Testing Safety-critical Discrete-State Systems – Mathematical Foundations and Concrete Algorithms

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Background

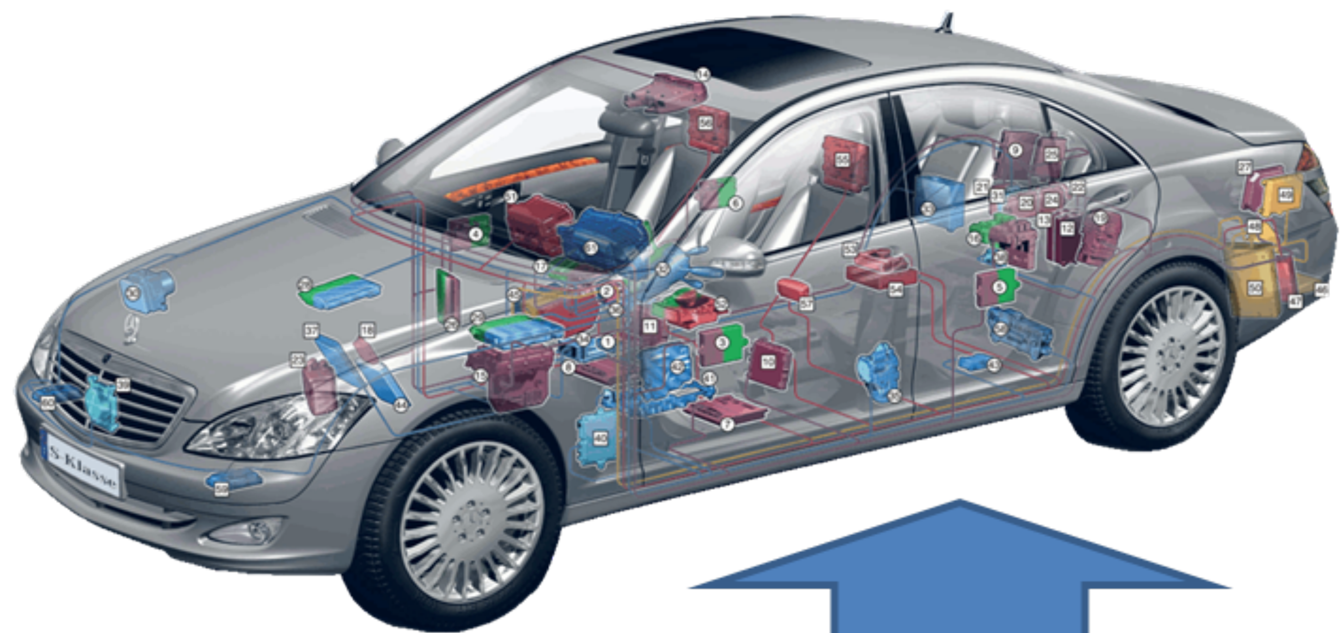
- **My research group at the University of Bremen**
  - Specialised on verification of safety-critical control systems
  - Focus on test automation
  - Collaboration with Prof. Dr. habil. Wen-ling Huang in this field

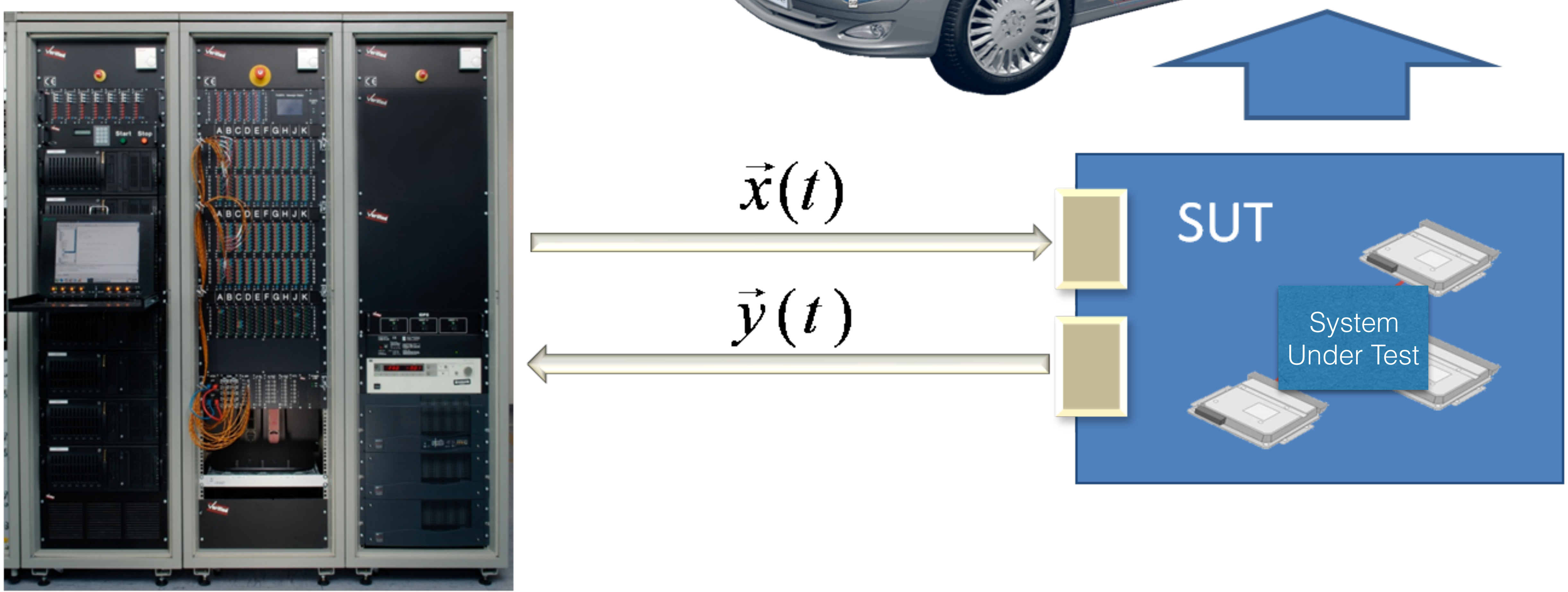
Background

- **Verified Systems International GmbH**
  - Founded 1998 as a spinoff company from the University of Bremen
  - Specialised on verification and validation of safety-critical systems – aerospace, railways, automotive
  - Tool development, hardware-in-the-loop test bench development, and service provision
  - Main customers Airbus, Siemens
  - 25 employees

Hardware-in-the-Loop Test Benches

For testing integrated HW/SW systems





An Observation . . .

- Many maths and computer science students in their first semesters seem to think that complex theory and difficult algorithms are only needed to pass exams . . .

- This is not true!

- Many of the most important innovations and products are based on highly complex mathematical foundations and on sophisticated software algorithms

Safety-critical systems – Examples

Safety-critical Systems

A **. . . safety-critical system** is a system whose failure or malfunction may result in one (or more) of the following outcomes:

- death or serious injury to people
- loss or severe damage to equipment/property
- environmental harm

Definition taken from https://en.wikipedia.org/wiki/Life-critical_system

Safety-critical Systems – Examples

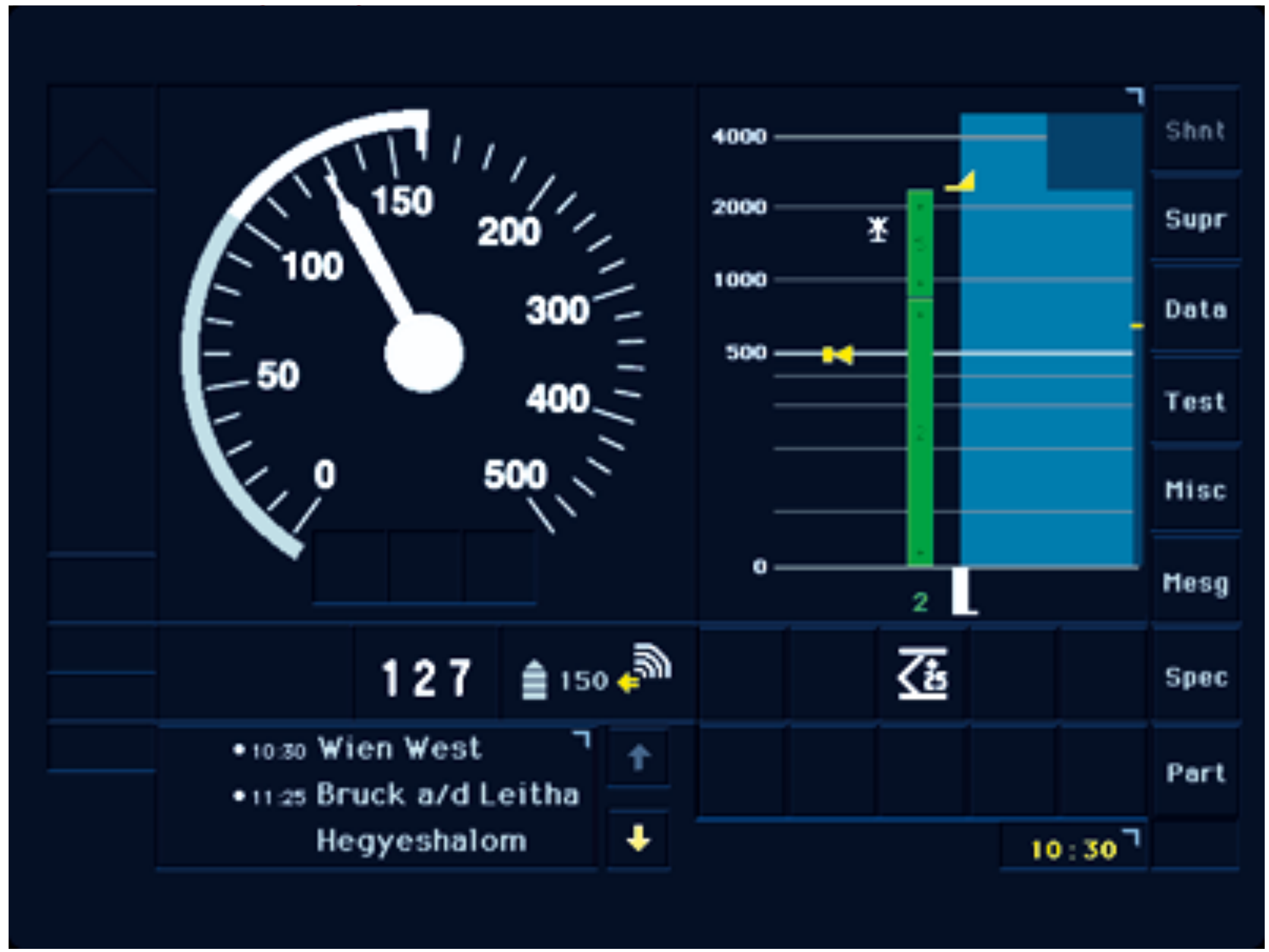
Airbag controller

Safety-critical Systems – Examples

Aircraft thrust reversal

Safety-critical Systems – Examples

Train speed supervision



Verification Requirements of International Standards

Verification Requirements of International Standards

- Safety-critical systems development and verification is controlled by laws
- These laws state that development and verification must follow the rules specified in applicable standards, such as
  - Avionic domain: **RTCA DO-178C**
  - Railway domain: **CENELEC EN50128:2011**
  - Automotive domain: **ISO 26262**

Verification Requirements of International Standards

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- These ... verification must ... able standards, such ...

Avionic System. A control computer in an aircraft

  - Avionic domain: **RTCA DO-178C**
  - Railway domain: **CENELEC EN50128:2011**
  - Automotive domain: **ISO 26262**

Verification Requirements of International Standards

- These standards differ in many details, but they contain some basic requirements
  - Development must be based on **requirements**
  - Every piece of software code and every hardware component must be **traced** back to at least one requirement

- For the most critical applications, requirements should be expressed by **formal models** with mathematical interpretation
    - **Syntax and static model semantics**: is the model well-formed?
    - **Behavioural model semantics**: how does the model state, including inputs and outputs, change over time?
- **Requirements (models) must be verified**

- **Code must be verified**
  - Does it implement the related requirements correctly?
  - Verification is preferably performed by **testing** the software integrated in the controller’s hardware
- Verification results need to be checked with respect to completeness and correctness
- Tools automating development or verification steps need to be **qualified**

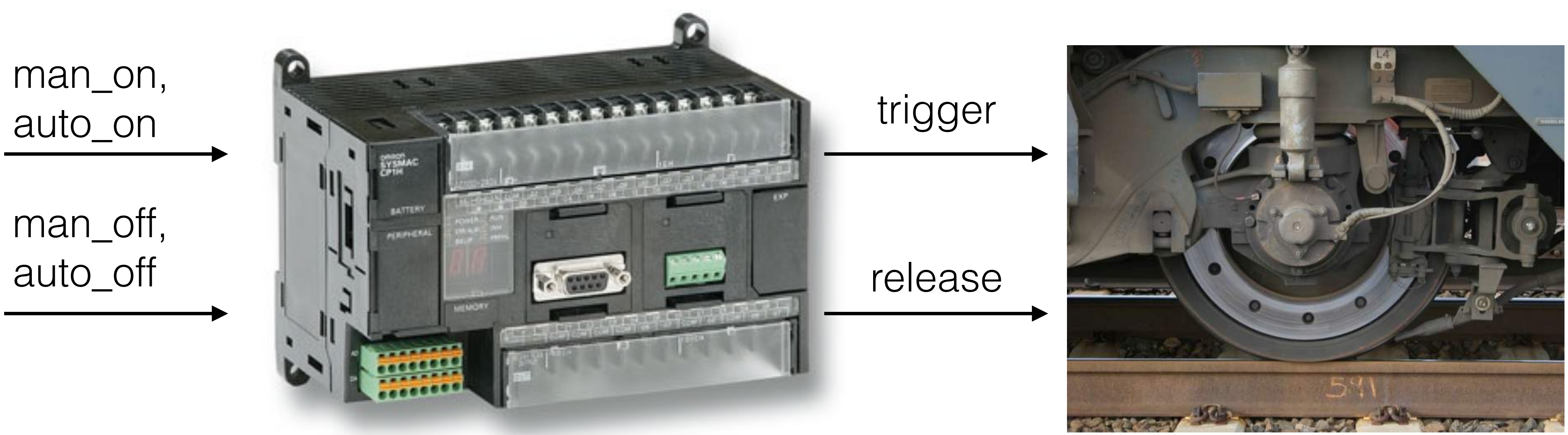
Motivation

- **Safety-critical systems can be developed by starting with a model of the required system behaviour**
- **The developed system can then be tested against the model**
  - **Input data to be exercised on the system under test (SUT) can be derived from the model**
  - **The behaviour of the SUT can be compared to the expected behaviour specified in the model**
  - **https://zh.wikipedia.org/wiki/生命攸關系統#.E9.81.8B.E8.BC.B8**

Motivation

- **Testing theories**
  - **Define methods to generate test cases from models**
    - **Test case. Sequence of input data + expected outputs to produced by the SUT when receiving these inputs**
  - **Specify which correctness properties are fulfilled if all test cases are passed by the SUT**
- **For safety-critical systems, the test strength (= the capability to uncover certain types of errors) of a testing theory must be proven**

- **Example: Model of a brake controller in a train**
  - **Controller receives commands to activate brakes**
    - **From train engine driver: *man_on*, *man_off***
    - **From a speed supervision computer: *auto_on*, *auto_off***
  - **Controller activates brakes by outputs *trigger* and *release***



- **Requirements for the brake controller**

  1. **When brakes are not activated, they can be triggered manually (*man_on*) or by the speed supervision computer (*auto_on*)**

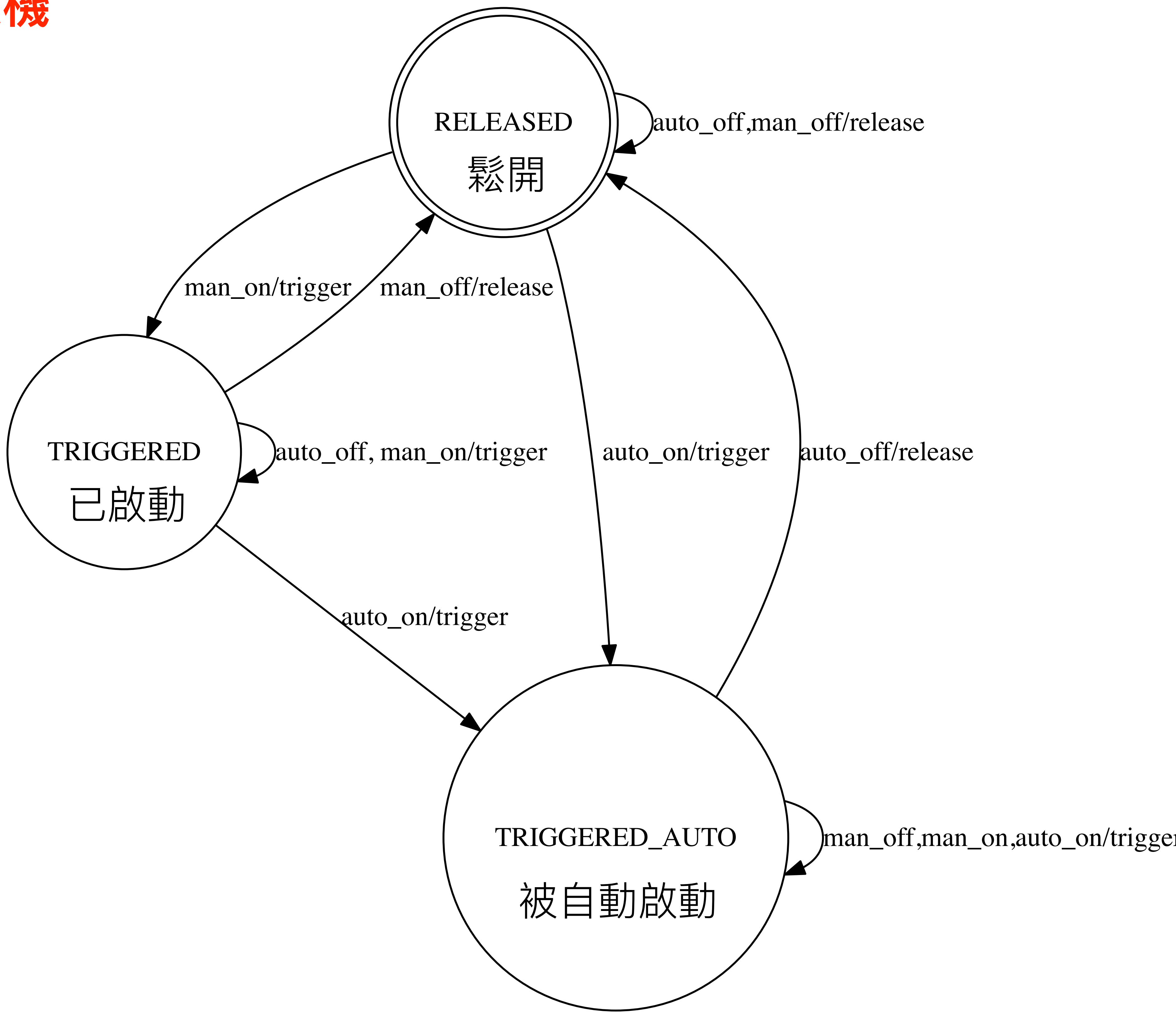
  2. **When brakes have been activated manually (*man_on*), they can only be released manually (*man_off*)**

  3. **When brakes have been activated via speed supervision computer (*auto_on*), they can be only released via command *auto_off* from the computer**

  4. **When the supervision computer sends *auto_on* while already braking, the brakes can only be released by *auto_off***

Finite State Machine modelling the behaviour of the brake controller

有限狀態機



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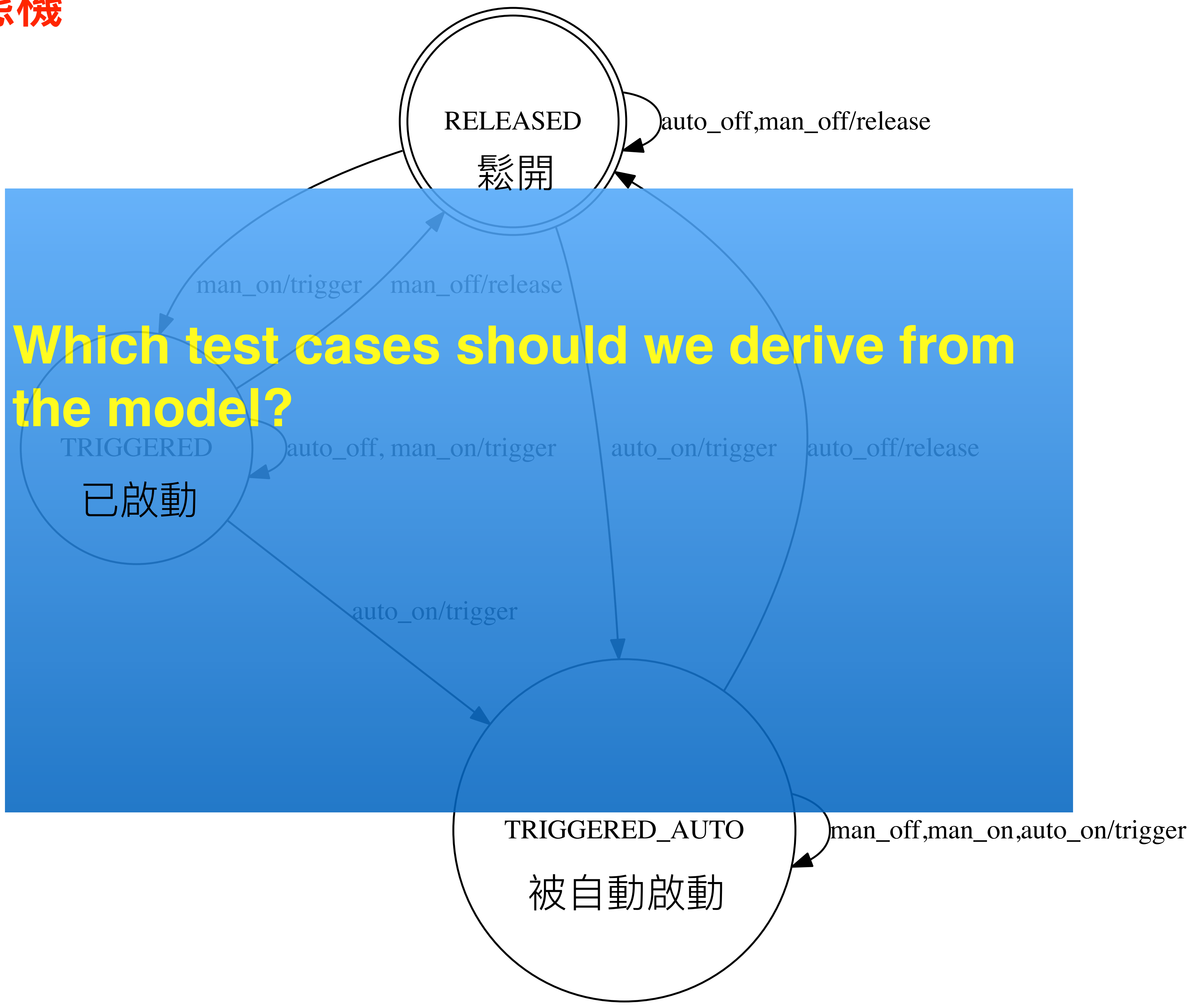

Which test cases should we derive from the model?

Finite State Machine modelling the behaviour of the brake controller

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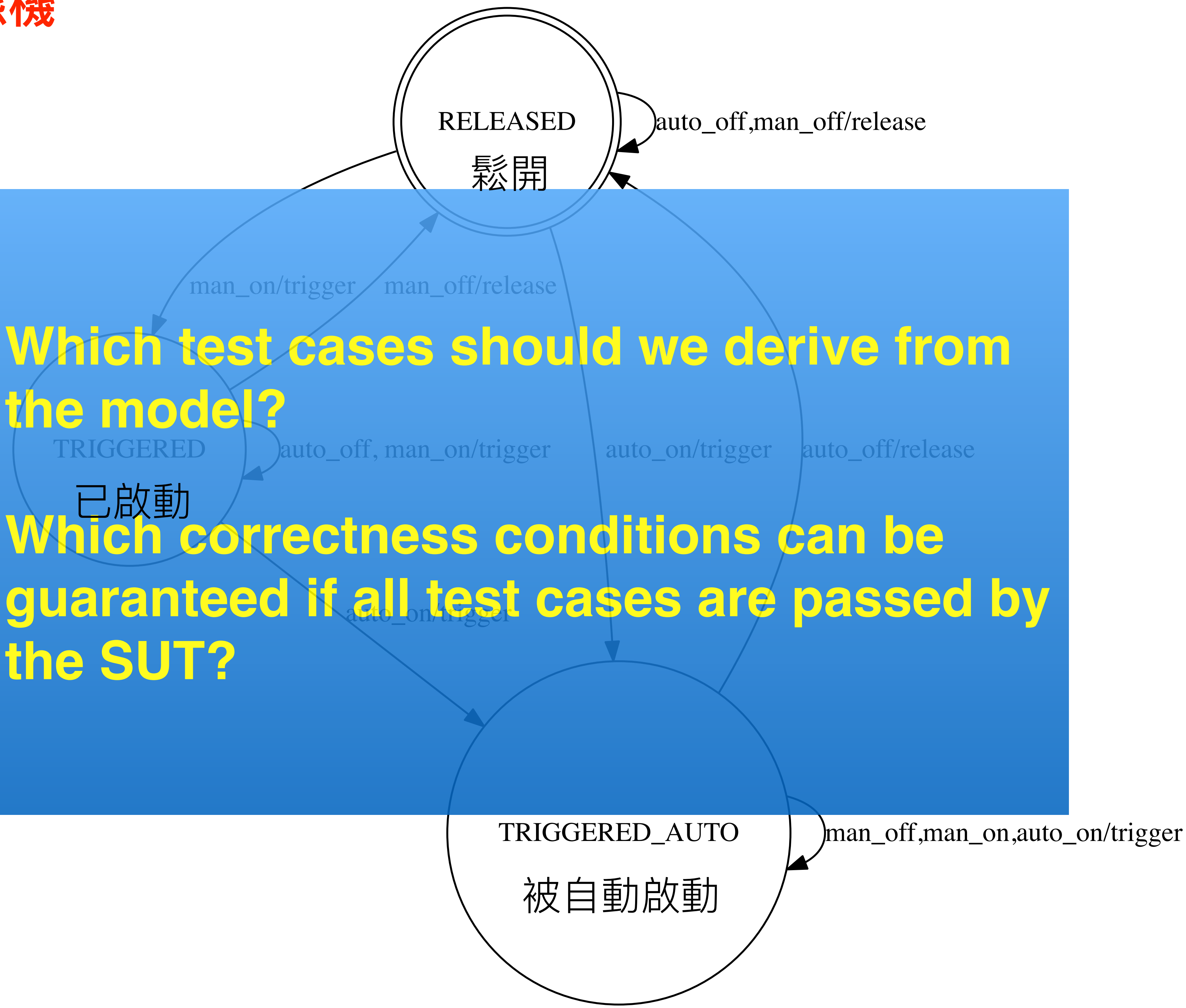

Which test cases should we derive from the model?

Which correctness conditions can be guaranteed if all test cases are passed by the SUT?

Overview

- **Mathematical definition of Finite State Machines**
- **Languages and Conformance Relations**
- **FSM properties: observability and minimality**
- **Fault Models**
- **Testing Theories**
  - **The W-Method for deterministic FSMs**
  - **The Wp-Method for nondeterministic FSMs**

Finite State Machines

$M = (Q, q_0, I, O, h)$

- $Q \neq \emptyset$: finite set of states 狀態集
- $q_0 \in Q$: initial state 初始狀態
- $I \neq \emptyset$: finite set of input alphabet 輸入字母表
- $O \neq \emptyset$: finite set of output alphabet 輸出字母表
- $h \subseteq Q \times I \times O \times Q$: transition relation 狀態遷移關係

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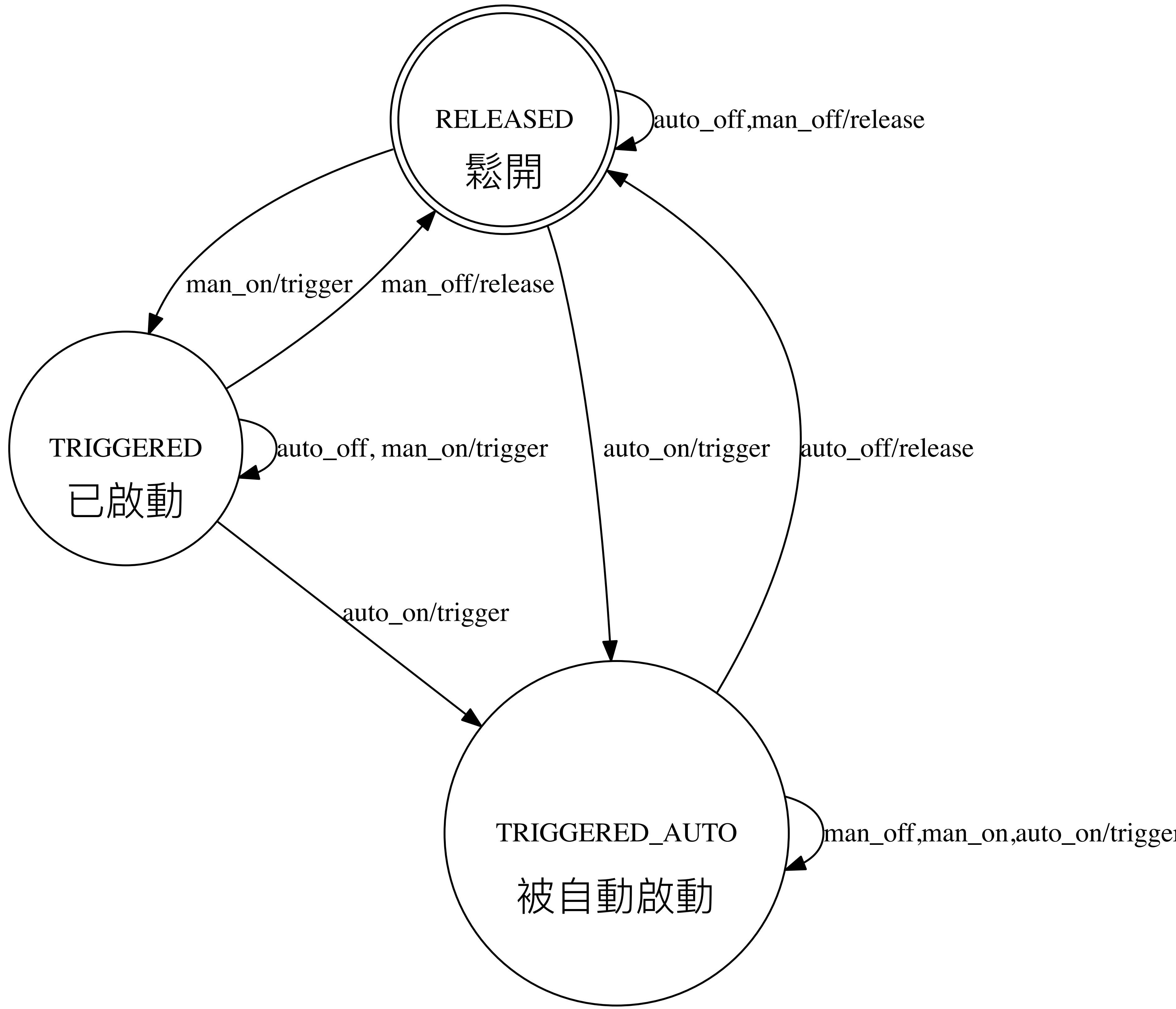

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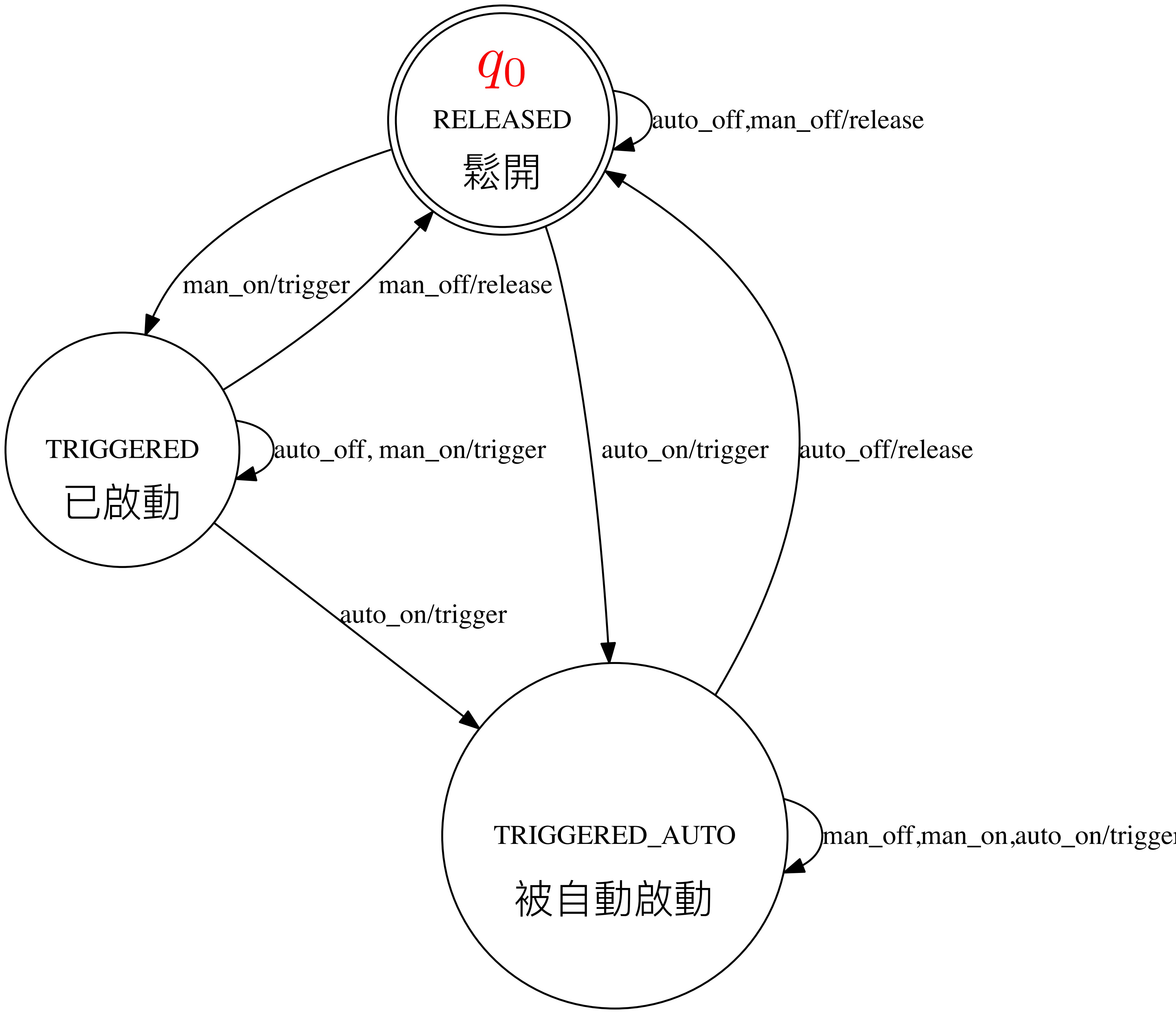

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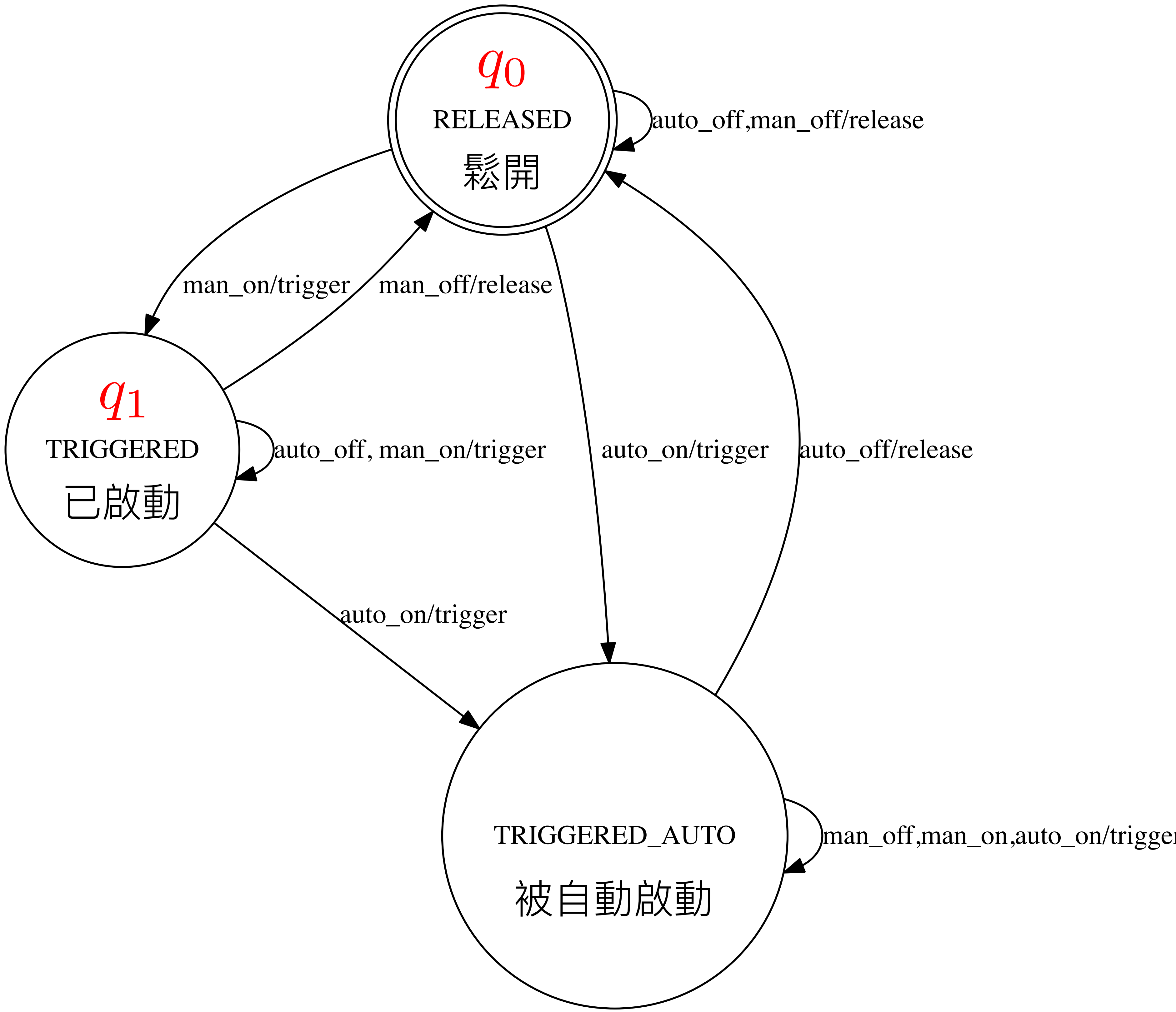

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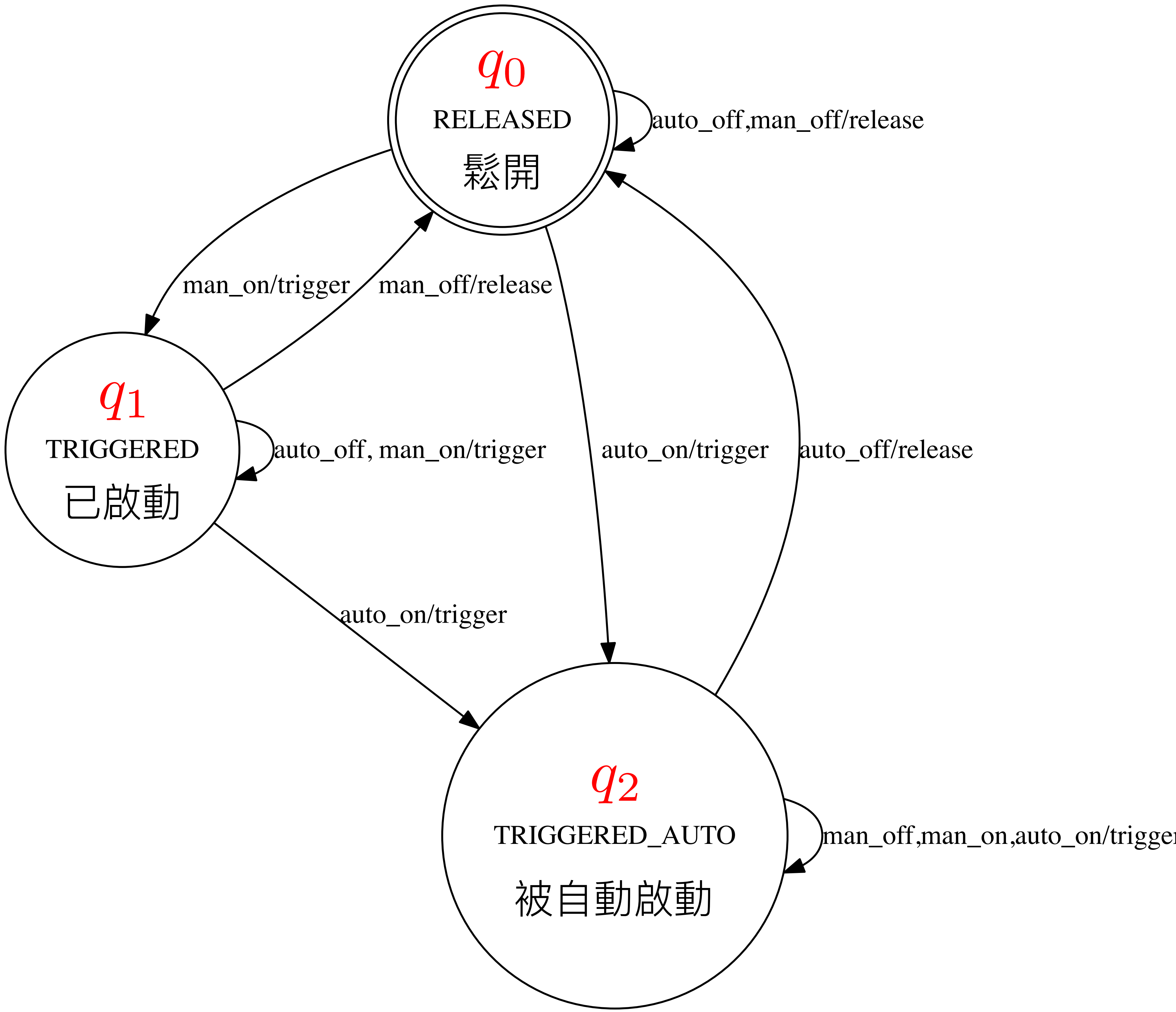
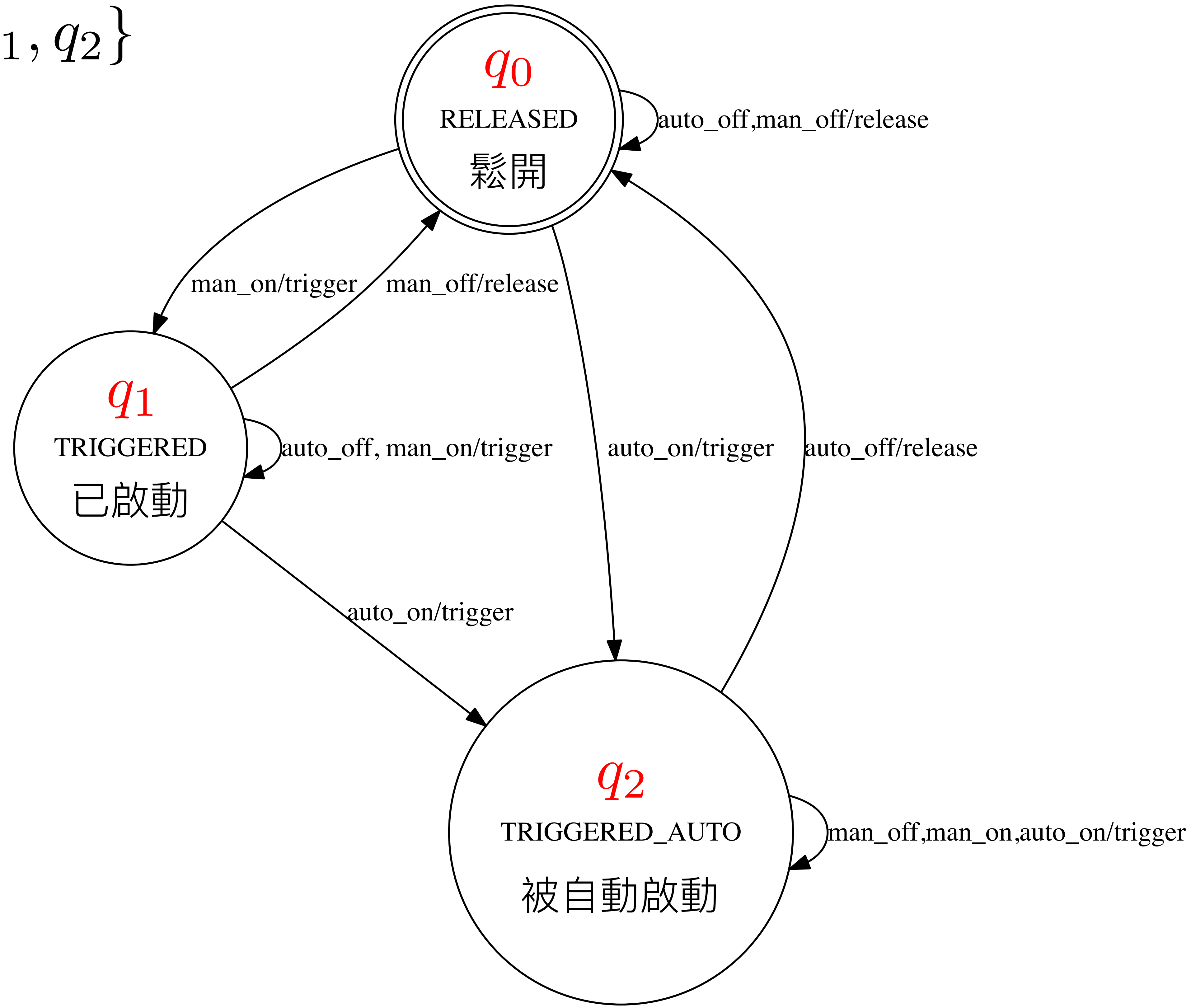


Finite State Machine modelling the behaviour of the brake controller

$$Q = \{q_0, q_1, q_2\}$$



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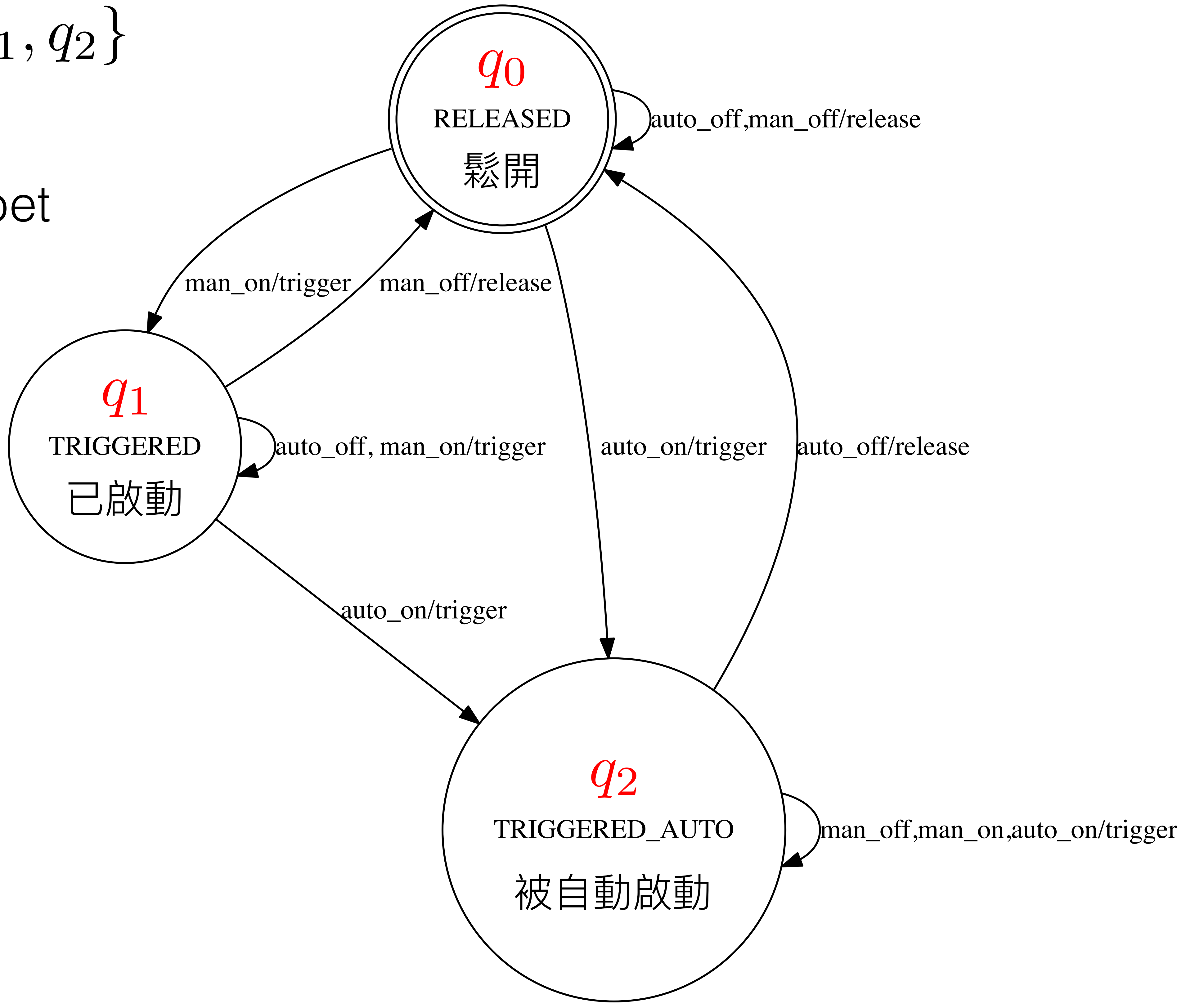
Input Alphabet



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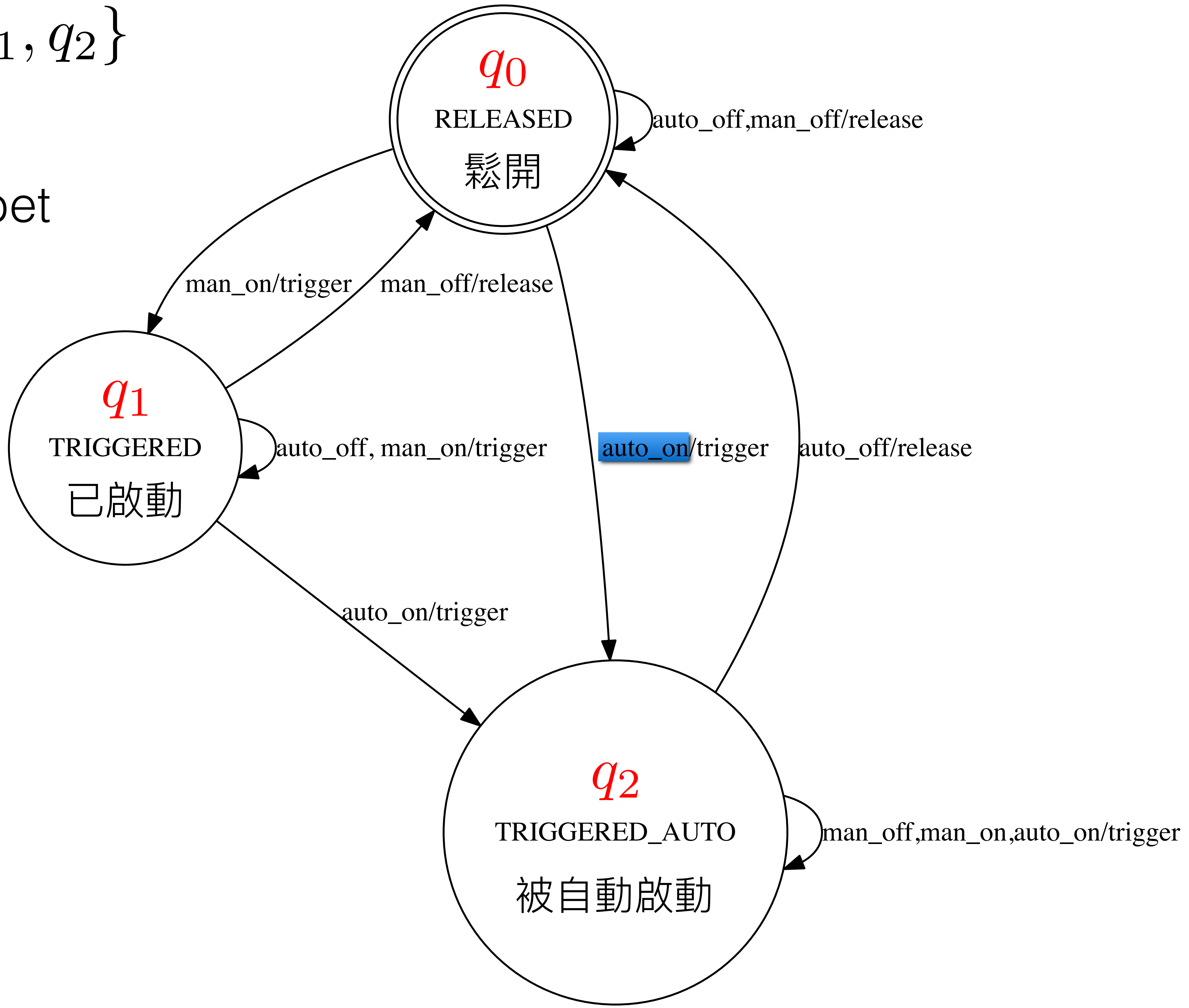

Finite State Machine modelling the behaviour of the brake controller

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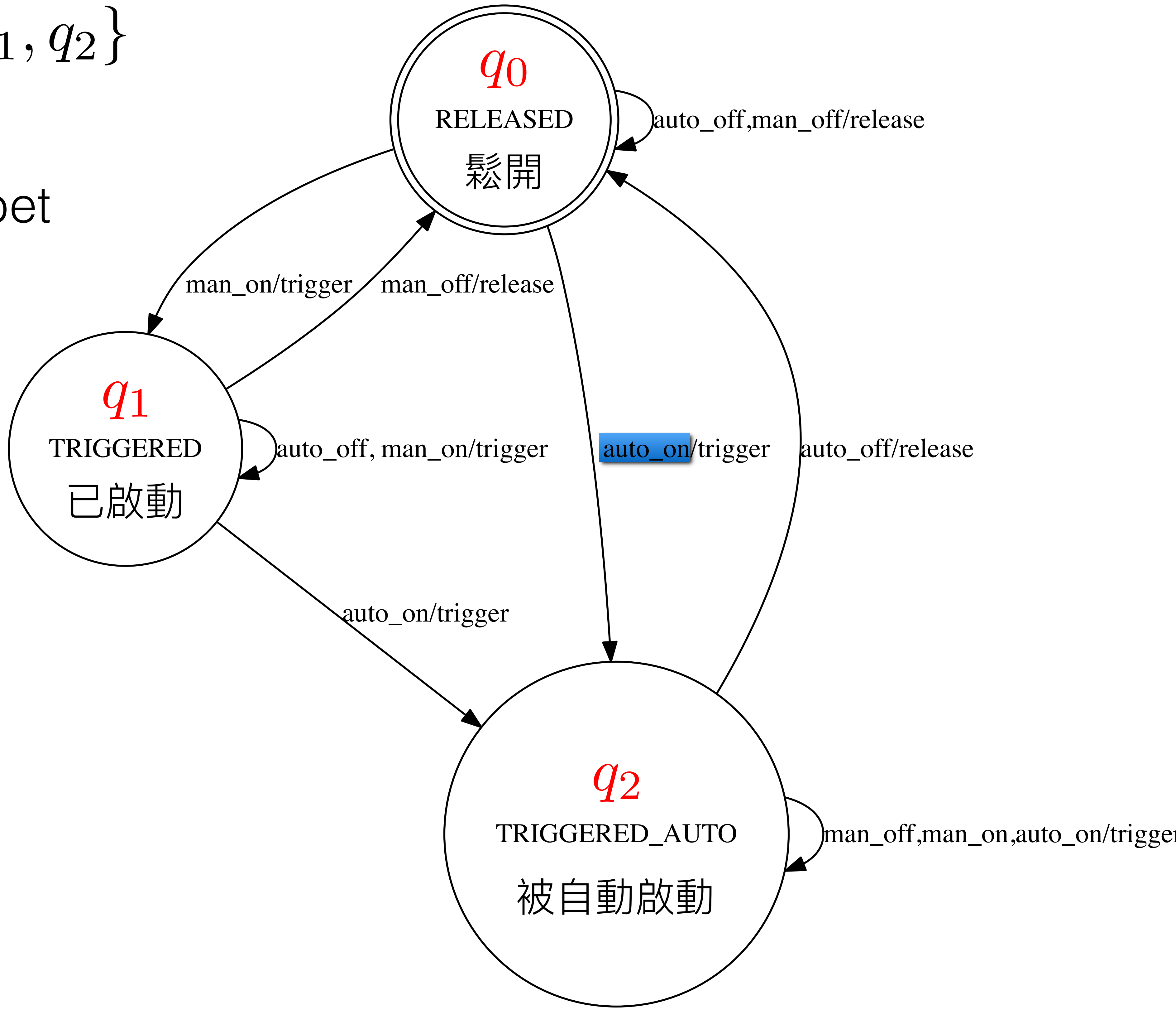
Input Alphabet

man_on,
auto_on



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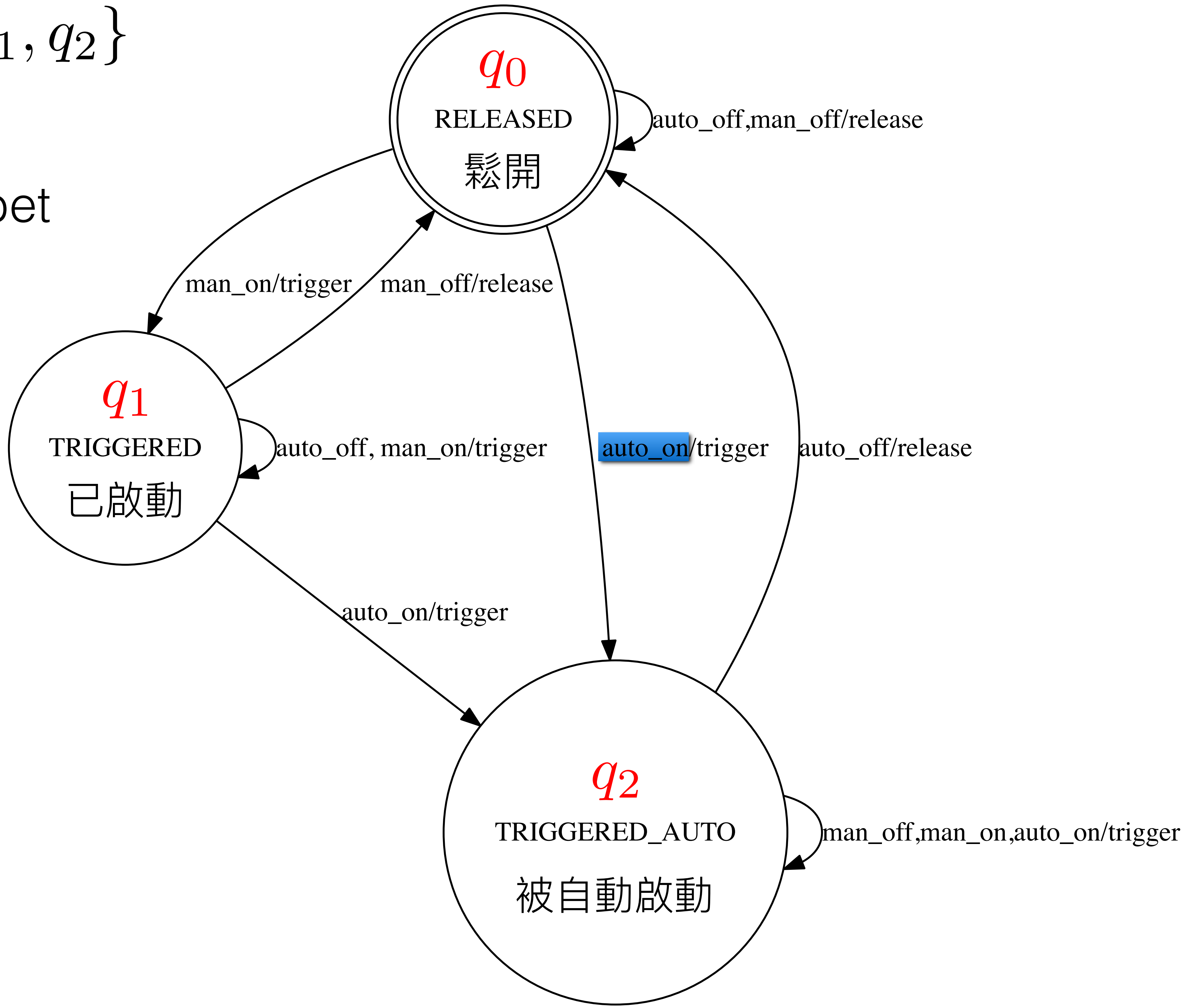
man_on,
auto_on
man_off,
auto_off



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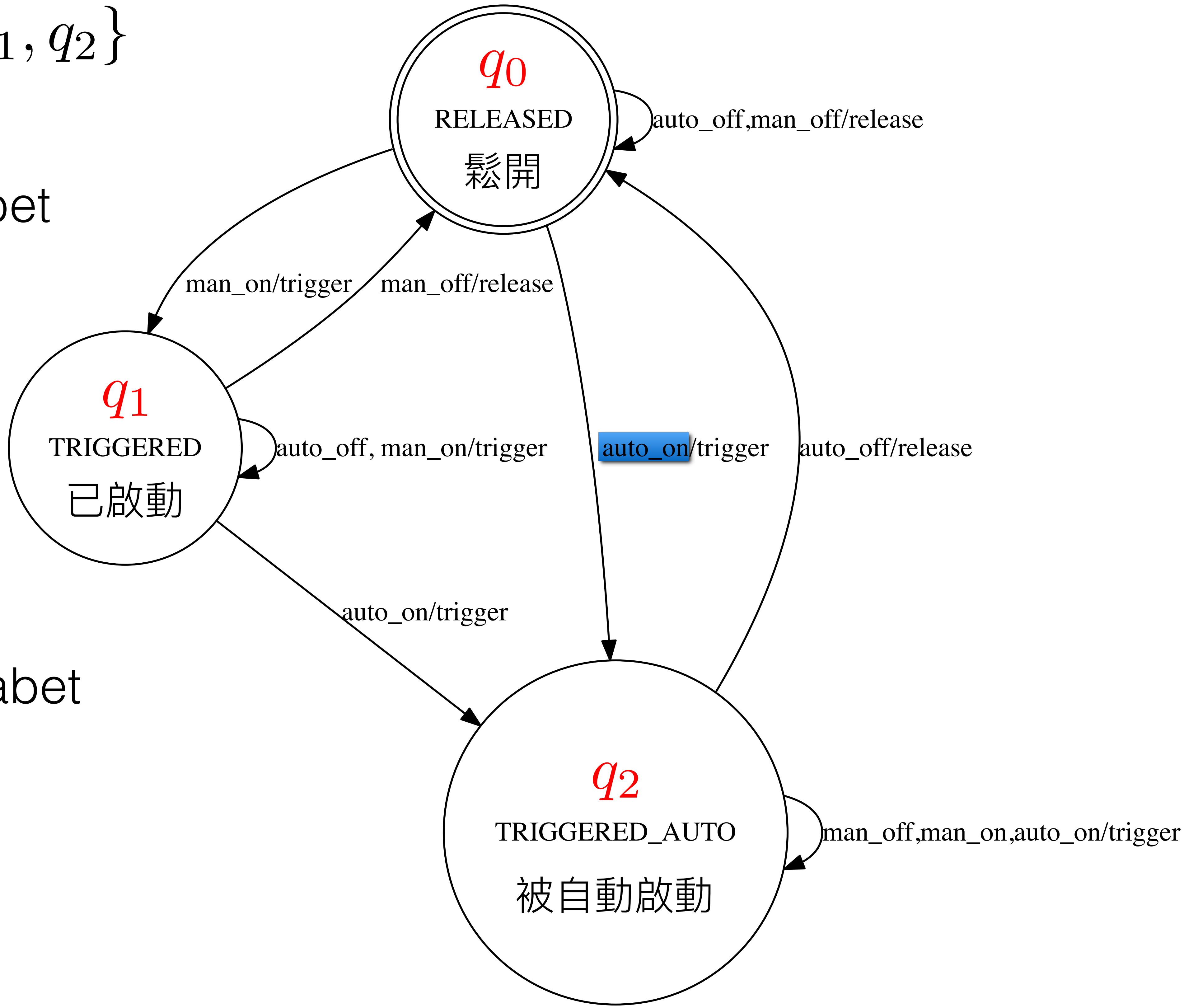

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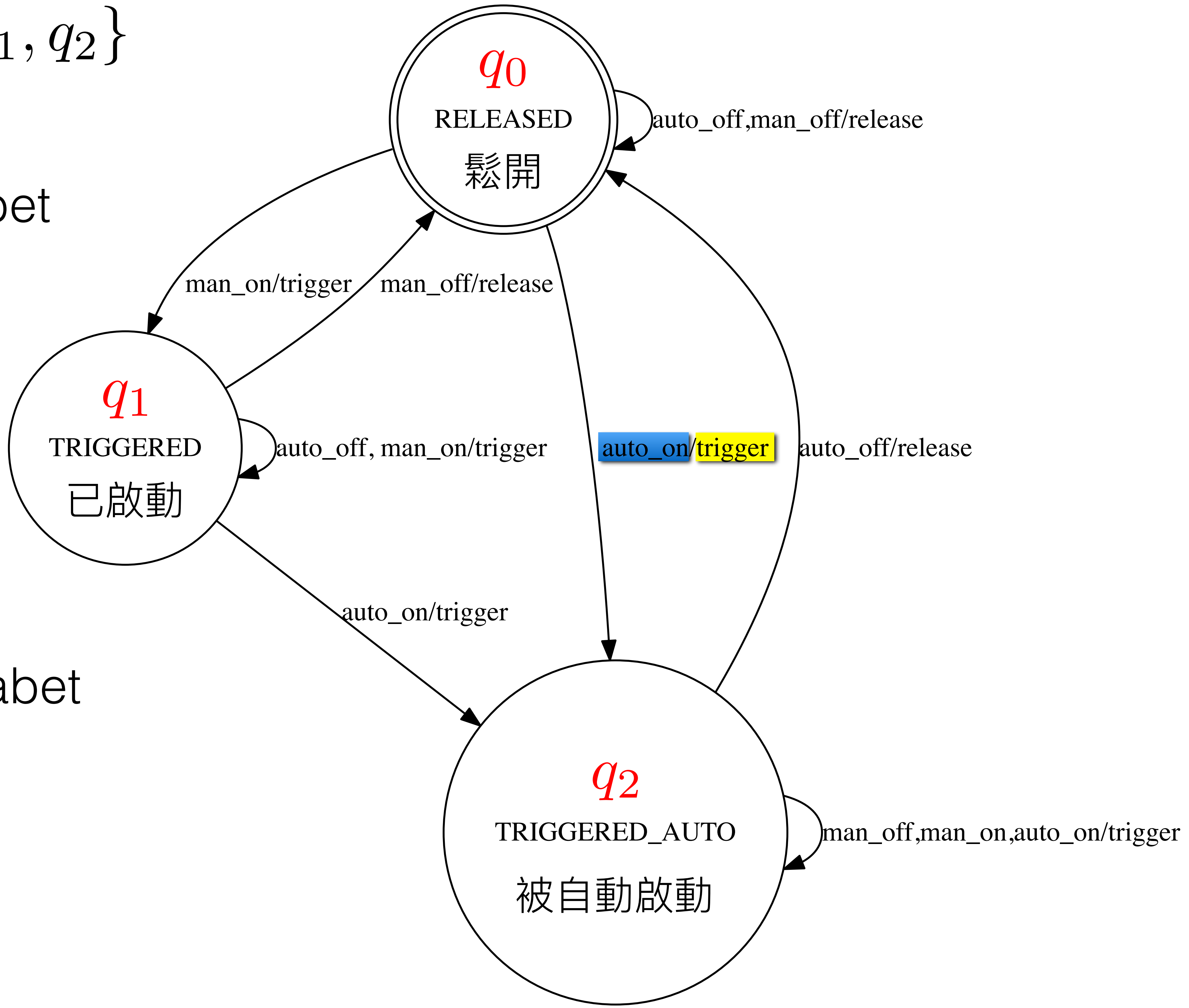


Finite State Machine modelling the behaviour of the brake controller

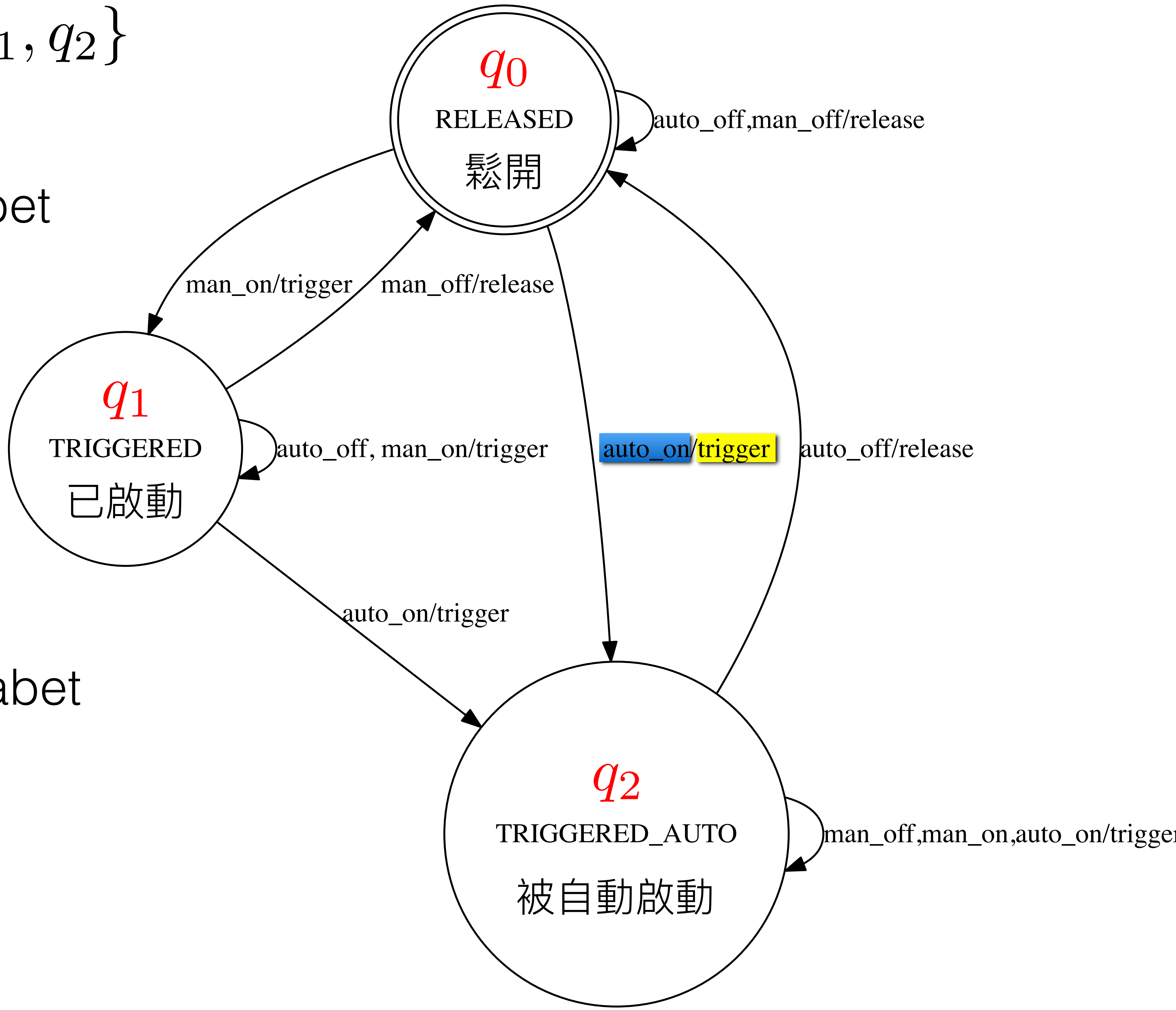
$$Q = \{q_0, q_1, q_2\}$$

Input Alphabet

man_on,
auto_on
man_off,
auto_off

Output Alphabet

trigger



Finite State Machine modelling the behaviour of the brake controller

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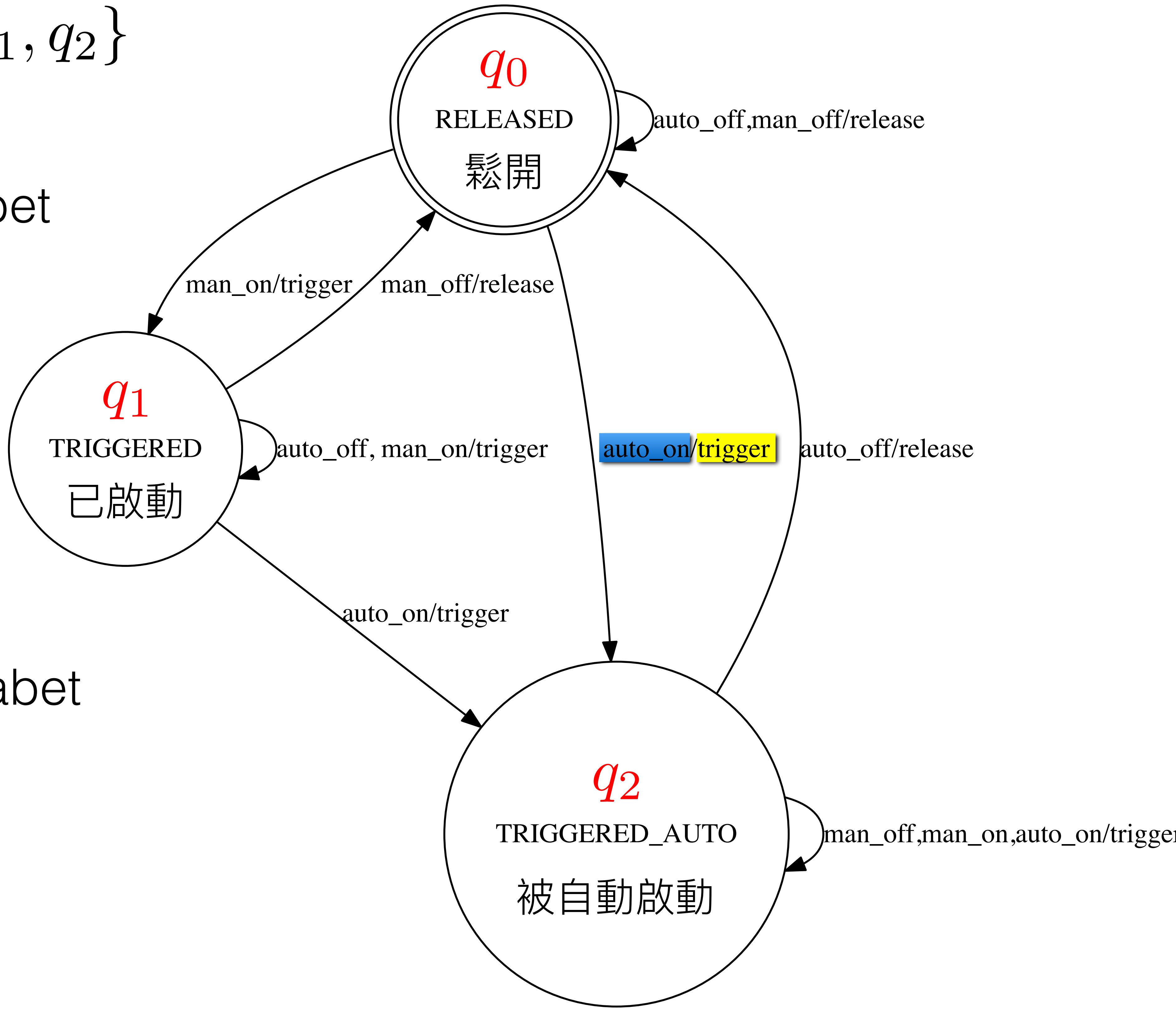
Input Alphabet

man_on,
auto_on
man_off,
auto_off

Output Alphabet

trigger

release



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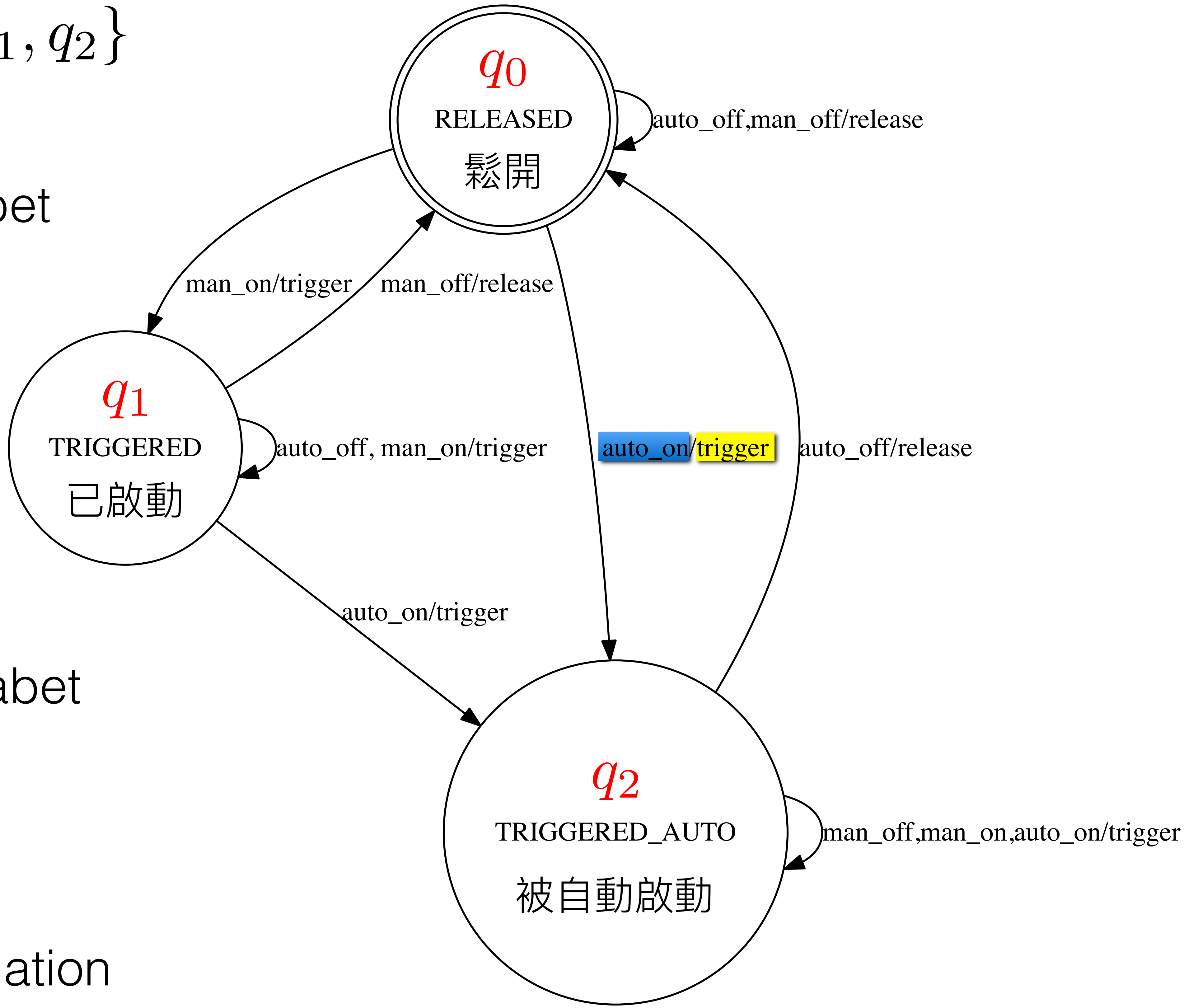

Input Alphabet

man_on,
auto_on
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Output Alphabet

trigger

release

Transition Relation

Finite State Machine modelling the behaviour of the brake controller

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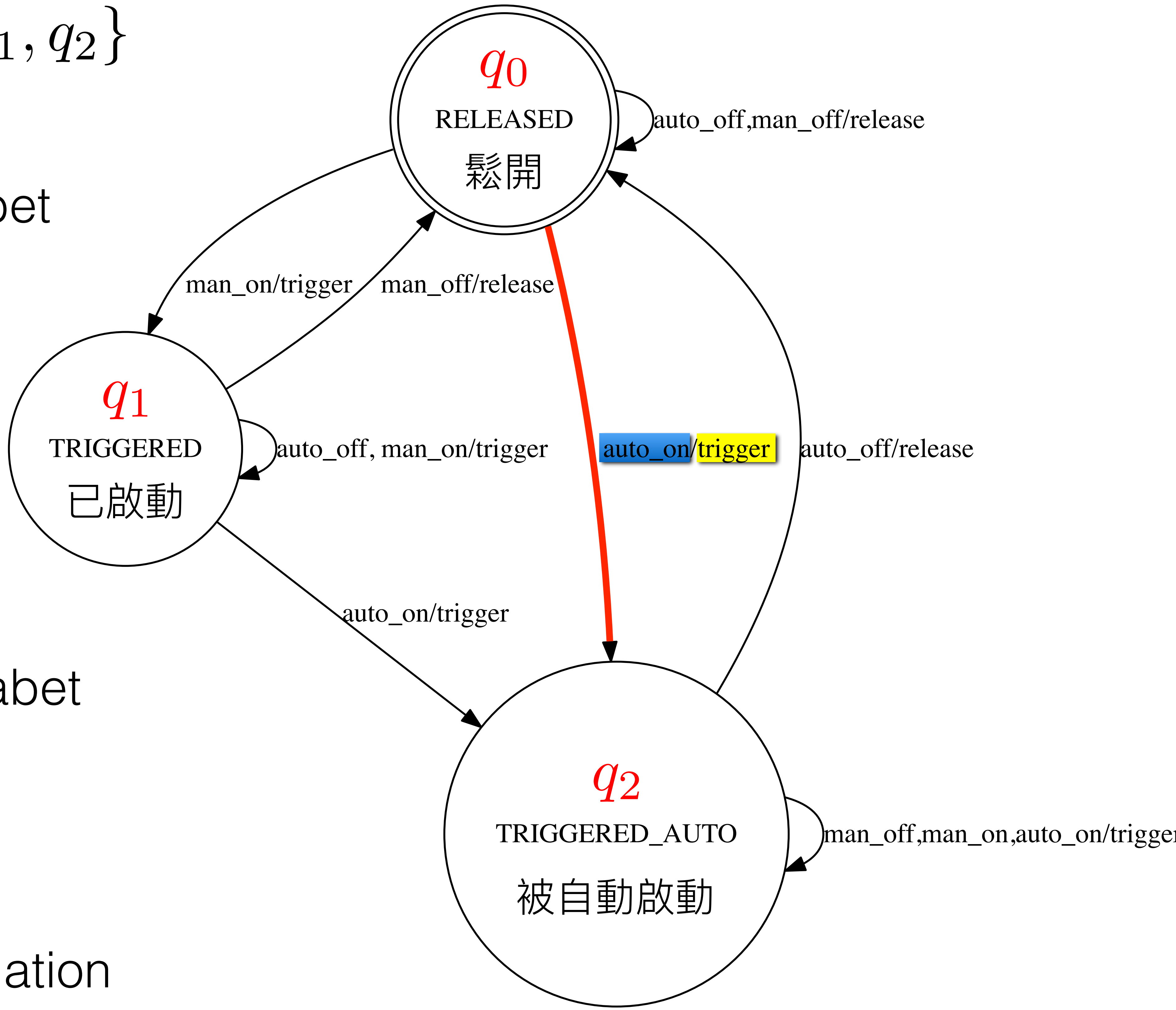

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Transition Relation

Finite State Machine modelling the behaviour of the brake controller

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Input Alphabet

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auto_on
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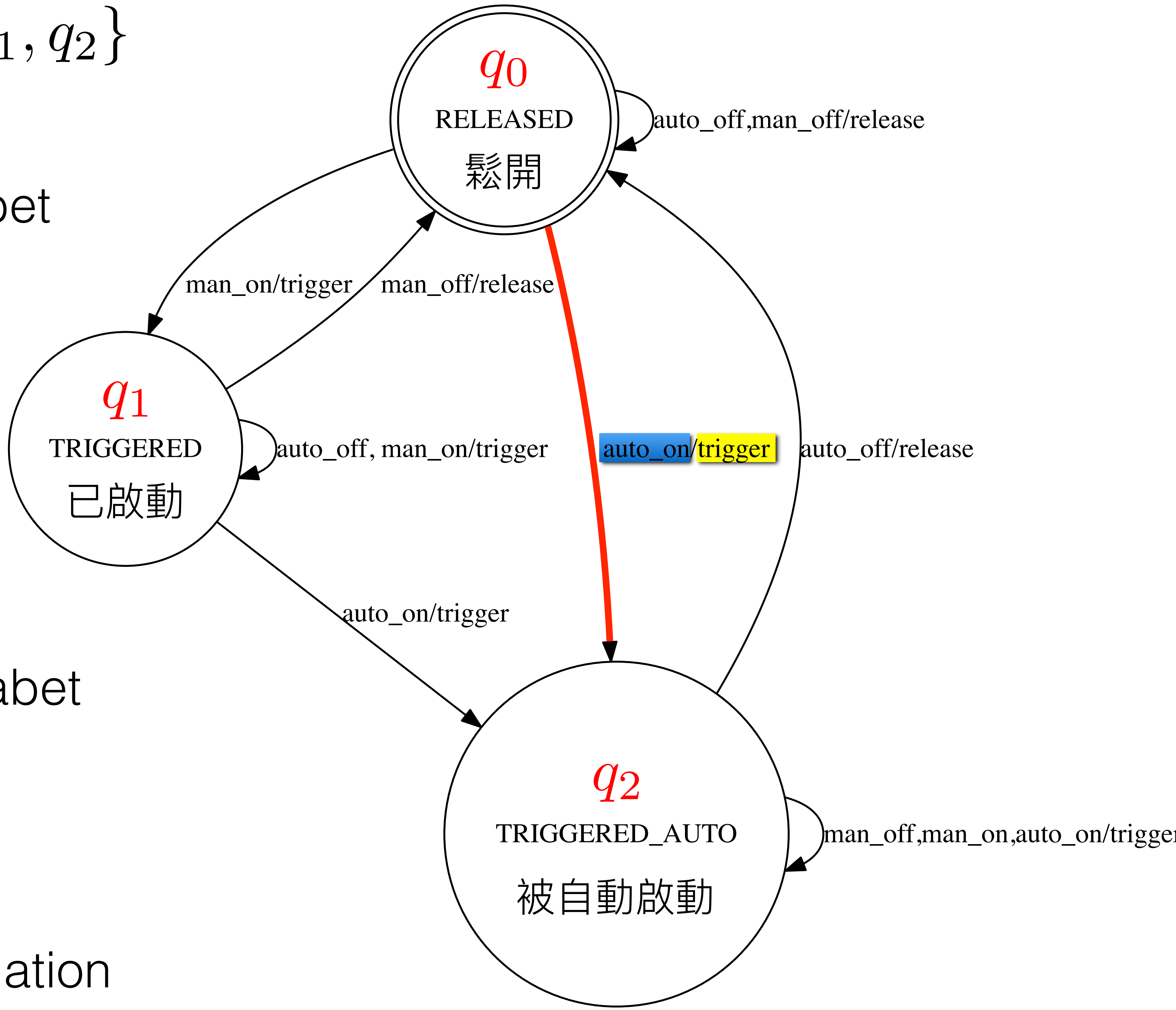
Output Alphabet

trigger

release

Transition Relation

$$(q_0, \text{auto\_on}, \text{trigger}, q_2), \ldots$$



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man_on,
auto_on
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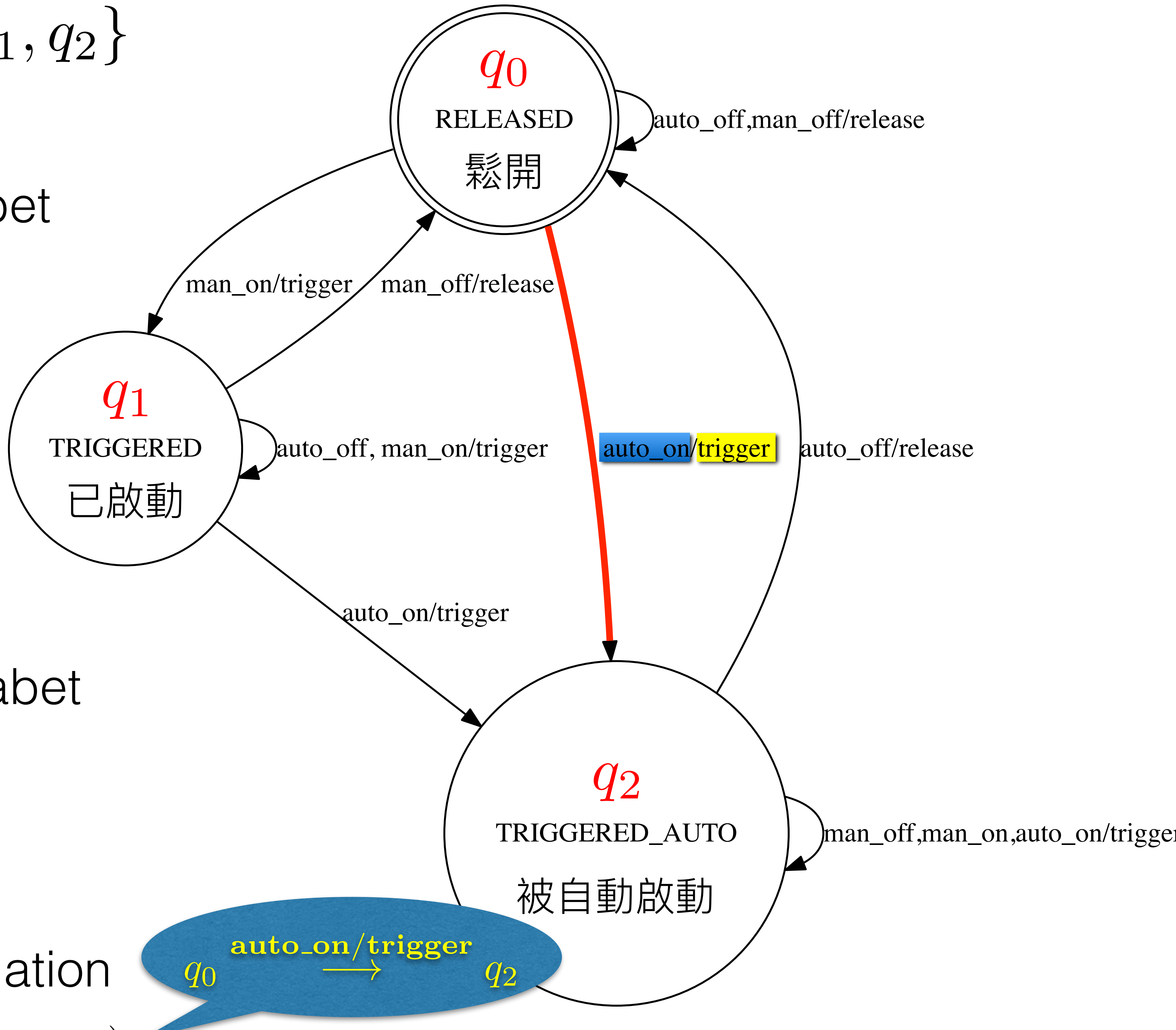

Output Alphabet

trigger

release

Transition Relation

$(q_0, \text{auto\_on}, \text{trigger}, q_2), \ldots$

Language

- $\Sigma := I \times O$ **alphabet** 字母表
- $\Sigma^* := \bigcup_{k \in \mathbf{N}_0} \{\sigma_1 \ldots \sigma_k \mid \sigma_i \in \Sigma, \forall i = 1, \ldots, k\}$ 有限字符序列集
- $\mathcal{L} \subseteq \Sigma^*$ **language over Σ** $:\Leftrightarrow$
  - $\varepsilon \in \mathcal{L}$ 空序列
  - $\mathcal{L}$ is prefix-closed 前置序列

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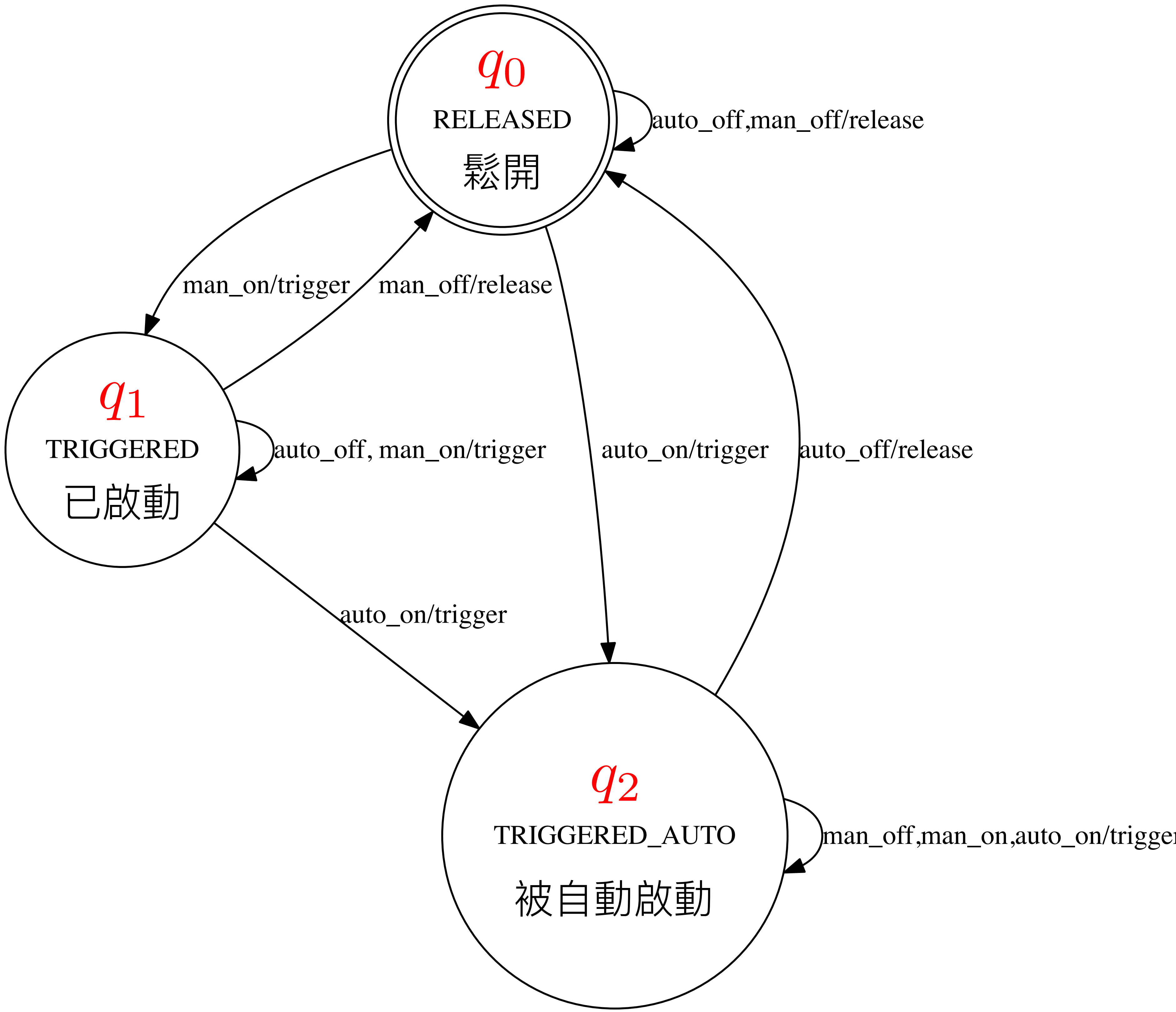
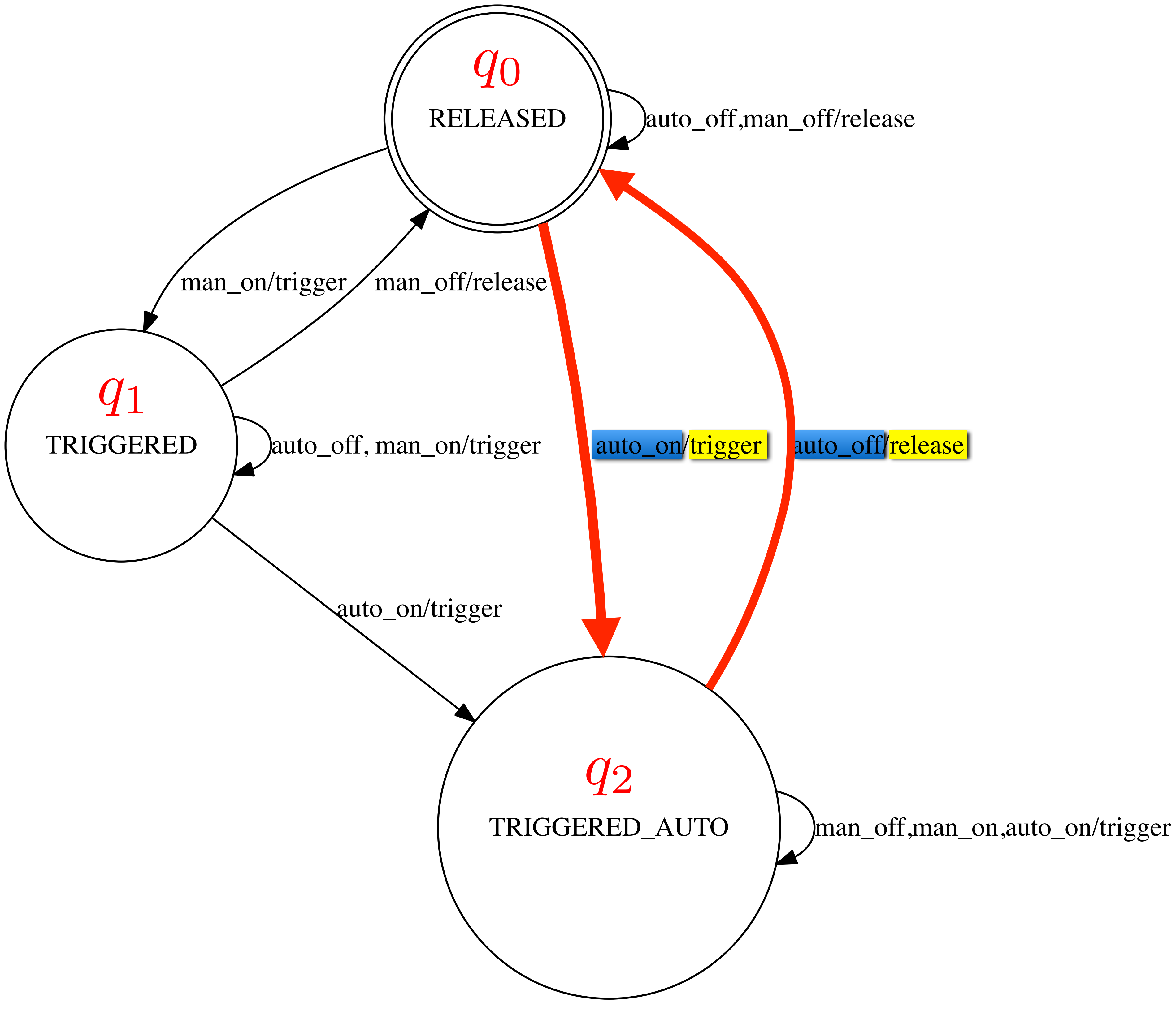
$$\forall \pi = \sigma_1 \ldots \sigma_k \in \mathcal{L} : \sigma_1 \ldots \sigma_i \in \mathcal{L}, \forall i \leq k$$

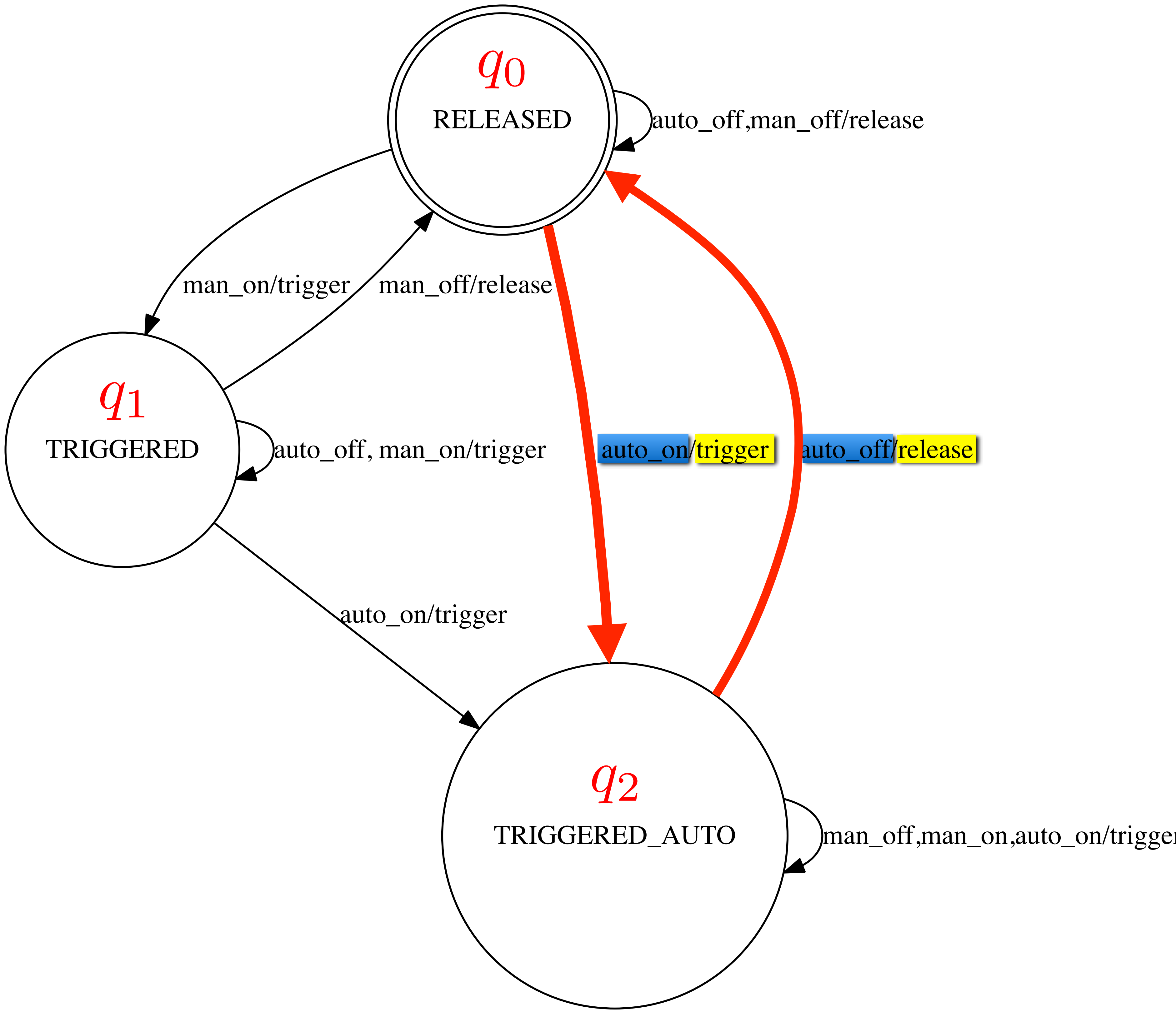
Finite State Machine modelling the behaviour of the brake controller



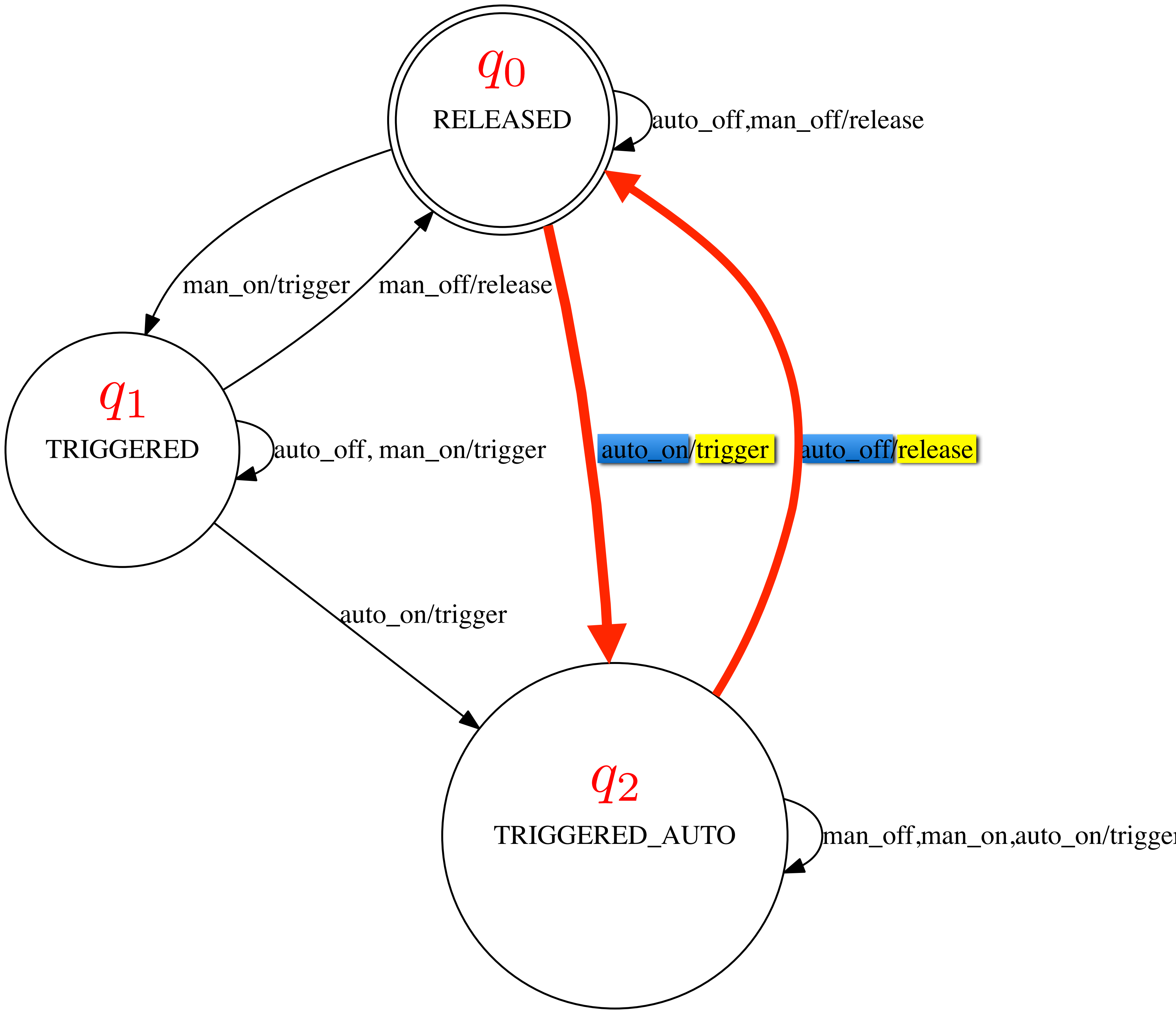


q_0
RELEASED
auto_off,man_off/release
man_on/trigger
man_off/release
q_1
TRIGGERED
auto_off, man_on/trigger
auto_on/trigger
auto_off/release
auto_on/trigger
q_2
TRIGGERED_AUTO
man_off,man_on,auto_on/trigger

$q_0 \xrightarrow{\textbf{auto\_on}/\text{trigger}} q_2 \xrightarrow{\textbf{auto\_off}/\text{release}} q_0$



$$q_0 \xrightarrow{\textbf{auto\_on}/\text{trigger}} q_2 \xrightarrow{\textbf{auto\_off}/\text{release}} q_0 \qquad (\textbf{auto\_on}, \textbf{trigger}).(\textbf{auto\_off}, \textbf{release}) \in L(q_0)$$



Language of FSM

$M = (Q, q_0, I, O, h)$

- $L(q) := \{\pi \in \Sigma^* \mid \exists q' \in Q, q \xrightarrow{\pi} q'\}$ **language of q**
- $q \sim q' :\Leftrightarrow L(q) = L(q')$ q q' **are equivalent**
- $L(M) := L(q_0)$ **language of M**

Conformance Relations

$M = (Q, q_0, I, O, h)$, $M' = (Q', q_0', I, O, h')$ two FSM.

- M and M' are **I/O equivalent** : $L(M') = L(M)$
- M' is an **I/O reduction** of M : $L(M') \subseteq L(M)$

FSM Properties

$$M = (Q, q_0, I, O, h)$$

- M is **input-complete** : 輸入完備性

  $\forall q \in Q \wedge x \in I, \exists y \in O \wedge q' \in Q : q \xrightarrow{x/y} q'$

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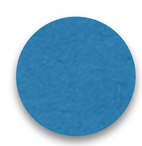

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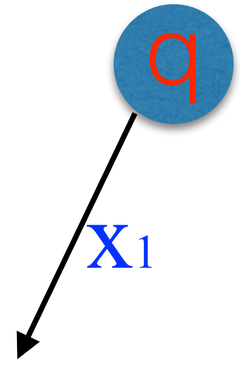

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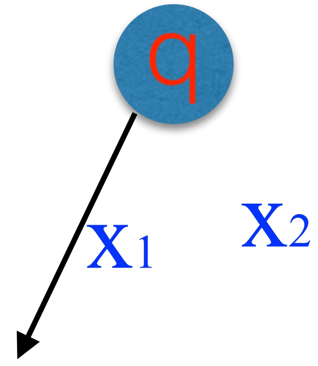

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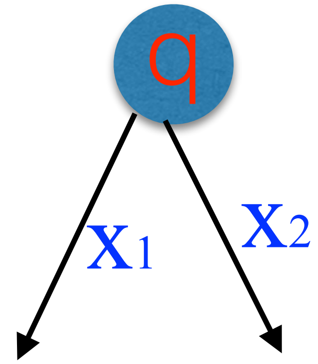

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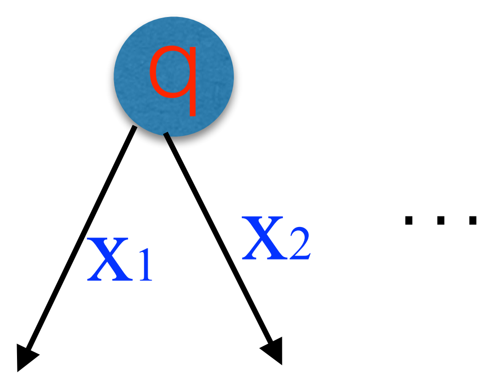

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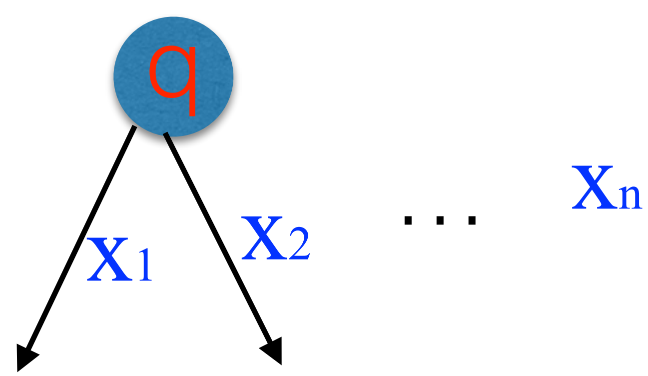

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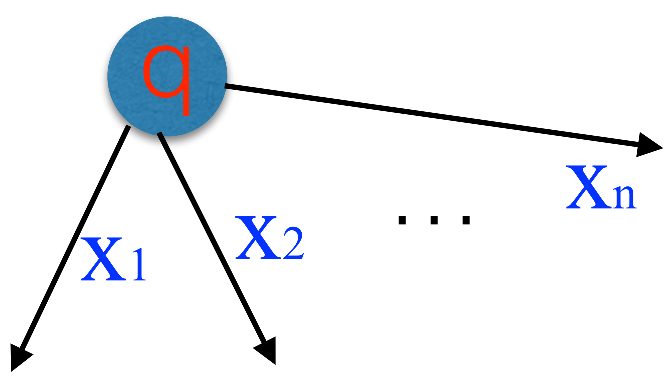

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- M is **input-complete** : 輸入完備性

  $$\forall q \in Q \wedge x \in I, \exists y \in O \wedge q' \in Q : q \xrightarrow{x/y} q'$$

- M is **deterministic** : 確定性

  $$\forall q \overset{x/y_1}{\to} q_1, q \overset{x/y_2}{\to} q_2 \in h \Rightarrow y_1 = y_2 \wedge q_1 = q_2$$

FSM Properties

$$M = (Q, q_0, I, O, h)$$

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  $\forall q \in Q \wedge x \in I, \exists y \in O \wedge q' \in Q : q \xrightarrow{x/y} q'$

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  $\forall q \overset{x/y_1}{\rightarrow} q_1, q \overset{x/y_2}{\rightarrow} q_2 \in h \Rightarrow y_1 = y_2 \wedge q_1 = q_2$

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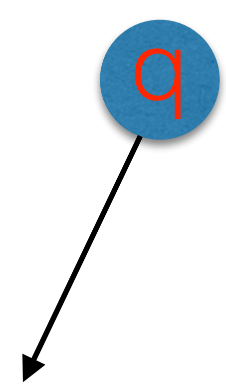

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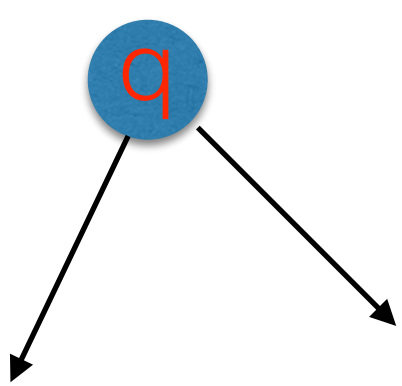

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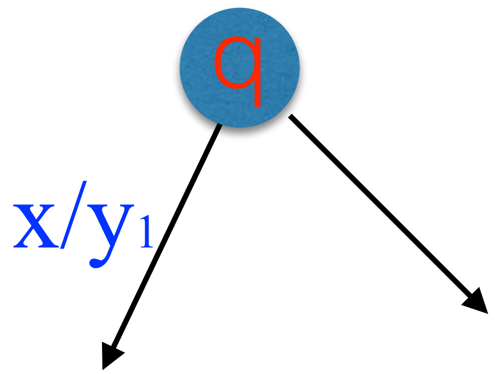

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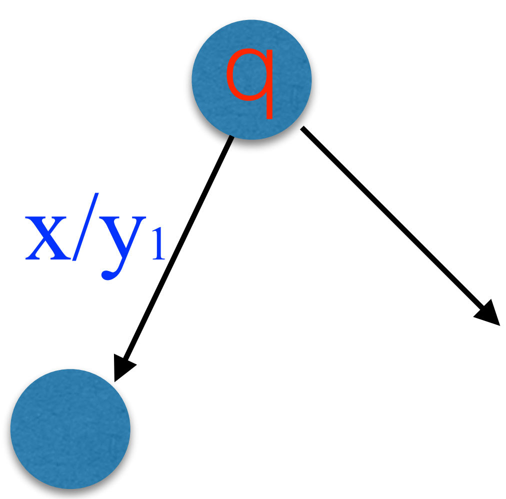

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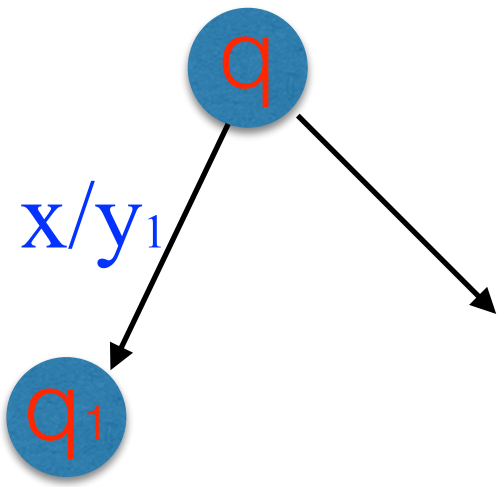

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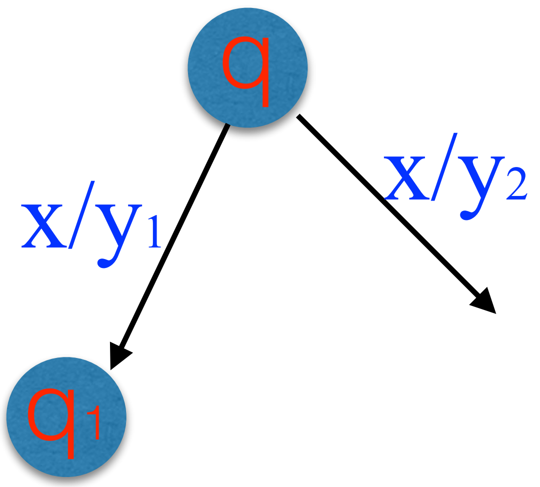

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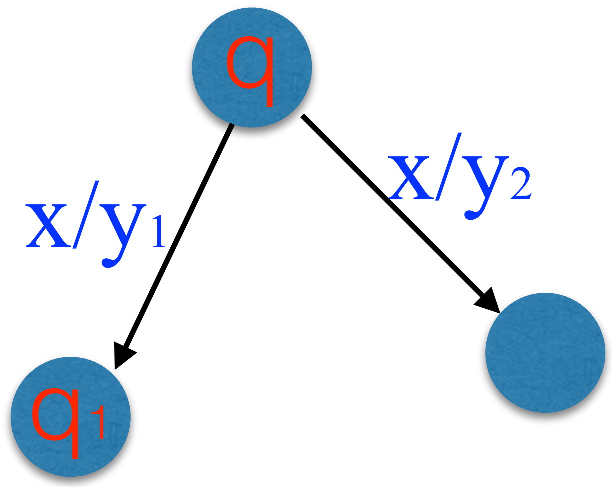

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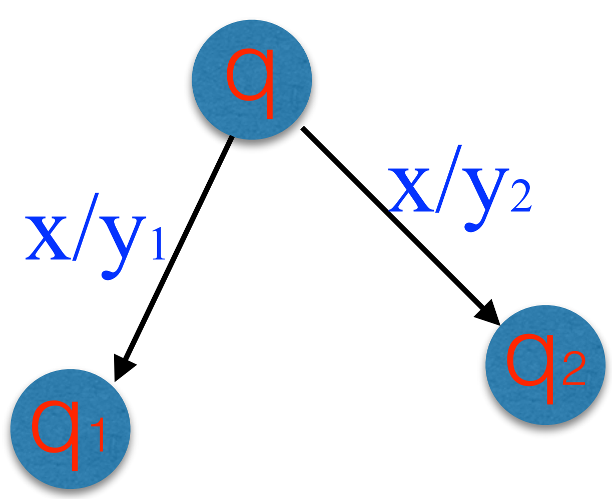

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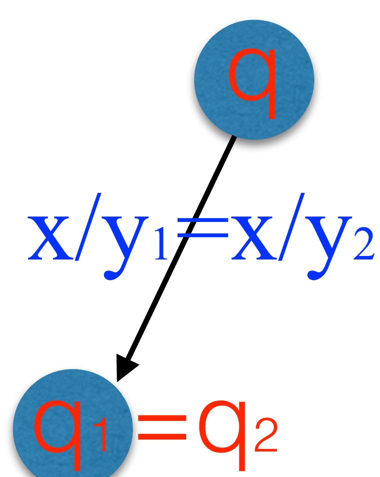

FSM Properties

可觀察的

- M is **observable**, if
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M is deterministic $\Rightarrow$ M is observable

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極小系統

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可觀察的

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極小系統

- M is **minimal**, if
  - $\forall q \in Q, \exists \pi \in L(q_0) : q_0 \xrightarrow{\pi} q$
  - $\forall q_1 \neq q_2 \in Q \Rightarrow L(q_1) \neq L(q_2)$

FSM Properties

可觀察的

- M is **observable**, if

$$\forall q \xrightarrow{x/y} q_1, q \xrightarrow{x/y} q_2 \in h \Rightarrow q_1 = q_2$$

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極小系統

- M is **minimal**, if
  - $\forall q \in Q, \exists \pi \in L(q_0) : q_0 \xrightarrow{\pi} q$ — initial connected
  - $\forall q_1 \neq q_2 \in Q \Rightarrow L(q_1) \neq L(q_2)$

Signature Sig is a set of

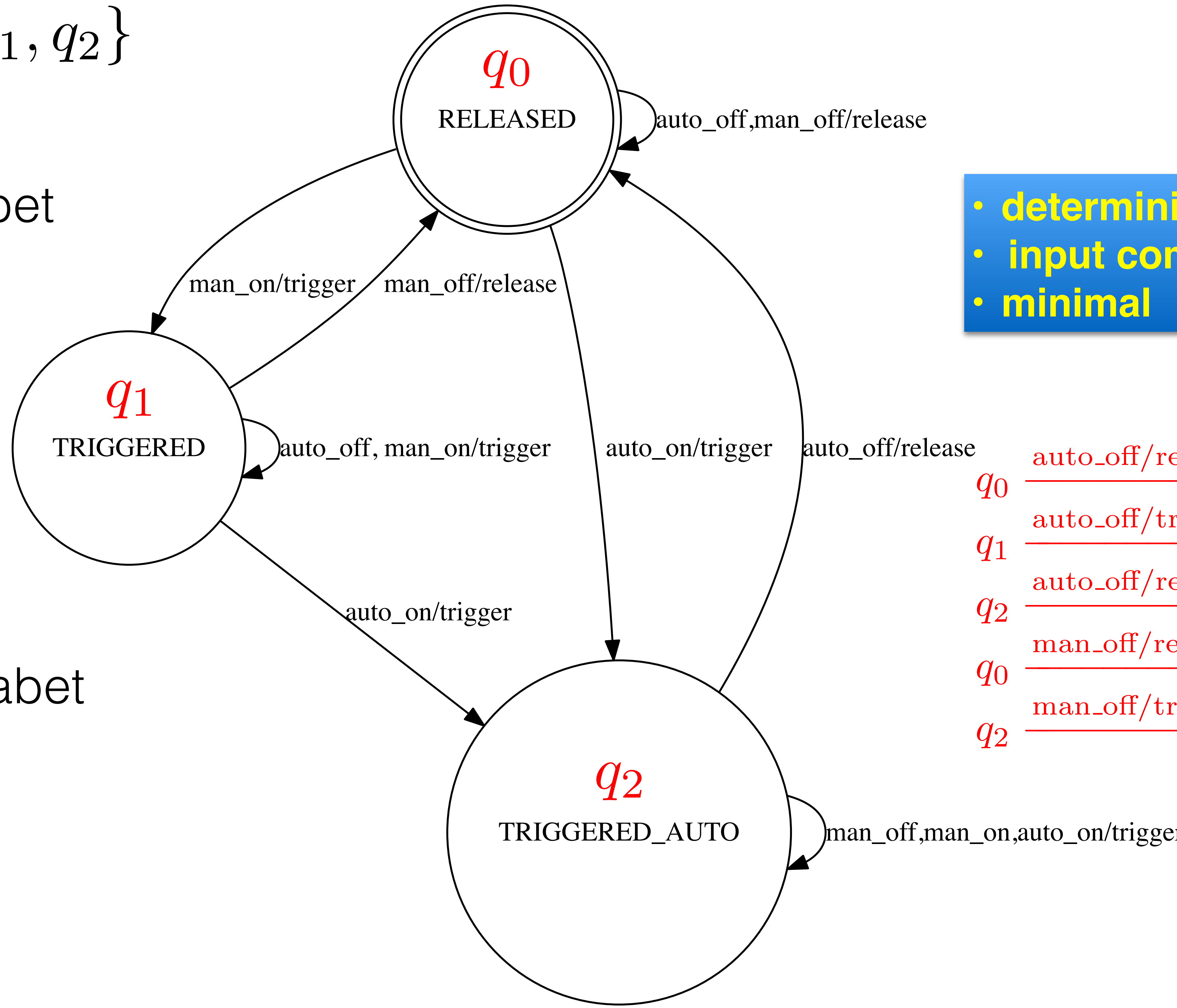
- input-complete
- minimal
- observable

finite state machines over $\Sigma = I \times O$

$$\forall M \;\text{ over } \Sigma,\; \exists M' \in \mathbf{Sig} : L(M) = L(M')$$

Finite State Machine modelling the behaviour of the brake controller

$$Q = \{q_0, q_1, q_2\}$$



Input Alphabet

man_on,
auto_on
man_off,
auto_off

Output Alphabet

trigger

release

- **deterministic**
- **input complete**
- **minimal**

$$q_0 \xrightarrow{\text{auto\_off/release}} q_0$$
$$q_1 \xrightarrow{\text{auto\_off/trigger}} q_1$$
$$q_2 \xrightarrow{\text{auto\_off/release}} q_0$$
$$q_0 \xrightarrow{\text{man\_off/release}} q_0$$
$$q_2 \xrightarrow{\text{man\_off/trigger}} q_2$$

$$M = (Q, q_0, I, O, h), M' = (Q', q_0', I, O, h') \in Sig$$

$L(M) = L(M') \Leftrightarrow M, M'$ **isomorphic**

$\exists f : M \to M'$:

- $Q \mapsto Q'$ bijection
- $q_0 \mapsto q_0'$
- $I \mapsto I$ identity map
- $O \mapsto O$ identity map
- $q_1 \stackrel{x/y}{\to} q_2 \in h \Leftrightarrow f(q_1) \stackrel{x/y}{\to} f(q_2) \in h'$

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Fault Models

$\mathcal{F}(M, I, O, \leq, \mathcal{D})$

- $M \in Sig$, **reference model** 參照模型
- $\leq \; \subseteq Sig \times Sig$, **conformance relation** 形變關係

  (I/O equivalence or I/O reduction)
- $\mathcal{D} \subseteq Sig$, **fault domain** 錯誤域

Test Cases

測試範例

Test case of deterministic FSM:
I/O sequence $\pi = x_1/y_1 \dots x_k/y_k \in \Sigma^*$

- M **passes** π, if $\pi \in L(M')$
- M **fails** π, if $\pi \notin L(M')$

Test Suite

測試範例組

test suite TS: a collection of test cases.

- M **passes** TS, if

  $\forall \pi \in TS,\ M$ passes π.

- M **fails** TS, if

  $\exists \pi \in TS,\ M$ fails π.

Complete Test Suites

完備測試範例組

$\mathcal{F}(M, I, O, \leq, \mathcal{D})$, fault model

$\mathbf{TS}$, test suite

- 可靠性 **Soundness**: $\forall M' \in \mathcal{D} : M' \leq M \Rightarrow M' \underline{\text{pass}}\, \mathbf{TS}$
- 全面性 **Exhaustiveness**: $\forall M' \in \mathcal{D} : M' \underline{\text{pass}}\, \mathbf{TS} \Rightarrow M' \leq M$
- 完備性 **Completeness**: Soundness + Exhaustiveness

$$\forall M' \in \mathcal{D} : M' \leq M \Leftrightarrow M' \underline{\text{pass}}\, \mathbf{TS}$$

Testing Theories

- **Deterministic FSM:**
- **T-Method**
- **Product Automata**
- **W-Method, Wp-Method**
- **Nondeterministic FSM:**
- **W-Method, Wp-Method**
- **Adaptive Testing**

Signature Sig is the set of

- input-complete
- minimal
- deterministic

finite state machines over $\Sigma = I \times O$

T-Method

$\mathcal{F}(M, I, O, \leq, \mathcal{D}_O)$, fault model

$M = (Q, q_0, I, O, h)$, $\forall M' \in \mathcal{D}_O \subseteq Sig$:

- $M' = (Q, q_0, I, O, h')$
- $\exists f : h \to h'$ bijective,
  $(q_1 \overset{x/y}{\longrightarrow} q_2) \mapsto (q_1 \overset{x/y'}{\longrightarrow} q_2)$

State Cover

State cover V of $M = (Q, q_0, I, O, h)$

- $V \subseteq L(M)$
- $\varepsilon \in V$
- $\forall q \in Q, \exists \pi \in V : q_0 \xrightarrow{\pi} q$.

q_0-after-$\pi = q$

State Cover

exists? finite?

State cover V of $M = (Q, q_0, I, O, h)$

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q_0-after-$\pi = q$

Lemma

Let $M = (Q, q_0, I, O, h) \in Sig$ and $\varepsilon \in U \subseteq L(M)$.
Then U is a state cover of M or
$\{q_0\text{-after-}\pi.\sigma \mid \pi \in U \wedge \sigma \in \Sigma \wedge \pi.\sigma \in L(M)\}$
$\not\subseteq \{q_0\text{-after-}\pi \mid \pi \in U\}$.

Transition Cover

Transition cover P of $M = (Q, q_0, I, O, h)$

- $P \subset L(M)$
- $\varepsilon \in P$
- $\forall q \in Q, \sigma = x/y \in L(q), \exists \pi \in P : q_0 \xrightarrow{\pi} q \wedge \pi.\sigma \in P$

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Transition Cover

Concatenation
For any $A, B_{\neq \varnothing} \subseteq \Sigma^*$.
$A.B := \{\pi.\iota \mid \pi \in A, \iota \in B\}$
Example: $\Sigma = \{a, b, c\}$
$A = \{\varepsilon\}, B = \{a.b\}, C = \{a, c\}$
$A.B = \{\varepsilon.a.b\} = \{a.b\} = B$
$B.C = \{a.b.a, a.b.c\}$

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V is a state cover
$\Rightarrow V \oplus (\{\varepsilon\} \cup \Sigma) = \big(V.(\{\varepsilon\} \cup \Sigma)\big) \cap L(M)$
$= V \cup \{\pi.\sigma \in L(M) \mid \pi \in V, \sigma \in \Sigma\}$
is a transition cover

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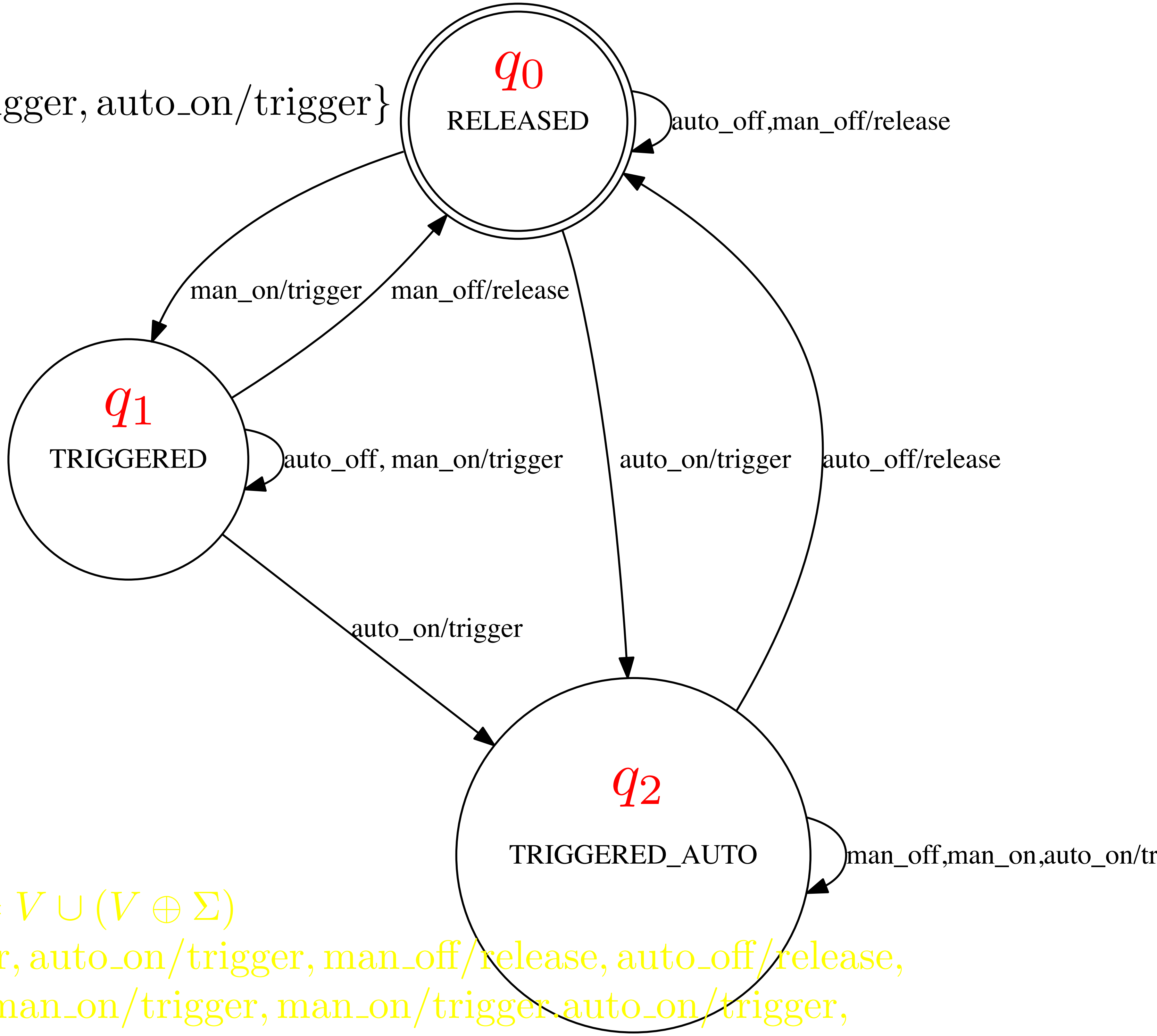
is a transition cover

Finite State Machine modelling the behaviour of the brake controller

- state cover $V = \{\varepsilon, \text{man\_on}/\text{trigger}, \text{auto\_on}/\text{trigger}\}$



- transition cover $P = V \cup (V \oplus \Sigma)$
  $= \{\varepsilon, \text{man\_on}/\text{trigger}, \text{auto\_on}/\text{trigger}, \text{man\_off}/\text{release}, \text{auto\_off}/\text{release},$
  $\text{man\_on}/\text{trigger}.\text{man\_on}/\text{trigger}, \text{man\_on}/\text{trigger}.\text{auto\_on}/\text{trigger},$
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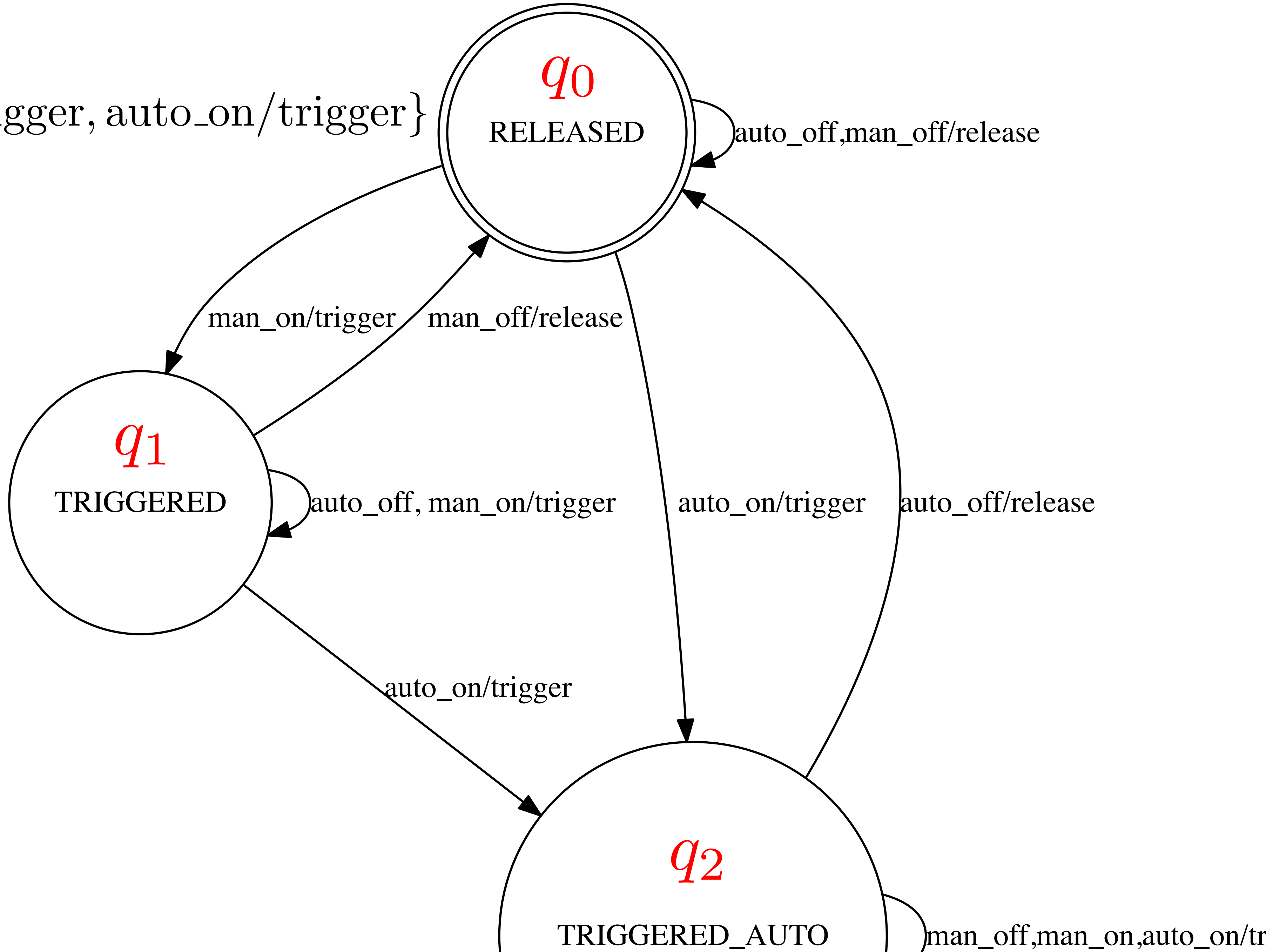

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  $\text{auto\_on}/\text{trigger}.\text{man\_off}/\text{trigger}, \text{auto\_on}/\text{trigger}.\text{auto\_off}/\text{release}\}$

T-Method

Every $\mathbf{TS} = P$ transition cover of M
is a complete test suite of $\mathcal{F}(M, I, O, \sim, \mathcal{D}_O)$

Proof:

Suppose M', M are not I/O equivalent.

Then there exists $\pi \in \Sigma^*$, $\sigma \neq \sigma' \in \Sigma$ such that $\pi.\sigma \in L(M)$ and $\pi.\sigma' \in L(M')$ with $\sigma_I = \sigma'_I$.

Let $q_0 \xrightarrow{\pi} q$, $q \xrightarrow{\sigma} q_1 \in h$, and $q \xrightarrow{\sigma'} q_1 \in h'$.

Since **TS** is a transition cover, there is $\tau \in \mathbf{TS}$ such that $q_0 \xrightarrow{\tau} q \in h$ and $\tau.\sigma \in \mathbf{TS}$.

Let $q_0 \xrightarrow{\tau'} q \in h'$ with $\tau_I = \tau'_I$.

Then $q_0 \xrightarrow{\tau'} q \xrightarrow{\sigma'} q_1 \in h'$ and $q_0 \xrightarrow{\tau} q \xrightarrow{\sigma} q_1 \in h$.

Since $\tau'_I.\sigma'_I = \tau_I.\sigma_I$ and $\tau'_O.\sigma'_O \neq \tau_O.\sigma_O$, we have $\tau.\sigma \notin L(M')$

Hence M' fails the test case $\tau.\sigma \in \mathbf{TS}$.

W-Method

M. P. Vasilevskii 1973 and Tsun S. Chow 1978

$\mathcal{F}(M, I, O, \leq, \mathcal{D}_m)$, fault model

$$\mathcal{D}_m = \{M' = (Q', q_0', I, O, h') \in Sig \mid |Q'| \leq m\}$$

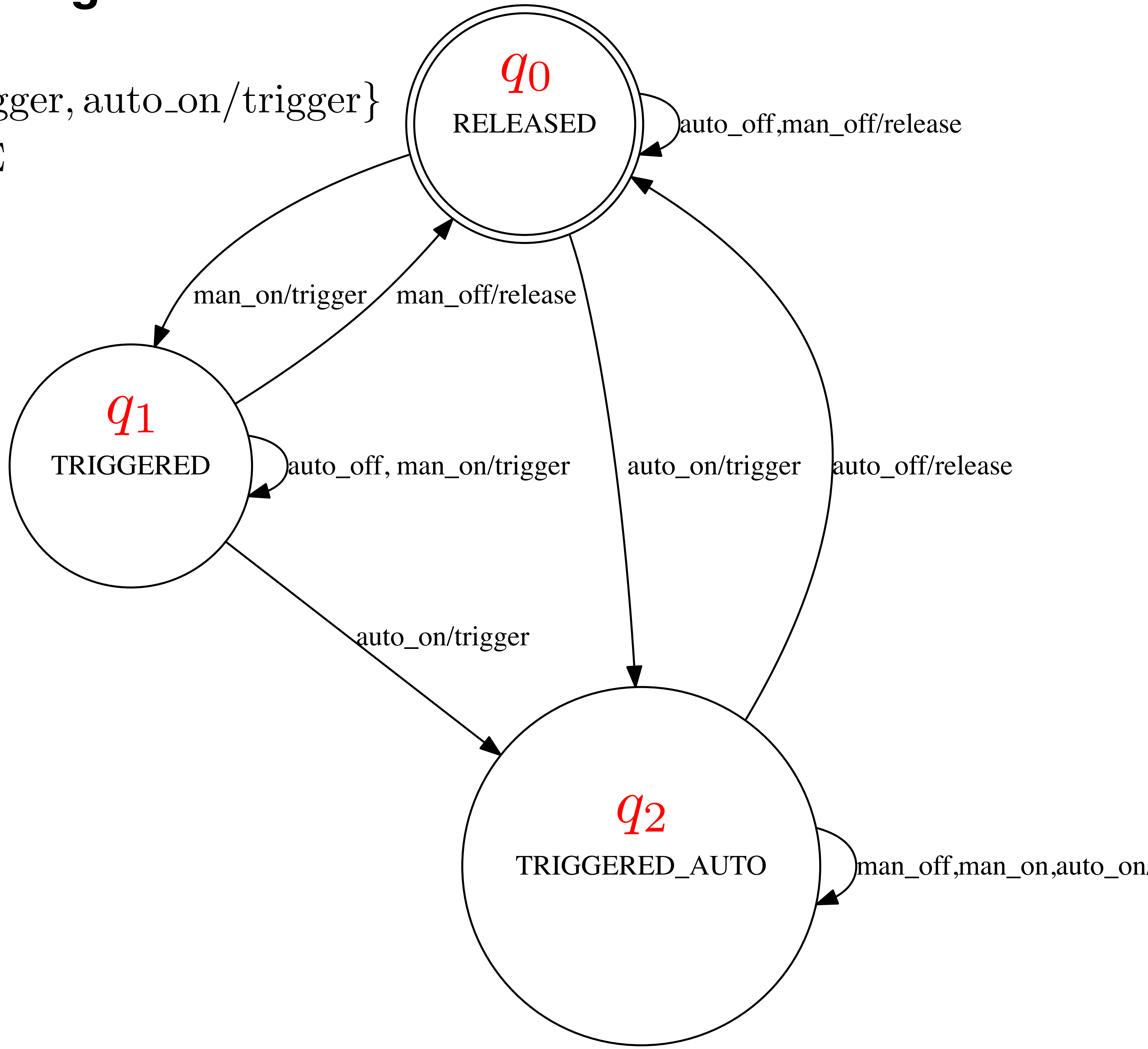
Characterization Set

Characterization set W of $M = (Q, q_0, I, O, h)$

- $W \subseteq \Sigma^*$ is a set of I/O sequences
- $\forall q_1 \neq q_2 \in Q, \exists \tau_1 \neq \tau_2 \in W : {\tau_1}_I = {\tau_2}_I \wedge \tau_i \in L(q_i), i = 1, 2$

Finite State Machine modelling the behaviour of the brake controller

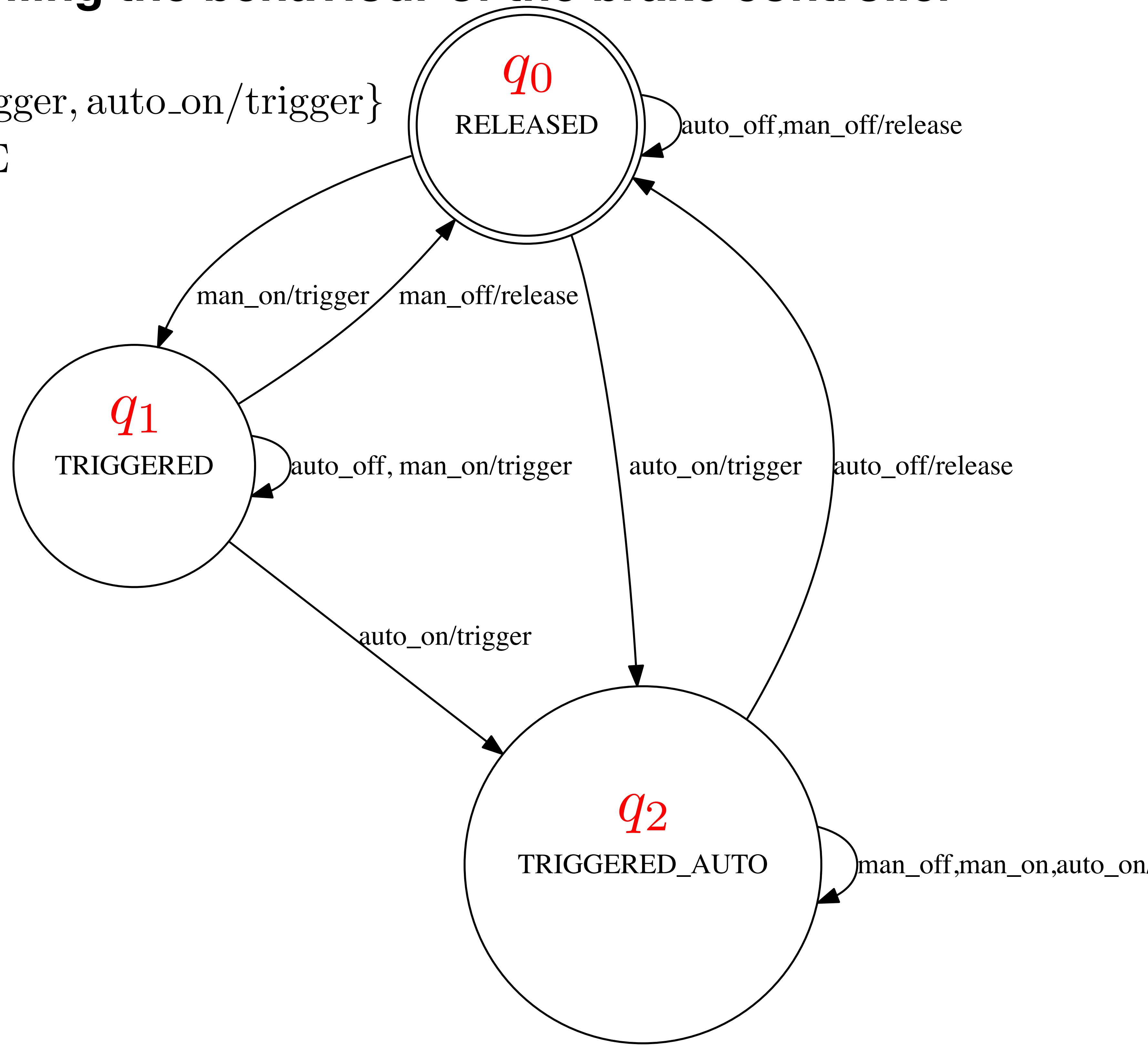
- state cover $V = \{\varepsilon, \text{man\_on/trigger}, \text{auto\_on/trigger}\}$
- transition cover $P = V \cup V \oplus \Sigma$



Finite State Machine modelling the behaviour of the brake controller

- state cover $V = \{\varepsilon, \text{man\_on/trigger}, \text{auto\_on/trigger}\}$
- transition cover $P = V \cup V \oplus \Sigma$

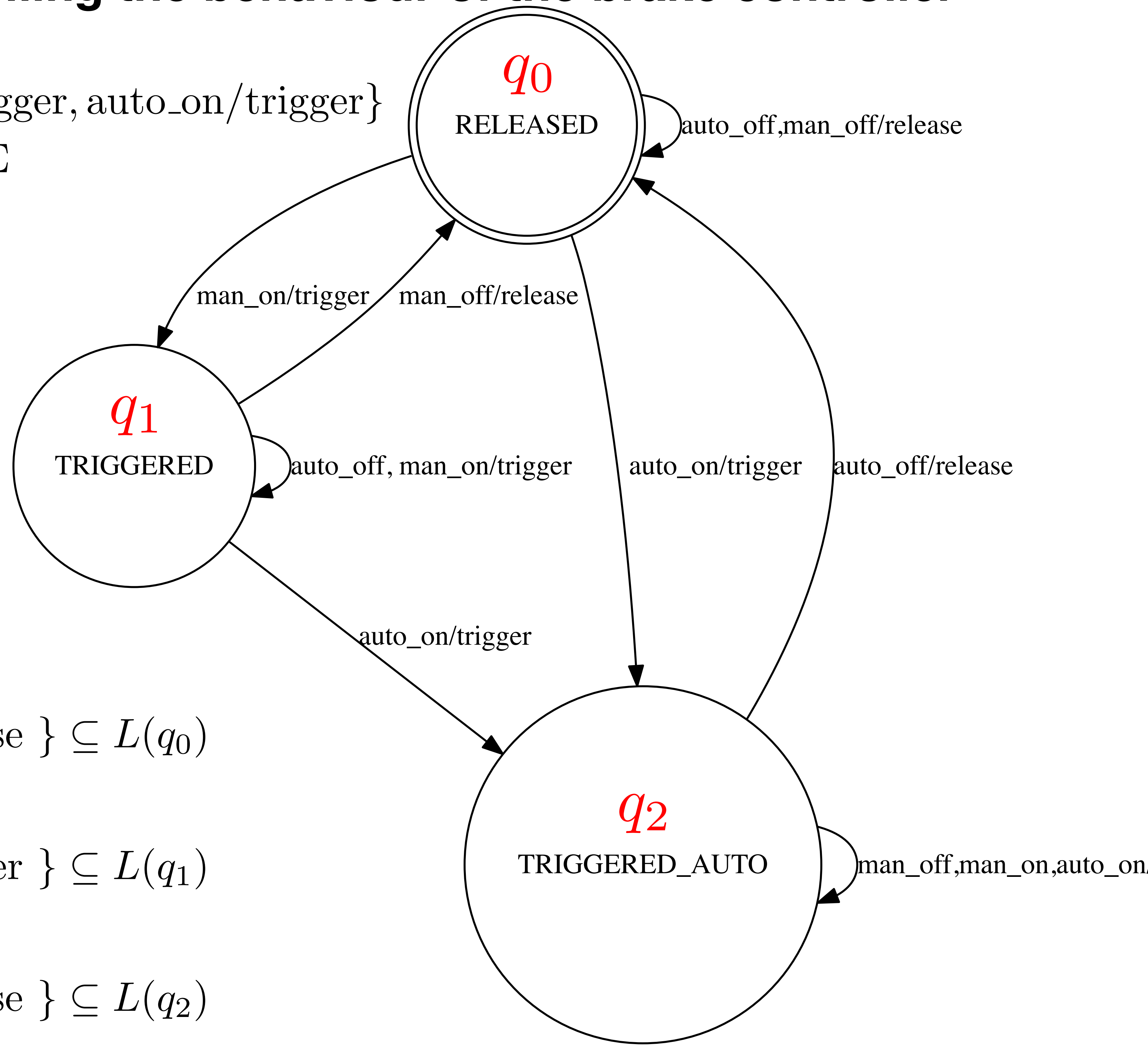
$$q_0 \xrightarrow{\text{auto\_off/release}} q_0$$
$$q_1 \xrightarrow{\text{auto\_off/trigger}} q_1$$
$$q_2 \xrightarrow{\text{auto\_off/release}} q_0$$
$$q_0 \xrightarrow{\text{man\_off/release}} q_0$$
$$q_2 \xrightarrow{\text{man\_off/trigger}} q_2$$



Finite State Machine modelling the behaviour of the brake controller

- state cover $V = \{\varepsilon, \text{man\_on}/\text{trigger}, \text{auto\_on}/\text{trigger}\}$
- transition cover $P = V \cup V \oplus \Sigma$

$$q_0 \xrightarrow{\text{auto\_off}/\text{release}} q_0$$
$$q_1 \xrightarrow{\text{auto\_off}/\text{trigger}} q_1$$
$$q_2 \xrightarrow{\text{auto\_off}/\text{release}} q_0$$
$$q_0 \xrightarrow{\text{man\_off}/\text{release}} q_0$$
$$q_2 \xrightarrow{\text{man\_off}/\text{trigger}} q_2$$



- $\{\text{man\_off}/\text{release}, \text{auto\_off}/\text{release}\ \} \subseteq L(q_0)$
- $\{\text{man\_off}/\text{release}, \text{auto\_off}/\text{trigger}\ \} \subseteq L(q_1)$
- $\{\text{man\_off}/\text{trigger}, \text{auto\_off}/\text{release}\ \} \subseteq L(q_2)$

Finite State Machine modelling the behaviour of the brake controller

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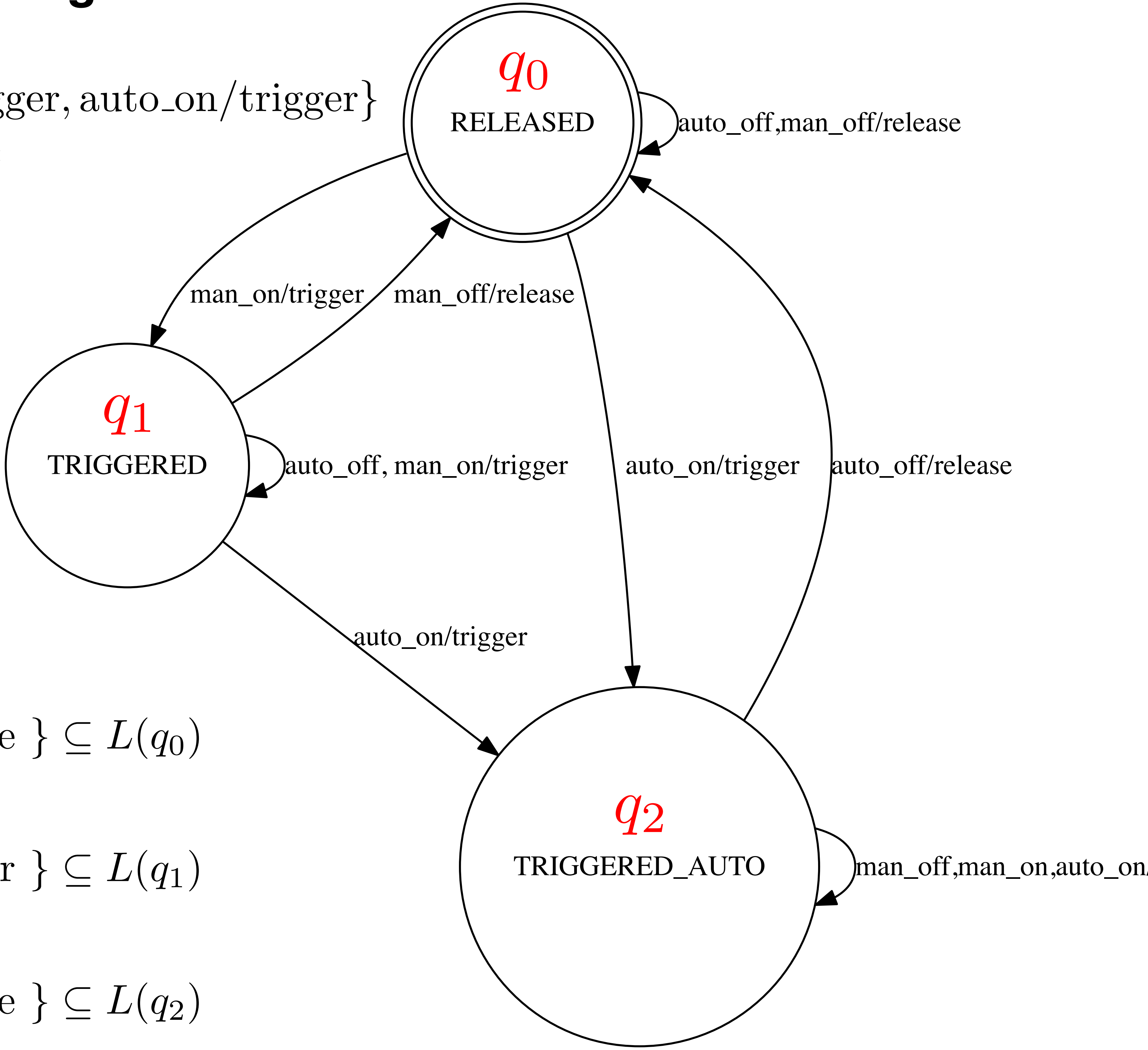
- transition cover $P = V \cup V \oplus \Sigma$



$$q_0 \xrightarrow{\text{auto\_off/release}} q_0$$
$$q_1 \xrightarrow{\text{auto\_off/trigger}} q_1$$
$$q_2 \xrightarrow{\text{auto\_off/release}} q_0$$
$$q_0 \xrightarrow{\text{man\_off/release}} q_0$$
$$q_2 \xrightarrow{\text{man\_off/trigger}} q_2$$

- $\{\text{man\_off/release}, \text{auto\_off/release}\} \subseteq L(q_0)$
- $\{\text{man\_off/release}, \text{auto\_off/trigger}\} \subseteq L(q_1)$
- $\{\text{man\_off/trigger}, \text{auto\_off/release}\} \subseteq L(q_2)$
- characterization set $W = \{\text{man\_off/trigger}, \text{man\_off/release}, \text{auto\_off/trigger}, \text{auto\_off/release}\}$

W-Method

Every $\mathbf{TS} = V \oplus \left(\bigcup_{i=0}^{m-n+1} \Sigma^i\right) \oplus W$
is a complete test suite of $\mathcal{F}(M, I, O, \sim, \mathcal{D}_m), n = |Q|$

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$$\mathbf{TS}_I = V_I . \left(\bigcup_{i=0}^{m-n+1} I^i\right) . W_I$$

Step 1.
$M = (Q, q_0, I, O, h), M' = (Q', q_0', I, O, h') \in Sig.$
Suppose $\exists f : Q \to Q'$:

- $f(q_0) = q_0'$
- $(q_1, x, y, q_2) \in h \Rightarrow (f(q_1), x, y, f(q_2)) \in h'$

Then $L(M) = L(M')$.

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homomorphism

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Then $L(M) = L(M')$.

Proof of step 1.

Suppose $f : Q \to Q', f(q_0) = q'_0$, is a homomorphism.
Then $\forall x_1 \dots x_k/y_1 \dots y_k \in L(M)$, $\exists q_i \in Q$, $i = 1, \dots, k$:

$q_0 \stackrel{x_1/y_1}{\to} q_1 \stackrel{x_2/y_2}{\to} \dots \stackrel{x_k/y_k}{\to} q_k$ and

$q'_0 = f(q_0) \stackrel{x_1/y_1}{\to} f(q_1) \stackrel{x_2/y_2}{\to} \dots \stackrel{x_k/y_k}{\to} f(q_k)$

Then $x_1 \dots x_k/y_1 \dots y_k \in L(M')$ and $L(M) \subseteq L(M')$.
Since M, M' are input complete and deterministic,
we have $L(M') = L(M)$.

Step 2.

$M' = (Q', q'_0, I, O, h') \in \mathcal{D}_m$.

Suppose M' pass $V \oplus \bigcup_{i=0}^{m-n} \Sigma^i \oplus W$

Then $V \oplus \bigcup_{i=0}^{m-n} \Sigma^i$ is a state cover of M' and

$V \oplus \bigcup_{i=0}^{m-n+1} \Sigma^i$ is a transition cover of M'.

Proof of step 2.

1. $M' \underline{\textbf{pass}} (V. \bigcup_{i=0}^{m-n+1} \Sigma^i.W) \cap L(M)$
   $\Rightarrow (V. \bigcup_{i=0}^{m-n+1} \Sigma^i.W) \cap L(M) = (V. \bigcup_{i=0}^{m-n+1} \Sigma^i.W) \cap L(M')$
   $\Rightarrow V \oplus \bigcup_{i=0}^{m-n+1} \Sigma^i \oplus W = V \oplus' \bigcup_{i=0}^{m-n+1} \Sigma^i \oplus' W$

2. $|\{q_0'\text{-after-}\pi) \mid \pi \in V\}| \geq n$

3. $\{q_0'\text{-after-}\pi \mid \pi \in V \oplus \bigcup_{i=0}^{m-n} \Sigma^i\} = Q'$

Proof of $|\{\{\mathbf{q_0'}\text{-after-}\pi \mid \pi \in \mathbf{V}\}| \geq \mathbf{n}$

Let

- $\pi_0 = \varepsilon$
- $\{\pi_i \mid i = 0, \ldots, n-1\} \subseteq V$ state cover of M
- $q_0 \xrightarrow{\pi_i} q_i$
- $q_0' \xrightarrow{\pi_i} q_i'$

Then $i \neq j \Rightarrow q'_i \neq q'_j$:

1. $q_i \neq q_j \Rightarrow \exists \tau_i \neq \tau_j \in W : \tau_{i_I} = \tau_{j_I}, \tau_i \in L(q_i), \tau_j \in L(q_j)$

   (W is a characterisation set of M)

2. $\tau_i \in L'(q'_i), \tau_j \in L'(q'_j) \wedge \tau_{i_I} = \tau_{j_I}$

3. M' is deterministic $\Rightarrow L'(q'_i) \neq L'(q'_j) \Rightarrow q'_i \neq q'_j$

Hence $n = |\{q'_0, \ldots, q'_{n-1}\}| \leq |\{q'_0\text{-after-}\pi \mid \pi \in V\}|$

Step 3.

$M' = (Q', q'_0, I, O, h') \in \mathcal{D}_m$.

Suppose M' pass $V \oplus \bigcup_{i=0}^{m-n+1} \Sigma^i \oplus W$.

Then $\exists f : M' \to M$ homomorphism.

Proof of step 3.
Let

- $Q' =: \{q'_0, \ldots, q'_{m-1}\}$
- $\{\varepsilon\} \cup \{\pi_i \mid i = 1, \ldots m-1\} \subseteq V \oplus \bigcup_{i=0}^{m-n} \Sigma^i$, a state cover of M'.
- $f : Q' \to Q$, $f(q'_0) = q_0$ and $f(q'_i) = q_0$-after-π_i.

Proof of step 3.
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- $f : Q' \to Q$, $f(q'_0) = q_0$ and $f(q'_i) = q_0$-after-π_i.

Then $f(q)$ is the unique state of M such that
$\pi \in L(q') \Leftrightarrow \pi \in L(f(q)), \forall \pi \in W$

Proof of step 3.
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Then $f(q)$ is the unique state of M such that
$\pi \in L(q') \Leftrightarrow \pi \in L(f(q)), \forall \pi \in W$

Then

$$x/y \in L(q'_i) \Leftrightarrow x/y \in L(q_i), \qquad \forall x/y \in \Sigma$$

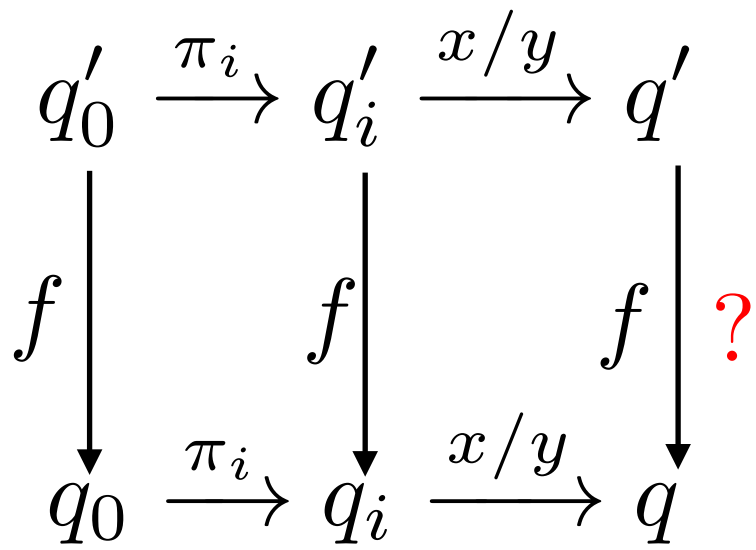
$$[q_0, q'_0\ \underline{\mathrm{pass}}(V \oplus \bigcup_{i=0}^{m-n} \Sigma^i) \oplus \Sigma]$$

$$\tau \in L(q'_i) \Leftrightarrow \tau \in L(q_i), \qquad \forall \tau \in W$$

$$[q_0, q'_0\ \underline{\mathrm{pass}}(V \oplus \bigcup_{i=0}^{m-n} \Sigma^i) \oplus W]$$

$$(x/y).\tau \in L(q'_i) \Leftrightarrow (x/y).\tau \in L(q_i), \qquad \forall x/y \in \Sigma, \tau \in W$$

$$[q_0, q'_0\ \underline{\mathrm{pass}}(V \oplus \bigcup_{i=0}^{m-n} \Sigma^i) \oplus \Sigma \oplus W]$$



$$\pi \in L(q') \Leftrightarrow \pi \in L(q), \forall \pi \in W$$
$$\Rightarrow f(q') = q$$

Wp-Method

$\mathcal{F}(M, I, O, \leq, \mathcal{D}_m)$, fault model

$\mathcal{D}_m = \{M' = (Q', q'_0, I, O, h') \subseteq Sig \mid |Q'| \leq m\}$

1. V a state cover of M.
2. $P = V \oplus (\{\varepsilon\} \cup \Sigma)$ a transition cover of M
3. $R = P \setminus V$.
4. W a characterisation set of M.
5. $\{W_0, \ldots, W_{n-1}\}$ *state identification sets* of M, such that
   - $W_i \subseteq pref(W)$ for $i = 0, \ldots, n-1$.
   - W_i distinguishes q_i from all other states in Q.

Finite State Machine modelling the behaviour of the brake controller

- state cover $V = \{\varepsilon, \text{man\_on/trigger}, \text{auto\_on/trigger}\}$
- transition cover $P = V \cup V \oplus \Sigma$

$$q_0 \xrightarrow{\text{auto\_off/release}} q_0$$
$$q_1 \xrightarrow{\text{auto\_off/trigger}} q_1$$
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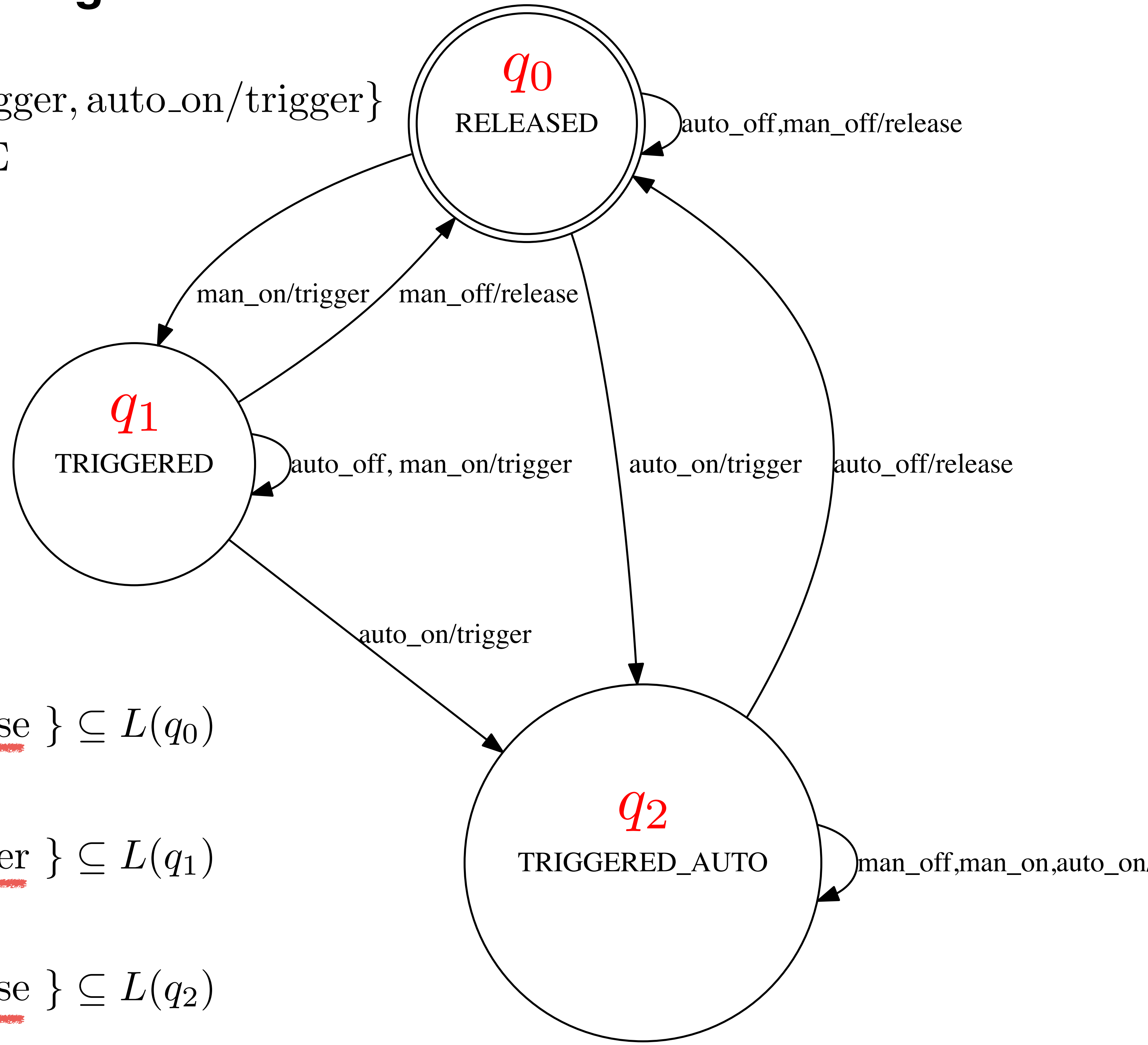

- $\{\text{man\_off/release}, \text{auto\_off/release}\} \subseteq L(q_0)$

W0

- $\{\text{man\_off/release}, \text{auto\_off/trigger}\} \subseteq L(q_1)$

W1

- $\{\text{man\_off/trigger}, \text{auto\_off/release}\} \subseteq L(q_2)$

W2

- characterization set $W = \{\text{man\_off/trigger}, \text{man\_off/release}, \text{auto\_off/trigger}, \text{auto\_off/release}\}$

Wp-Method

- $Wp_1 = V \oplus \left(\bigcup_{i=0}^{m-n} \Sigma^i \right) \oplus W$
- $Wp_2 = R \oplus \Sigma^{m-n} \oplus \{W_0, \ldots, W_{n-1}\}$
- $\mathbf{TS} = Wp_1 \cup Wp_2$
  is a complete test suite of $\mathcal{F} = (M, I, O, \sim, \mathcal{D}_m)$.

$$U \oplus \{W_0, \ldots, W_{n-1}\} =$$

$$\bigcup_{\pi \in U \wedge q_i = q_0\text{-after-}\pi} \{\pi\}.W_i$$

Wp-Method

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Further Reading

1. Publications of Jan Peleska, Wen-ling Huang, and their co-authors. http://www.informatik.uni-bremen.de/agbs/jp/jp_papers_e.html

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