

Formalizing Safety Requirements Using Controlling Automata

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Abstract

Safety is an important element of dependability. It is defined as the absence of accidents. Most accidents involving software-intensive systems have been system accidents, which are caused by unsafe inter-system or inter-component interactions. To validate the absence of system hazards concerning dysfunctional interactions, industrials call for approaches of modeling system safety requirements and interaction constraints among components. This paper proposes such a formalism, namely interface control systems (or shortly C-Systems). An interface C-System is composed of an interface automaton and a controlling automaton, which formalizes safe interactions and restricts system behavior at the meta level. This framework differs from the framework of traditional model checking. It explicitly separates the tasks of product engineers and safety engineers, and provides a top-down technique for modeling a system with safety constraints, and for automatically composing a safe system that conforms to safety requirements. The contributions of this work include formalizing safety requirements and a way of automatically ensuring system safety.

1. System Safety Requirements

Critical systems are always controlled by software applications, which overcome the shortcomings of human control, but also introduce new failure modes that are changing the nature of accidents [1]. *Inter-system* and *inter-component* dependability are becoming important, since industrials are developing complicated software-intensive systems which consist of numerous components (subsystems) and a huge number of actions (both internal and interactive). A recent challenge of dependability is the *system accident*, caused by increasing *inter-system* and *inter-component couplings* and their *interactive complexity* [2][3]. In contrast, accidents arising from component failures are termed *component failure accidents*.

System safety and *component reliability* are different elements of dependability. They are system property and component property, respectively [2]. *Reliability* is defined as the capability that a component satisfies its specified

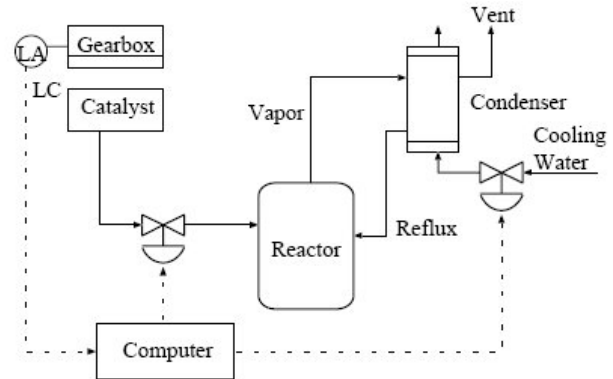


Figure 1. A Chemical Reactor Design

behavioral requirements, whereas *safety* is defined as the absence of accidents — events involving an unacceptable loss [4]. People are now constructing intellectually unmanageable software systems that go beyond human cognitive limits. This allows potentially *unsafe interactions* to be undetected. Accidents often result from hazardous interactions among perfectly functioning components.

As an example, a system accident occurred in a batch chemical reactor in England [5]. The design of the system is shown in Fig. 1. The computer controlled the input flow of cooling water into the condenser and the input flow of catalyst into the reactor by manipulating the valves. The computer was told that if any component in the plant gets abnormal, it had to leave all controlled variables as they were and to sound an alarm. On one occasion, the computer just started to increase the cooling water flow, after a catalyst had been added into the reactor. Then the computer received an abnormal signal indicating a low oil level in a gearbox, and it reacted as its requirements specified: sounded an alarm and maintained all the control variables with their present condition. Since the water flow was kept at a low rate, then the reactor overheated, the relief valve lifted and the contents of the reactor were discharged into the atmosphere.

Some other system accidents in avionics are also due to uncontrolled interactions between components [6]. The self-destructing explosion of Ariane 5 launcher was resulted from the successive failures of the active Inertial Reference

System (IRS) and the backup IRS [6]. Ariane 5 adopted the same reference system as Ariane 4. However, the profile of Ariane 5 was different from that of Ariane 4 — the acceleration communicated as input value to IRS of Ariane 5 was higher. Furthermore, the *interactions between IRS and other components* were not redefined and checked. Due to the overflow of input value computation, the IRS stopped working [7]. Then, the signaled error was interpreted as a launcher attitude, and led the control system to rotate the tailpipe at the end stop [8].

In these accidents, the components are reliable in terms of satisfying their specified requirements, but the systems are not safe as a whole. Since most software related accidents have been system accidents [1], people need to model and constrain interactions of system components to validate the absence of *dysfunctional interactions*. As Leveson mentioned in STAMP (Systems-Theoretic Accident Model and Processes) [1], these accidents result from inadequate *control* or enforcement of *safety-related constraints* of the systems.

Traditionally, in order to validate the absence of system hazards, industrials identify system safety requirements [9][10], and use model checking to verify if system behaviors conform to safety requirements [11].

In this paper, we will consider safety requirements as control structures that restrict system behaviors at meta-model level. That is, the two models of a system and its safety constraints will be developed at the same time. Then the two models are “combined” to deduce a safe system.

This paper is organized as follows: the architecture of our approach is presented in Section 2. To illustrate the idea, a preliminary introduction on interface automata appears in Section 3. The interface C-System based on controlling automata is introduced in Sections 4 and 5, where examples are used to illustrate how to formalize safety rules and combine them with a system specification. In Section 6, we compare our work to classic verification techniques, such as model checking, and conclude the paper.

2. The Architecture of our Methodology

The most popular technique of system safety verification is *model checking* [12]. Hundreds of checking patterns are collected for system engineers [13] and specific uses in safety engineering [11]. In this framework, we have three steps in verifying a system. At first, we formalize system behavior as a model (e.g., a finite-state transition system, a Kripke model [14]). At the second step, we specify the safety constraints that we aim at validating using temporal logics [13]. At the third step, a certain checking algorithm is used to search for a counterexample which is an execution trace violating the specified features. If the algorithm finds such a counterexample, we have to modify the original design to ensure safety constraints.

Unlike model checking, our architecture takes another way. It consists of the following steps:

(1) Modeling system behavior, including specifications of its components, internal and external interactions, e.g., using interface automata.

(2) Modeling system safety constraints using a certain formal technique, e.g., controlling automata in this paper.

(3) Combining these two models to deduce a safe system model, that is, a system model whose behavior is in accordance with its safety constraints.

As [15] mentioned, system behavior specifies an *operational semantics*, which defines what a system is able to do. System behavior modeling is achieved by *product engineers* (designers), such as programmers and developers. In the example of the chemical reactor control system, the actions “opening the catalyst flow”, “opening the cooling water flow” and “sounding an alarm” are actions of the system behavior.

In the second step, the model of safety constraints specifies a *correctness semantics*, which defines what a system is authorized to do. This process is the duty of *safety engineers* whose responsibility is to assure system safety. Safety engineers may consist of requirement engineers, testing engineers, managers from higher socio-technical levels who define safety standards or regulations [1], etc. In the example of the chemical reactor system, the constraint “opening the catalyst flow must be followed by opening the cooling water flow” is an instance of system safety constraints.

In the third step, in order to ensure system safety, we combine a system model with its safety constraints model. Then we ensure that the system is safe under the constraints specifying safety requirements. A precondition of this approach is that we must formalize safety requirements. And we also need to carefully define the composition of a system model and its constraints model. We will introduce such means based on controlling automata.

3. Preliminary: Interface Automata

To model component-based concurrent systems with different input, output and internal actions, the theory of interface automata [16] extends Input/Output automata [17][18], which extends classic automata theory [19].

Unlike I/O automata, an interface automaton is not required to be input-enabled (i.e., some inputs may be recognized as illegal in some states) and only allows the composition of two automata (I/O automata allow the composition of infinite automata), and a synchronization of one output and one input action results a hidden action after the composition.

Definition 1: An **interface automaton** (simply an automaton) is a tuple $A = (Q, \Sigma^I, \Sigma^O, \Sigma^H, \delta, S)$, where:

(1) Q is a set of **states**.

(2) $\Sigma^I, \Sigma^O, \Sigma^H$ are pairwise disjoint sets of **input, output**

and internal actions, respectively. Let $\Sigma = \Sigma^I \cup \Sigma^O \cup \Sigma^H$ be the set of **actions**.

(3) $\delta \subseteq Q \times \Sigma \times Q$ is a set of **labeled transitions**.

(4) $S \subseteq Q$ is a set of **start states**, where $|S| \leq 1$. \square

In the graph notation, a transition $p_k : (q, a, q') \in \delta$ is denoted by an arc from q to q' labeled $p_k : a$, where p_k is the name of the transition. To discriminate explicitly the different sets of actions in diagrams, we may suffix a symbol “?”, “!” or “;” to an input, output or internal action, respectively.

The composition of two composable automata allows the automata to synchronize on shared actions, and asynchronously interleave all other actions.

Definition 2: Two interface automata A and B are **composable** if $\Sigma_A^H \cap \Sigma_B = \emptyset$, $\Sigma_A^I \cap \Sigma_B^I = \emptyset$, $\Sigma_A^O \cap \Sigma_B^O = \emptyset$, $\Sigma_B^H \cap \Sigma_A = \emptyset$. We let $shared(A, B) = \Sigma_A \cap \Sigma_B$. \square

Definition 3: If A and B are composable interface automata, their **product** $A \otimes B$ is the interface automaton defined by

- (1) $Q_{A \otimes B} = Q_A \times Q_B$
- (2) $\Sigma_{A \otimes B}^I = (\Sigma_A^I \cup \Sigma_B^I) - shared(A, B)$
- (3) $\Sigma_{A \otimes B}^O = (\Sigma_A^O \cup \Sigma_B^O) - shared(A, B)$
- (4) $\Sigma_{A \otimes B}^H = \Sigma_A^H \cup \Sigma_B^H \cup shared(A, B)$
- (5)

$$\begin{aligned} \delta_{A \otimes B} = \{ & p_i : ((v, u), a, (v', u)) \mid p_i : (v, a, v') \in \delta_A \\ & \wedge a \notin shared(A, B) \wedge u \in Q_B \} \\ \cup \{ & p_j : ((v, u), a, (v, u')) \mid p_j : (u, a, u') \in \delta_B \\ & \wedge a \notin shared(A, B) \wedge v \in Q_A \} \\ \cup \{ & p_{ij} : ((v, u), a, (v', u')) \mid p_i : (v, a, v') \in \delta_A \\ & \wedge p_j : (u, a, u') \in \delta_B \wedge a \in shared(A, B) \} \end{aligned}$$

(6) $S_{A \otimes B} = S_A \times S_B$. \square

Note that the name of the transition p_{ij} of $A \otimes B$ may contain the names of two original transitions $p_i \in \delta_A$ and $p_j \in \delta_B$.

In the product $A \otimes B$, there may be **illegal states**, where one component is able to send an output $a \in shared(A, B)$ and the other is not able to receive a .

The composition of two interface automata A, B is obtained by restricting the product of the two automata to the set $Cmp(A, B)$ of **compatible states**, which are the states from which there exists a legal environment that can prevent entering illegal states.

Definition 4: If A and B are composable interface automata, their **composition** $A||B$ is the interface automaton defined by

- (1) $Q_{A||B} = Cmp(A, B)$
- (2) $\Sigma_{A||B}^I = \Sigma_{A \otimes B}^I$
- (3) $\Sigma_{A||B}^O = \Sigma_{A \otimes B}^O$
- (4) $\Sigma_{A||B}^H = \Sigma_{A \otimes B}^H$
- (5) $\delta_{A||B} = \delta_{A \otimes B} \cap (Cmp(A, B) \times \Sigma_{A||B} \times Cmp(A, B))$
- (6) $S_{A||B} = S_{A \otimes B} \cap Cmp(A, B)$. \square

4. Safety Constraints on a Single Component

In this section, we start from a simple case – modeling safety constraints on a single component. In the example of the batch chemical reactor (C.f. Fig. 1), the computer system behavior is modeled using an interface automaton A of Fig. 2(1). The automaton A includes a set of input actions $\Sigma^I = \{l\}$ (low oil signal), a set of output actions $\Sigma^O = \{c, w, a\}$ (opening catalyst flow, opening water flow, sounding an alarm, respectively), and a set of internal actions $\Sigma^H = \{e\}$ (ending all operations).

The normal operational behavior includes opening the catalyst flow (p_1), then opening the water flow (p_2), etc., resulting in an infinite execution trace $p_1 p_2 p_1 p_2 \dots$. To respond to abnormal signals as soon as possible, the states q_0, q_1 both have a transition labeled l , which leads to a state that can sound an alarm (p_5) and stop the process (p_6). Unfortunately, this design leads to hazardous behaviors: $(cw)^* clae$, that is, after a sequence of opening catalyst and water flows $(cw)^*$, then the catalyst flow is opened (c) when an abnormal signal is received (l), then an alarm is sounded (a). So water is not added after the catalyst flow is opened. This sequence of events leads to the accident mentioned in Section 1.

Note that this hazard is due to the uncontrolled sequences of transitions — p_1 must be followed by p_2 and not by p_4 . To solve this problem, we need to specify the authorized sequences (satisfying safety constraints) on the transitions δ and not on the actions Σ . Thus, these constraints are not at the behavioral model level, but at the meta-model level. We propose the concept of *controlling automata* to formalize safety constraints. Then, we combine a controlling automaton with the system automaton.

Definition 5: A **controlling automaton** \hat{A} over an interface automaton $A = (Q, \Sigma, \delta, S)$ is a tuple $\hat{A} = (\hat{Q}, \hat{\Sigma}, \hat{\delta}, \hat{S})$, where:

- (1) \hat{Q} is a set of **states** disjoint with Q .
- (2) $\hat{\Sigma}$ is a set of **terminals**, such that $\hat{\Sigma} = \delta$.
- (3) $\hat{\delta} \subseteq \hat{Q} \times \hat{\Sigma} \times \hat{Q}$ is a set of **labeled transitions**.
- (4) $\hat{S} \subseteq \hat{Q}$ is a nonempty set of **start states**. \square

Note that the transitions δ of A are terminals of \hat{A} , so we say that \hat{A} is at the meta level of A . Figure 3 illustrates the 3 levels in our framework. Let Σ^* be a set of execution traces of actions, A describes the behavior on Σ . \hat{A} specifies the behavior on the A -transitions ($\hat{\Sigma} = \delta$), that is, a behavior on the behavior of A . This meta-behavior expresses safety requirements.

In the example, to prevent accidents, we need to impose the safety constraint “opening catalyst must be followed by opening water,” that is, “whenever the transition $p_1 : c$ occurs, the transition $p_2 : w$ must occur after that”. This constraint can be formalized as a controlling automaton \hat{A} of Fig. 2(2). When we express this constraint, we only specify the sequence of transitions p_1, p_2 at the meta-model level, and we concern little about the implementation of

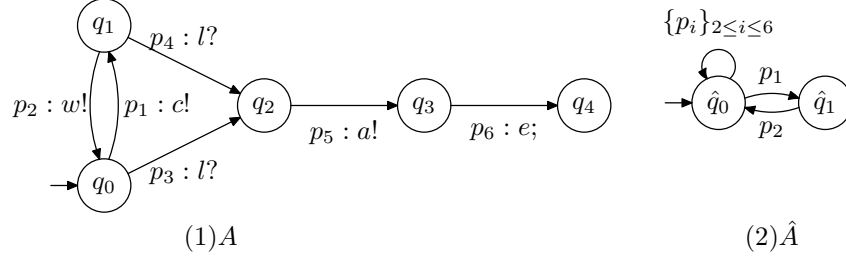


Figure 2. Automata of the Reactor Control System

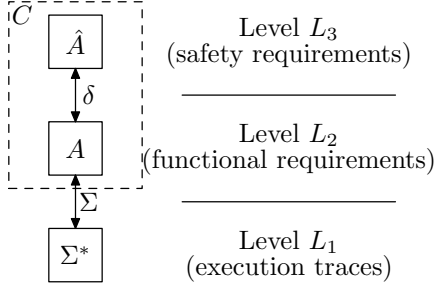


Figure 3. A 3-levels Overview

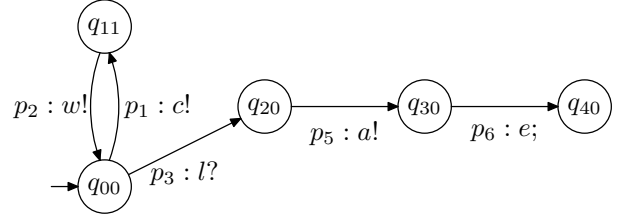


Figure 4. The Meta-Composition C

the system at the model level. The next step is to compose the system automaton A with its controlling automaton \hat{A} , and automatically generate a system C satisfying the safety requirement.

Definition 6: The **meta-composition** C of an interface automaton $A = (Q, \Sigma, \delta, S)$ and a controlling automaton $\hat{A} = (\hat{Q}, \hat{\Sigma}, \hat{\delta}, \hat{S})$ over A is a tuple:

$$C = A \xrightarrow{\hat{A}} \hat{A} = (Q \times \hat{Q}, \Sigma, \delta', S \times \hat{S}) \quad (1)$$

where $p_k : ((q_i, \hat{q}_j), a, (q_m, \hat{q}_n)) \in \delta'$ iff,

- (1) $p_k : (q_i, a, q_m) \in \delta$, and
- (2) $(\hat{q}_j, p_k, \hat{q}_n) \in \hat{\delta}$.

We say that A and \hat{A} constitute an **interface control system** (or simply **interface C-System**). \square

The symbol $\xrightarrow{\hat{A}}$ is called *meta-composition operator*, and read “meta-compose”. Its left and right operands are an automaton and a controlling automaton, respectively. Notice that an interface C-System is equivalent to the meta-composition C of an interface automaton and a controlling automaton.

Notice that $\delta = \{p_k\}_{k \in \mathcal{K}}$ plays a key role in associating transitions of A and terminals of \hat{A} . For our example, we combine the automata A and \hat{A} of Fig. 2, thus we get the automaton $C = A \xrightarrow{\hat{A}} \hat{A}$ of Fig. 4 where q_{ij} denotes (q_i, \hat{q}_j) .

The meta-composition contains exactly all the paths satisfying the safety constraint. Formally, we have the following theorem (the proof is omitted for its simpleness and intuitiveness from the definition):

Theorem 7: Given A, \hat{A} and the meta-composition C , an **execution trace** $t_\Sigma \in \Sigma^*$ is recognized by C iff, t_Σ

is recognized by A , and its **transition trace** $t_\delta \in \delta^*$ is recognized by \hat{A} . \square

Obviously, the set of traces of C is a subset of the traces of A . Formally, let $L(A)$ be the set of traces of A (i.e. the language of A), we have $L(C) \subseteq L(A)$.

Thanks to \hat{A} , the hazardous execution traces, for example $cwclae$, which exists in A , will be eliminated, because its transition trace $p_1 p_2 p_1 p_4 p_5 p_6 \notin L(\hat{A})$ (the language of \hat{A}). The comparison between A of Fig. 2(1) and C of Fig. 4 highlights the hazardous transition p_4 of A . However, in general, this diagnosis is much more complex and cannot be achieved manually, since a real system A has too many states to be expressed clearly on a paper. That is why we developed a formal and automated method for eliminating hazardous transitions.

5. Safety Constraints on Multi-Components

To illustrate this case, we use an example concerning a system composed of two components with interactions: a candy vending machine and a customer. We hope that, since this class of examples is so popular in the literatures of formal methods (e.g., Hoare’s Communicating Sequential Processes (CSP) and I/O automata [17]), they will provide an interesting illustration of our idea. The candy machine A_m , specified in Fig. 5(1), may receive inputs b_1, b_2 indicating that buttons 1 and 2 are pushed, respectively. It may output s, a , indicating candy dispensation actions, SKYBARs and ALMONDJOYs, respectively. The machine may receive several inputs before delivering a candy. A greedy user A_u , specified in Fig. 5(2), can push buttons b_1, b_2 or get a candy s, a . The greedy user does not wait for a candy bar before

pressing a button again.

The composition of the machine behavior and the user behavior is defined by $A_{mu} = A_m || A_u$ of Fig. 5(3), where q_{ij} denotes the composite state (m_i, u_j) , $p_{i,j}$ denotes two synchronized transitions $\{p_i, p_j\}$. A transition of the composition may be composed of two transitions of components. For example, $p_{1,13} : s$ is a synchronization of $p_1 : s!$ and $p_{13} : s?$, which belong to A_m and A_u , respectively. Generally, a transition of $A = P || Q$ may be composed of one or two transitions of its components, where two transitions constitute a synchronization.

In the context of meta-composition, a composite transition is allowed if and only if both of its sub-transitions are allowed by its controlling automaton. Thus, we define the meta-composition operator as follows:

Definition 8: The **meta-composition** (or interface C-System) C of a composition $A = P || Q$ and a controlling automaton $\hat{A} = (\hat{Q}, \hat{\Sigma}, \hat{\delta}, \hat{S})$ over A is a tuple:

$$C = A \xrightarrow{\hat{A}} = (Q_A \times \hat{Q}, \Sigma_A, \delta', S_A \times \hat{S}) \quad (2)$$

where $p_{\mathcal{I}} : ((v, u, q), a, (v', u', q')) \in \delta'$ ($p_{\mathcal{I}}$ contains a set of transitions $\{p_k\}_{k \in \mathcal{I}}$) iff,

- (1) $p_{\mathcal{I}} : (((v, u), a, (v', u')) \in \delta_A$, and
- (2) $\forall k : k \in \mathcal{I} \bullet (q, p_k, q') \in \hat{\delta}$. □

Notice that the specification of the example allows a hazardous situation: the greedy user repeatedly pushes the buttons without giving the machine a chance to dispense a candy bar (e.g., the transition labeled $p_{5,11} : b_1$ of q_{11} does not allow the transition (q_{11}, s, q_{00}) to be fired). To prevent this situation, the following constraints forbid successive occurrences of pressing buttons: “the transitions p_{11}, p_{12} are not allowed, when interactions occur between the machine and the user”. Differing from the previous example, this type of constraints needs to synchronize the actions of the machine and of the user.

Formalizing the constraints, the semantics of the controlling automaton A_c of Fig. 6(1) is: whenever the user pushes a button (p_9, p_{10}) , she or he cannot push it again (p_{11}, p_{12}) , but can only wait for a candy bar.

Combining the whole system A_{mu} with its constraint A_c , we get the system $C = (A_m || A_u) \xrightarrow{\hat{A}} A_c$ in Fig. 6(2), where q_{ijk} denotes the composite state (m_i, u_j, c_k) . All of its execution traces satisfy the constraint, and thus prevent the hazardous situation.

Since we formally defined the *meta-composition operator*, it can be easily implemented to be an automated tool. Thus, it can be applied to more complex systems.

6. Conclusion

We proposed formalizing system safety requirements using controlling automata. As we illustrated using examples, this approach can formally model safe interactions between components or systems. This framework differs from the

one of model checking. It explicitly separates the tasks of product engineers and safety engineers, and provides a technique for modeling a system with safety constraints, and for automatically composing a safe system that conforms to safety requirements.

The essential ideas of our approach are the separation and formalization of the system specification A (core functional requirements) and the safety constraints \hat{A} (safety requirements). The automaton A handles inputs to produce outputs using activities depending on the states, whereas the controlling automaton \hat{A} treats activities to produce the set of acceptable activities depending on safety requirements.

Our framework has different objectives and uses different approaches to those of model checking. Model checking techniques use a *bottom-up approach* — it verifies execution traces Σ^* at the lower level L_1 to prove the correctness and safety of the system model A at the middle level L_2 (see Fig. 3). However, our proposal uses a *top-down approach* — we model safety requirements as acceptable sequences of transitions (δ^*) at the higher level L_3 to ensure the correct use of A . Then any execution trace (at L_1) that conforms to the meta-composition C is definitely a safe execution. The two techniques are complementary. Model checking may be used to reduce the design fault likelihood, and our approach can be applied to avoid behavior that are not in accordance with some critical safety requirements.

This paper continues our work on *C-Systems* (formal language control systems). In [20], we actually proposed the *input/output C-System*. The *context-free C-System* was proposed in [21] for restricting the use of modeling languages, in order to ensure guidelines and consistency rules of UML.

In the future, it might be a good direction to study the formalization of parameterized safety constraints. Another direction is empirical case study on applying this formalism in large and complex systems.

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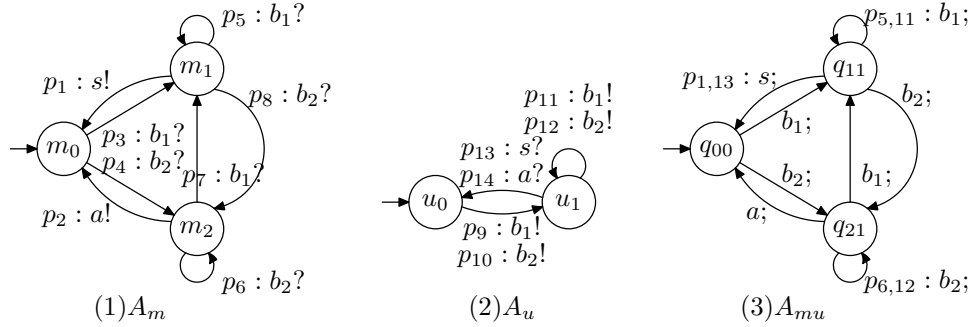


Figure 5. Automata of the Candy Machine System

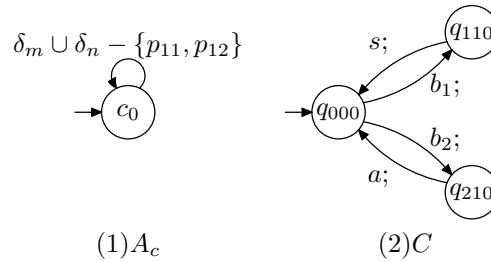


Figure 6. A Safety Constraint of the Candy Machine System

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