an expression for XOR, i.e.,

$$r = f(x, y) = x \oplus y,$$

a function described by the following truth table:

x	y	r
0	0	0
0	1	1
1	0	1
1	1	0

Based on the fact there are $n = 2$ inputs and 1 output, we can use

$$\begin{array}{lll} I_0 & \equiv & x \\ I_1 & \equiv & y \\ O & \equiv & r \end{array}$$

Part 3: general-purpose derivation (2)

Method #1

Example

Consider the example of deriving an expression for XOR, i.e.,

$$r = f(x, y) = x \oplus y,$$

a function described by the following truth table:

x	y	r
0	0	0
0	1	1
1	0	1
1	1	0

$\rightsquigarrow i = 1$
 $\rightsquigarrow i = 2$

The algorithm steps are as follows:

1. Clearly $T = \{1, 2\}$, because
 - ▶ $O \equiv r = 1$ in rows 1 and 2,
 - ▶ $O \equiv r = 0$ in rows 0 and 3.

Part 3: general-purpose derivation (2)

Method #1

Example

Consider the example of deriving an expression for XOR, i.e.,

$$r = f(x, y) = x \oplus y,$$

a function described by the following truth table:

x	y	r
0	0	0
0	1	1
1	0	1
1	1	0

$$\leadsto t_1 = \neg x \wedge y$$

$$\leadsto t_2 = x \wedge \neg y$$

The algorithm steps are as follows:

2. Each term t_i for $i \in T = \{1, 2\}$ is formed as follows:

► For $i = 1$, we find

► $I_0 \equiv x = 0$ and so we use $\neg x$,

► $I_1 \equiv y = 1$ and so we use y

and hence form the term $t_1 = \neg x \wedge y$.

► For $i = 2$, we find

► $I_0 \equiv x = 1$ and so we use x ,

► $I_1 \equiv y = 0$ and so we use $\neg y$

and hence form the term $t_2 = x \wedge \neg y$.

Part 3: general-purpose derivation (2)

Method #1

Example

Consider the example of deriving an expression for XOR, i.e.,

$$r = f(x, y) = x \oplus y,$$

a function described by the following truth table:

x	y	r
0	0	0
0	1	1
1	0	1
1	1	0

$$\begin{array}{ll} \rightsquigarrow & t_1 = \neg x \wedge y \\ \rightsquigarrow & t_2 = x \wedge \neg y \end{array}$$

The algorithm steps are as follows:

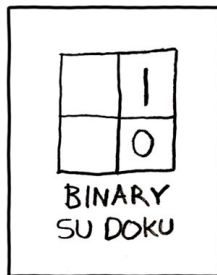
3. The expression implementing the function is therefore

$$\begin{aligned} e &= \bigvee_{i \in T} t_i \\ &= \bigvee_{i \in \{1,2\}} t_i \\ &= (\neg x \wedge y) \vee (x \wedge \neg y) \end{aligned}$$

which is in SoP form.

Part 3: general-purpose derivation (3)

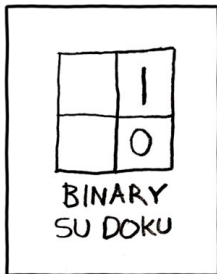
Method #2: Karnaugh map



<https://xkcd.com/74>

Part 3: general-purpose derivation (3)

Method #2: Karnaugh map



► Idea:

$$\begin{aligned}(x \wedge y) \vee (x \wedge \neg y) &\equiv x \wedge (y \vee \neg y) && \text{(distribution)} \\ &\equiv x \wedge 1 && \text{(inverse)} \\ &\equiv x && \text{(identity)}\end{aligned}$$

Part 3: general-purpose derivation (4)

Method #2: Karnaugh map

Algorithm

Input: A truth table for some Boolean function f , with n inputs and 1 output

Output: A Boolean expression e that implements f

1. Draw a rectangular $(p \times q)$ -element grid, st.
 - 1.1 $p \equiv q \equiv 0 \pmod{2}$, and
 - 1.2 $p \cdot q = 2^n$and each row and column represents one input combination; order rows and columns according to a **Gray code**.
2. Fill the grid elements with the output corresponding to inputs for that row and column.
3. Cover rectangular groups of adjacent 1 elements which are of total size 2^m for some m , aiming for
 - 3.1 *bigger* groups, and
 - 3.2 *fewer* groupsbecause this produces a simpler expression; groups can “wrap around” edges of the grid, and/or overlap.
4. Translate each group into one term of an SoP form Boolean expression e .

Part 3: general-purpose derivation (5)

Method #2: Karnaugh map

Example

Natural sequence			Gray code sequence		
$\langle 0, 0, 0, 0 \rangle$	$\mapsto$	$0_{(10)}$	$\langle 0, 0, 0, 0 \rangle$	$\mapsto$	$0_{(10)}$
$\langle 1, 0, 0, 0 \rangle$	$\mapsto$	$1_{(10)}$	$\langle 1, 0, 0, 0 \rangle$	$\mapsto$	$1_{(10)}$
$\langle 0, 1, 0, 0 \rangle$	$\mapsto$	$2_{(10)}$	$\langle 1, 1, 0, 0 \rangle$	$\mapsto$	$3_{(10)}$
$\langle 1, 1, 0, 0 \rangle$	$\mapsto$	$3_{(10)}$	$\langle 0, 1, 0, 0 \rangle$	$\mapsto$	$2_{(10)}$
$\langle 0, 0, 1, 0 \rangle$	$\mapsto$	$4_{(10)}$	$\langle 0, 1, 1, 0 \rangle$	$\mapsto$	$6_{(10)}$
$\langle 1, 0, 1, 0 \rangle$	$\mapsto$	$5_{(10)}$	$\langle 0, 0, 1, 0 \rangle$	$\mapsto$	$4_{(10)}$
$\langle 0, 1, 1, 0 \rangle$	$\mapsto$	$6_{(10)}$	$\langle 1, 0, 1, 0 \rangle$	$\mapsto$	$5_{(10)}$
$\langle 1, 1, 1, 0 \rangle$	$\mapsto$	$7_{(10)}$	$\langle 1, 1, 1, 0 \rangle$	$\mapsto$	$7_{(10)}$
$\vdots$			$\vdots$		

Part 3: general-purpose derivation (6)

Method #2: Karnaugh map

Example

Consider an example 4-input, 1-output function:

w	x	y	z	r
0	0	0	0	1
0	0	0	1	1
0	0	1	0	1
0	0	1	1	0
0	1	0	0	1
0	1	0	1	1
0	1	1	0	0
0	1	1	1	0
1	0	0	0	1
1	0	0	1	0
1	0	1	0	1
1	0	1	1	1
1	1	0	0	0
1	1	0	1	0
1	1	1	0	0
1	1	1	1	1

Part 3: general-purpose derivation (6)

Method #2: Karnaugh map

Example

Consider an example 4-input, 1-output function:

w	x	y	z	r
0	0	0	0	1
0	0	0	1	1
0	0	1	0	1
0	0	1	1	0
0	1	0	0	1
0	1	0	1	1
0	1	1	0	0
0	1	1	1	0
1	0	0	0	1
1	0	0	1	0
1	0	1	0	1
1	0	1	1	1
1	1	0	0	0
1	1	0	1	0
1	1	1	0	0
1	1	1	1	1

		w			
		x			
		00	01	11	10
y	00	1	1	0	1
	01	1	1	0	0
	11	0	0	1	1
	10	1	0	0	1

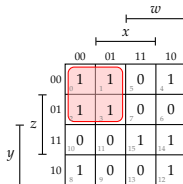
Part 3: general-purpose derivation (6)

Method #2: Karnaugh map

Example

Consider an example 4-input, 1-output function:

w	x	y	z	r
0	0	0	0	1
0	0	0	1	1
0	0	1	0	1
0	0	1	1	0
0	1	0	0	1
0	1	0	1	1
0	1	1	0	0
0	1	1	1	0
1	0	0	0	1
1	0	0	1	0
1	0	1	0	1
1	0	1	1	1
1	1	0	0	0
1	1	0	1	0
1	1	1	0	0
1	1	1	1	1



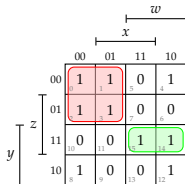
Each group translates into one term of the SoP form expression

$$r = (\neg w \quad \quad \quad \wedge \quad \neg y \quad \quad)$$

Example

Consider an example 4-input, 1-output function:

w	x	y	z	r
0	0	0	0	1
0	0	0	1	1
0	0	1	0	1
0	0	1	1	0
0	1	0	0	1
0	1	0	1	1
0	1	1	0	0
0	1	1	1	0
1	0	0	0	1
1	0	0	1	0
1	0	1	0	1
1	0	1	1	1
1	1	0	0	0
1	1	0	1	0
1	1	1	0	0
1	1	1	1	1



Each group translates into one term of the SoP form expression

$$r = \left(\begin{array}{cccc} \neg w & \wedge & \neg y & \\ w & \wedge & y & \wedge z \end{array} \right) \vee$$

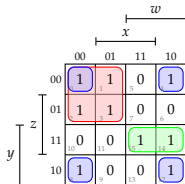
Part 3: general-purpose derivation (6)

Method #2: Karnaugh map

Example

Consider an example 4-input, 1-output function:

w	x	y	z	r
0	0	0	0	1
0	0	0	1	1
0	0	1	0	1
0	0	1	1	0
0	1	0	0	1
0	1	0	1	1
0	1	1	0	0
0	1	1	1	0
1	0	0	0	1
1	0	0	1	0
1	0	1	0	1
1	0	1	1	1
1	1	0	0	0
1	1	0	1	0
1	1	1	0	0
1	1	1	1	1



Each group translates into one term of the SoP form expression

$$r = (\neg w \wedge \neg y) \vee (w \wedge y \wedge z) \vee (\neg x \wedge \neg z)$$

Part 3: general-purpose derivation (7)

Method #2: Karnaugh map

Example

Consider an example 3-input, 1-output function:

x	y	z	r
0	0	0	0
0	0	1	0
0	1	0	1
0	1	1	1
1	0	0	0
1	0	1	?
1	1	0	1
1	1	1	?

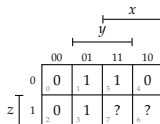
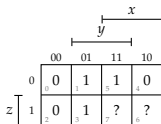
Part 3: general-purpose derivation (7)

Method #2: Karnaugh map

Example

Consider an example 3-input, 1-output function:

x	y	z	r
0	0	0	0
0	0	1	0
0	1	0	1
0	1	1	1
1	0	0	0
1	0	1	?
1	1	0	1
1	1	1	?



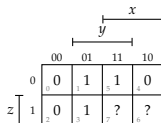
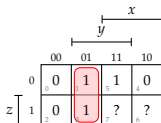
Part 3: general-purpose derivation (7)

Method #2: Karnaugh map

Example

Consider an example 3-input, 1-output function:

x	y	z	r
0	0	0	0
0	0	1	0
0	1	0	1
0	1	1	1
1	0	0	0
1	0	1	?
1	1	0	1
1	1	1	?



Each group translates into one term of the SoP form expressions

$$r = (\neg x \wedge y)$$

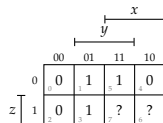
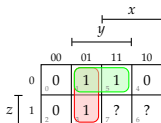
Part 3: general-purpose derivation (7)

Method #2: Karnaugh map

Example

Consider an example 3-input, 1-output function:

x	y	z	r
0	0	0	0
0	0	1	0
0	1	0	1
0	1	1	1
1	0	0	0
1	0	1	?
1	1	0	1
1	1	1	?



Each group translates into one term of the SoP form expressions

$$r = (\neg x \wedge y) \vee (y \wedge \neg z)$$

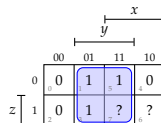
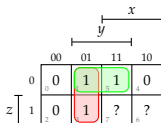
Part 3: general-purpose derivation (7)

Method #2: Karnaugh map

Example

Consider an example 3-input, 1-output function:

x	y	z	r
0	0	0	0
0	0	1	0
0	1	0	1
0	1	1	1
1	0	0	0
1	0	1	?
1	1	0	1
1	1	1	?



Each group translates into one term of the SoP form expressions

$$r = (\neg x \wedge y) \vee (y \wedge \neg z)$$

$$r = y$$

where effective use of don't care states yields a clear improvement!

Part 3: general-purpose derivation (8)

Method #2: Karnaugh map

Example

Consider an example 3-input, 1-output function:

x	y	z	r
0	0	0	1
0	0	1	0
0	1	0	1
0	1	1	0
1	0	0	1
1	0	1	1
1	1	0	0
1	1	1	1

Part 3: general-purpose derivation (8)

Method #2: Karnaugh map

Example

Consider an example 3-input, 1-output function:

x	y	z	r
0	0	0	1
0	0	1	0
0	1	0	1
0	1	1	0
1	0	0	1
1	0	1	1
1	1	0	0
1	1	1	1

				x			
				y			
				00	01	11	10
z	0	1	1	0	1		
	1	0	0	1	1		

Part 3: general-purpose derivation (8)

Method #2: Karnaugh map

Example

Consider an example 3-input, 1-output function:

x	y	z	r
0	0	0	1
0	0	1	0
0	1	0	1
0	1	1	0
1	0	0	1
1	0	1	1
1	1	0	0
1	1	1	1

				x			
				y			
				00	01	11	10
z	0	1	1	0	1		
	1	0	0	1	1		

Each group translates into one term of the SoP form expression

$$r = (\quad x \quad \quad \wedge \quad z \quad)$$

Part 3: general-purpose derivation (8)

Method #2: Karnaugh map

Example

Consider an example 3-input, 1-output function:

x	y	z	r
0	0	0	1
0	0	1	0
0	1	0	1
0	1	1	0
1	0	0	1
1	0	1	1
1	1	0	0
1	1	1	1

		x			
		y			
		00	01	11	10
z	0	1 ₀	1 ₁	0 ₅	1 ₄
	1	0 ₂	0 ₃	1 ₆	1 ₇

Each group translates into one term of the SoP form expression

$$r = (\quad x \quad \wedge \quad z \quad) \vee (\quad x \quad \wedge \quad \neg y \quad)$$

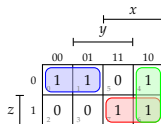
Part 3: general-purpose derivation (8)

Method #2: Karnaugh map

Example

Consider an example 3-input, 1-output function:

x	y	z	r
0	0	0	1
0	0	1	0
0	1	0	1
0	1	1	0
1	0	0	1
1	0	1	1
1	1	0	0
1	1	1	1



Each group translates into one term of the SoP form expression

$$r = (\quad x \quad \quad \quad \wedge \quad z \quad) \vee \\ (\quad x \quad \wedge \quad \neg y \quad \quad \quad) \vee \\ (\quad \neg x \quad \quad \quad \wedge \quad \neg z \quad)$$

Part 3: general-purpose derivation (9)

Method #2: Karnaugh map

Example

Consider an example 4-input, 2-output function:

w	x	y	z	r_1	r_0
0	0	0	0	0	0
0	0	0	1	0	1
0	0	1	0	1	0
0	0	1	1	?	?
0	1	0	0	0	1
0	1	0	1	1	0
0	1	1	0	0	0
0	1	1	1	?	?
1	0	0	0	1	0
1	0	0	1	0	0
1	0	1	0	0	1
1	0	1	1	?	?
1	1	0	0	?	?
1	1	0	1	?	?
1	1	1	0	?	?
1	1	1	1	?	?

Part 3: general-purpose derivation (9)

Method #2: Karnaugh map

Example

Consider an example 4-input, 2-output function:

w	x	y	z	r_1	r_0
0	0	0	0	0	0
0	0	0	1	0	1
0	0	1	0	1	0
0	0	1	1	?	?
0	1	0	0	0	1
0	1	0	1	1	0
0	1	1	0	0	0
0	1	1	1	?	?
1	0	0	0	1	0
1	0	0	1	0	0
1	0	1	0	0	1
1	0	1	1	?	?
1	1	0	0	?	?
1	1	0	1	?	?
1	1	1	0	?	?
1	1	1	1	?	?

		w			
		x			
r_1		00	01	11	10
00		0	0	?	1
01		0	1	?	0
11		?	?	?	?
10		1	0	?	0
z	y				

		w			
		x			
r_0		00	01	11	10
00		0	1	?	0
01		1	0	?	0
11		?	?	?	?
10		0	0	?	1
z	y				

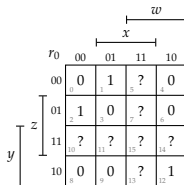
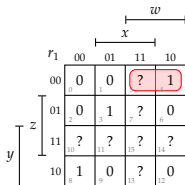
Part 3: general-purpose derivation (9)

Method #2: Karnaugh map

Example

Consider an example 4-input, 2-output function:

w	x	y	z	r_1	r_0
0	0	0	0	0	0
0	0	0	1	0	1
0	0	1	0	1	0
0	0	1	1	?	?
0	1	0	0	0	1
0	1	0	1	1	0
0	1	1	0	0	0
0	1	1	1	?	?
1	0	0	0	1	0
1	0	0	1	0	0
1	0	1	0	0	1
1	0	1	1	?	?
1	1	0	0	?	?
1	1	0	1	?	?
1	1	1	0	?	?
1	1	1	1	?	?



Each group translates into one term of the SoP form expressions

$$r_1 = (\quad w \quad \wedge \quad \neg y \quad \wedge \quad \neg z \quad)$$

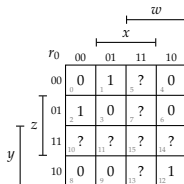
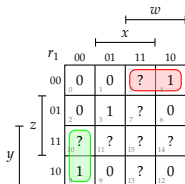
Part 3: general-purpose derivation (9)

Method #2: Karnaugh map

Example

Consider an example 4-input, 2-output function:

w	x	y	z	r_1	r_0
0	0	0	0	0	0
0	0	0	1	0	1
0	0	1	0	1	0
0	0	1	1	?	?
0	1	0	0	0	1
0	1	0	1	1	0
0	1	1	0	0	0
0	1	1	1	?	?
1	0	0	0	1	0
1	0	0	1	0	0
1	0	1	0	0	1
1	0	1	1	?	?
1	1	0	0	?	?
1	1	0	1	?	?
1	1	1	0	?	?
1	1	1	1	?	?



Each group translates into one term of the SoP form expressions

$$r_1 = (w \wedge \neg y \wedge \neg z) \vee (y \wedge \neg w \wedge \neg x)$$

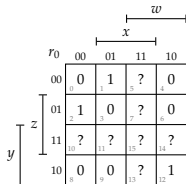
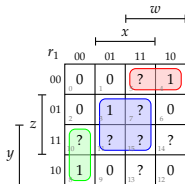
Part 3: general-purpose derivation (9)

Method #2: Karnaugh map

Example

Consider an example 4-input, 2-output function:

w	x	y	z	r_1	r_0
0	0	0	0	0	0
0	0	0	1	0	1
0	0	1	0	1	0
0	0	1	1	?	?
0	1	0	0	0	1
0	1	0	1	1	0
0	1	1	0	0	0
0	1	1	1	?	?
1	0	0	0	1	0
1	0	0	1	0	0
1	0	1	0	0	1
1	0	1	1	?	?
1	1	0	0	?	?
1	1	0	1	?	?
1	1	1	0	?	?
1	1	1	1	?	?



Each group translates into one term of the SoP form expressions

$$r_1 = (\quad w \quad \wedge \quad \neg y \quad \wedge \quad \neg z \quad) \vee \\ (\quad y \quad \wedge \quad \neg w \quad \wedge \quad \neg x \quad) \vee \\ (\quad x \quad \wedge \quad z \quad)$$

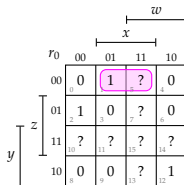
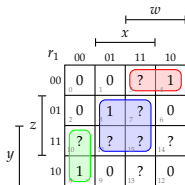
Part 3: general-purpose derivation (9)

Method #2: Karnaugh map

Example

Consider an example 4-input, 2-output function:

w	x	y	z	r_1	r_0
0	0	0	0	0	0
0	0	0	1	0	1
0	0	1	0	1	0
0	0	1	1	?	?
0	1	0	0	0	1
0	1	0	1	1	0
0	1	1	0	0	0
0	1	1	1	?	?
1	0	0	0	1	0
1	0	0	1	0	0
1	0	1	0	0	1
1	0	1	1	?	?
1	1	0	0	?	?
1	1	0	1	?	?
1	1	1	0	?	?
1	1	1	1	?	?



Each group translates into one term of the SoP form expressions

$$r_1 = (\quad w \quad \wedge \quad \neg y \quad \wedge \quad \neg z \quad) \vee \\ (\quad y \quad \wedge \quad \neg w \quad \wedge \quad \neg x \quad) \vee \\ (\quad x \quad \wedge \quad z \quad)$$

$$r_0 = (\quad x \quad \wedge \quad \neg y \quad \wedge \quad \neg z \quad)$$

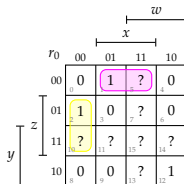
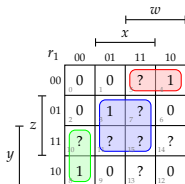
Part 3: general-purpose derivation (9)

Method #2: Karnaugh map

Example

Consider an example 4-input, 2-output function:

w	x	y	z	r_1	r_0
0	0	0	0	0	0
0	0	0	1	0	1
0	0	1	0	1	0
0	0	1	1	?	?
0	1	0	0	0	1
0	1	0	1	1	0
0	1	1	0	?	?
0	1	1	1	?	?
1	0	0	0	1	0
1	0	0	1	0	0
1	0	1	0	0	1
1	0	1	1	?	?
1	1	0	0	?	?
1	1	0	1	?	?
1	1	1	0	?	?
1	1	1	1	?	?



Each group translates into one term of the SoP form expressions

$$r_1 = (w \wedge \neg y \wedge \neg z) \vee (y \wedge \neg w \wedge \neg x) \vee (x \wedge z)$$

$$r_0 = (x \wedge \neg y \wedge \neg z) \vee (z \wedge \neg w \wedge \neg x)$$

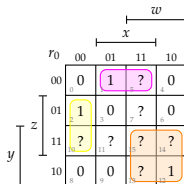
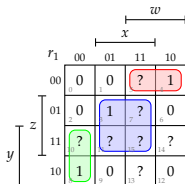
Part 3: general-purpose derivation (9)

Method #2: Karnaugh map

Example

Consider an example 4-input, 2-output function:

w	x	y	z	r_1	r_0
0	0	0	0	0	0
0	0	0	1	0	1
0	0	1	0	1	0
0	0	1	1	?	?
0	1	0	0	0	1
0	1	0	1	1	0
0	1	1	0	?	?
0	1	1	1	?	?
1	0	0	0	1	0
1	0	0	1	0	0
1	0	1	0	0	1
1	0	1	1	?	?
1	1	0	0	?	?
1	1	0	1	?	?
1	1	1	0	?	?
1	1	1	1	?	?



Each group translates into one term of the SoP form expressions

$$r_1 = (w \wedge \neg y \wedge \neg z) \vee (y \wedge \neg w \wedge \neg x) \vee (x \wedge z)$$

$$r_0 = (x \wedge \neg y \wedge \neg z) \vee (z \wedge \neg w \wedge \neg x) \vee (w \wedge y)$$

► Take away points:

1. **Bad news:** even (relatively) simple problems present numerous challenges, e.g.,
 - how do we describe what the design should do?
 - how do we structure the design?
 - what sort of standard cell library do we use?
 - do we aim for the fewest gates?
 - do we aim for shortest critical path?
 - how do we cope with propagation delay and fan-out?
 - ...
2. **Good news:** the approaches we've covered, i.e.,
 - special-purpose design patterns,
 - special-purpose building-block components,
 - general-purpose derivation and optimisation of Boolean expressions,allows us to address such challenges: in combination, they support development of effective (combinatorial) design and implementation.
3. **Good news:** in many cases, use of appropriate **Electronic Design Automation (EDA)** tools can provide (semi-)automatic solutions.

Additional Reading

- ▶ *Wikipedia: Combinational logic*. URL: https://en.wikipedia.org/wiki/Combinational_logic.
- ▶ D. Page. “Chapter 2: Basics of digital logic”. In: *A Practical Introduction to Computer Architecture*. 1st ed. Springer, 2009.
- ▶ W. Stallings. “Chapter 11: Digital logic”. In: *Computer Organisation and Architecture*. 9th ed. Prentice Hall, 2013.
- ▶ A.S. Tanenbaum and T. Austin. “Section 3.2.2: Combinatorial circuits”. In: *Structured Computer Organisation*. 6th ed. Prentice Hall, 2012.

References

- [1] [Wikipedia: Combinational logic](https://en.wikipedia.org/wiki/Combinational_logic). URL: https://en.wikipedia.org/wiki/Combinational_logic (see p. 64).
- [2] D. Page. “Chapter 2: Basics of digital logic”. In: *A Practical Introduction to Computer Architecture*. 1st ed. Springer, 2009 (see p. 64).
- [3] W. Stallings. “Chapter 11: Digital logic”. In: *Computer Organisation and Architecture*. 9th ed. Prentice Hall, 2013 (see p. 64).
- [4] A.S. Tanenbaum and T. Austin. “Section 3.2.2: Combinatorial circuits”. In: *Structured Computer Organisation*. 6th ed. Prentice Hall, 2012 (see p. 64).