High-Assurance Separation Kernels: A Survey on Formal Methods

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Separation kernels provide temporal/spatial separation and controlled information flow to their hosted applications. They are introduced to decouple the analysis of applications in partitions from the analysis of the kernel itself. More than 20 implementations of separation kernels have been developed and widely applied in critical domains, e.g., avionics/aerospace, military/defense, and medical devices. Formal methods are mandated by the security/safety certification of separation kernels and have been carried out since this concept emerged. However, this field lacks a survey to systematically study, compare, and analyze related work. On the other hand, high-assurance separation kernels by formal methods still face big challenges. In this paper, an analytical framework is first proposed to clarify the functionalities, implementations, properties and standards, and formal methods application of separation kernels. Based on the proposed analytical framework, a taxonomy is designed according to formal methods application, functionalities, and properties of separation kernels. Research works in the literature are then categorized and overviewed by the taxonomy. In accordance with the analytical framework, a comprehensive analysis and discussion of related work are presented. Finally, four challenges and their possible technical directions for future research are identified, e.g. specification bottleneck, multicore and concurrency, and automation of full formal verification.

CCS Concepts: •Software and its engineering → Operating systems; Formal methods; •Computer systems organization → Real-time operating systems; •Security and privacy → Formal methods and theory of security;

General Terms: Design, Security, Verification

Additional Key Words and Phrases: Separation Kernel, Formal Methods, Survey, Formal Specification, Formal Verification, Security, Safety

1. INTRODUCTION

High-assurance systems require compelling evidences to show that their delivered services satisfy critical properties, e.g. security and safety [McLean and Heitmeyer 1995]. If high-assurance systems fail to meet their critical requirements, it could result in security breaches, loss of lives, or significant property damage. Due to the criticality of such systems, it is highly desired that they are developed in a rigorous process. The avionics community has developed a set of guidelines for the rigorous development of safety-critical systems, e.g., DO-178B/C [RTCA, Inc. 1992; RTCA, Inc. 2011]. Whilst the Common Criteria (CC) [National Security Agency 2012] provides guidelines for security-critical systems. In high-assurance systems, Trusted Computing Base (TCB) [Department of Defense 1985] is defined as: “A small amount of software and hardware that security depends on and that we distinguish from a much larger amount that can misbehave without affecting security [Lampson et al. 1992]”.

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The concept of separation kernel is introduced [Rushby 1981] to dissociate the kernel verification from the verification of trusted code belonging to separated components. The main purpose of separation kernels is to enforce the separation of all software components while reducing the size of the TCB. Security is carried out partly by separating physically system components, and partly by means of trusted functionality accomplished within some of those components being separated. The concept of separation kernel originates the Multiple Independent Levels of Security/Safety (MILS) [Jim et al. 2006] which is a high-assurance security/safety architecture based on separation [Rushby 1981] and controlled information flow [Denning 1976]. Separation kernels first came into use in the avionics domain, with the acceptance of Integrated Modular Avionics (IMA) [Parr and Edwards 1999] in this domain in the 1990s. A significant foundation of IMA is the separation of system resources into isolated computation spaces – called partitions. Separation kernels are adopted as partitioning kernels [OpenGroup 2003], which mainly concerns safety.

Separation kernels can be considered as a fundamental part of high-assurance systems. As a part of the TCB, separation kernels are small enough to allow formal verification of their correctness. The increasing evidences show successful applications of formal methods on software development, not only as theoretical research in the academy, but also deployed in industrial applications [Woodcock et al. 2009]. Traditionally, certified security is achieved by CC evaluation [National Security Agency 2012], in which formal methods are mandated for highest assurance levels. It requires comprehensive security analysis using formal representations of the security model and functional specification as well as formal proofs of correspondence between them. In particular, the Separation Kernel Protection Profile (SKPP) [National Security Agency 2007] is an instantiated profile of CC for separation kernels. Safety is usually governed by RTCA DO-178B [RTCA, Inc. 1992] whose successor DO-178C [RTCA, Inc. 2011] published in 2011 includes a technology supplement of formal methods.

Due to the wide application of high-assurance systems, applying formal methods on separation kernels has not only been a hot research topic since the concept emerged, but also attracted industrial concerns. Although more than 20 implementations have been developed in industry or academia, and furthermore formal methods have been applied on some of them for the purpose of CC and DO-178B/C certification, high-assurance separation kernels still face challenges [Barhorst et al. 2009; Alan and Robert 2015; D-MILS 2014]. The approaches and techniques of formal methods for separation kernels are numerous, but the topic lacks a state of the art survey and a comprehensive taxonomy to ease the application of formal methods over them. It is therefore significant and urgent to have a thorough and comprehensive study on this topic to provide a useful reference for further research and industrial applications. To the best of our knowledge, our work is the first to systematically overview, categorize, analyze and discuss formal methods application on separation kernels.

This paper aims at distilling the landscape in the field of formal methods application on separation kernels by studying, classifying, comparing, and analyzing related work for the purpose of figuring out challenges and potential research directions in future. Specifically, we present the following contributions in this paper:

(1) We propose an analytical framework to understand and classify related work. In the framework, we clarify a set of concepts related to separation kernels, define a reference architecture, compare implementations, study critical properties and related standards, and then identify an application schema of formal methods for separation kernels. The analytical framework is the foundation of this survey.

(2) We propose a taxonomy of applying formal methods on separation kernels according to the analytical framework. The first level of the taxonomy is designed according to the application schema of formal methods. The lower levels are based on the reference architecture and critical properties. Then, we group together the related work according to the taxonomy.

(3) We present a detailed analysis and discussion of the related work. We compare formal methods and certifications used in a comprehensive set of implementations. The importance of functionalities in the reference architecture is identified in formal specifications and models. Relations among
critical properties are clarified. The verified properties, used approaches, and sizes of research works on formal verification are compared. Then, we give an overall comparison of them according to the taxonomy.

(4) We discuss the challenges of applying formal methods on separation kernels and figure out potential research directions in this field. We identify four challenges, i.e., eliminating specification bottleneck, automating full formal verification, multicore and concurrency, and formal development and code generation. Then, we propose technical directions to address each challenge in future.

Compared to our previous work [Zhao et al. 2016c], contributions (1), (3), (4) and the proposed taxonomy in contribution (2) in this paper are new. The detailed description of research works in [Zhao et al. 2016c] is reorganized by the taxonomy and shortened to a brief overview of related work in contribution (2). The previous work is also extended by the research works of two new categories under the taxonomy. The rest of this paper is organized as follows. Section 2 presents the analytical framework. Section 3 presents the taxonomy and overview of research works in the literature. In Section 4, we analyze and discuss the research works through comprehensive comparisons. Section 5 identifies challenges and potential technical directions in this field. Finally, Section 6 gives the conclusion of this survey.

2. ANALYTICAL FRAMEWORK

In this section, we present an analytical framework for separation kernels. The framework is the foundation of the taxonomy, analysis and discussion in the next sections. First, we clarify a set of related concepts and propose a reference architecture for separation kernels in which common and optional components are identified. Second, we survey implementations from industry and academia. Third, we classify critical properties of separation kernels and survey related standards. Finally, we sketch out an application schema of formal methods for high-assurance separation kernels.

2.1. Concepts and Reference Architecture

We first clarify the relationship among concepts of security kernel, separation kernel, partitioning kernel, microkernel, and embedded hypervisor, which is shown in Fig. 1. The security kernel [Ames Jr et al. 1983] is the central part of systems to implement the basic security procedures for controlling access to system resources. Security requirements of systems to be assured are specified as security policies. A reference monitor controls the access of subjects to resources according to the policies. Separation kernels extend security kernels with partitions and map exported resources into partitions. Separation kernels enforce partitions to have spatial and temporal separation, and allow subjects belonging to partitions to cause flow to transfer information among them. The partitioning kernel [Rushby 2000; OpenGroup 2003; Leiner et al. 2007] is a variant of separation kernels in the domain of IMA and concerns safe separation largely based on an ARINC 653 [Aeronautical Radio, Inc. 2013] style separation scheme. Partitioning kernels specialize and enhance the temporal
and spatial separation with a static table-driven scheduling approach [Ramamritham and Stankovic 1994] and static resource allocation for partitions.

Unlike traditional operating systems, separation kernels do not provide services such as device drivers and file systems, but a set of very specific functionalities to enforce security separation and information flow controls, in order to keep them small enough to allow formal verification of their correctness. The primary motivation of these kernels is also the one behind microkernels [Wulf et al. 1974; Jochen 1993; Hohmuth et al. 2004]. In terms of the source code size, these kernels are usually sizing less than 10,000 lines of code, which is the code scale of microkernels. On the other hand, with the rise of more powerful multiprocessor embedded systems, virtualization provides a promising technique to improve functionalities of high-assurance systems [Heiser 2008; Aguiar and Hessel 2012]. Embedded hypervisors are consequently used to implement security kernels (e.g. [Paul 2005; Sailer et al. 2005a; Sailer et al. 2005b]), separation kernels (e.g. [XtratuM 2015; West et al. 2016]), and partitioning kernels (e.g. [VanderLeest 2010; Han and Jin 2011; VanderLeest et al. 2013]).

Due to the increasing complexity, scale, and mixed critical requirements of high-assurance systems, various techniques and approaches are integrated [Barhorst et al. 2009] together. From now on, we use the term separation kernel to cover the concepts of security kernel, original separation kernel, partitioning kernel, and embedded hypervisor. Based on the landscape of separation kernels, we propose a reference architecture, as shown in Fig. 2, for separation kernels to provide functionalities to analyze research works. We classify the functionalities into common and optional components. Common components represent a least set of functionalities to implement a separation kernel. Optional components are usually supported for complex systems. Hypervisor-based separation kernels usually manage partitions (i.e., VMs) and leave process management to guest OSs. The communication mechanism supports inter- and intra-partition communication. Policies may be security, safety, real-time, and fault-tolerance policies, etc. The configuration for separation, such as memory separation configuration and scheduling windows for partitions, can also be considered in the policies. Management of hardware (e.g. clock, timer, interrupt, and memory) are necessary for hypervisor-based separation kernels. However, simple separation kernels manipulate the underlying hardware via hardware interface.
2.2. Separation Kernel Implementations

Due to the wide acceptance of separation kernels, many implementations including industrial products and academic prototypes have been developed in recent years. In Table I, we compare twenty implementations from industry and academia. The time line in the 3rd column shows the time they started and the time they stopped development of the separation kernels. The underlying instruction set architectures (ISA) and whether they support multi-core processors are surveyed in columns 4 and 5, respectively. We also survey the development languages, the line of the code (LOC), and whether they are open-source.

By comparing these implementations, we have the following findings.

— Most of the separation kernels are still in use and developing. Very few open-source projects have stopped.

Table I. Comparison of Separation Kernel Implementations

| No | Name | Timeline | ISA | Multi Core | Language | LOC | Open Source |
|----|------|----------|-----|------------|----------|-----|-------------|
| 1  | PikeOS [SYSGO 2015] | ? - now | PowerPC, x86, ARM, MIPS, SPARC | ✓ | C, ASM | <10k | ✓ |
| 2  | VxWorks 653 [WindRiver 2015a] | ? - now | PowerPC | ✓ | C, ASM | ? | ✓ |
| 3  | VxWorks MILS [WindRiver 2015b] | ? - now | PowerPC | ✓ | C, ASM | ? | ✓ |
| 4  | INTEGRITY-178B [GreenHills 2015a] | ? - now | ARM, x86, PowerPC, MIPS | ✓ | C, ASM | ? | ✓ |
| 5  | INTEGRITY Multitvisor [GreenHills 2015b] | ? - now | x86, ARM, PowerPC | ✓ | C, ASM | ? | ✓ |
| 6  | LynxSecure [Lynx 2015b] | ? - now | x86 | ✓ | C, ASM | ? | ✓ |
| 7  | LynxOS-178 [Lynx 2015a] | ? - now | x86 PowerPC | ✓ | C, ASM | ? | ✓ |
| 8  | DDC-I Deco [DDC-I 2015] | ? - now | x86, PowerPC, ARM, MIPS | ✓ | C, ASM | ? | ✓ |
| 9  | AAMP72 [Collins 2015] | 2001 - now | N/A | ✓ | ? | ✓ |
| 10 | ED [Heitmeyer et al. 2006;2008] | 2006 - ? | ? | C, ASM | ≈ 3k | ✓ |
| 11 | ARLX hypervisor [Genesys 2015] | ? - now | x86, ARM | ✓ | C, ASM | ? | ✓ |

Industrial Implementations

Academic Implementations

12 scL4 [Murray et al. 2012;2013] | 2008 - now | ARM,x86 | ✓ | C, ASM | ≈ 9k | ✓ |
13 OKL4 Microvisor [Systems 2015] | 2009 - now | ARM | ✓ | C, ASM | ? | ✓ |
14 XtratuM [XtratuM 2015] | 2004 - now | SPARC, x86, PowerPC, ARM | ✓ | C, ASM | ≈ 9k | ✓ |
15 PROSPER [PROSPER 2015] | 2012 - now | ARM | ✓ | C, ASM | ? | ✓ |
16 Xenon [Freitas and McDermott 2011] | 2011 - ? | x86, ARM, PowerPC | ✓ | C, ASM | ? | ✓ |
17 Quest-V [West et al. 2016] | 2012 - now | x86 | ✓ | C, ASM | ? | ✓ |
18 Muen [Muen 2015] | 2013 - now | x86 | ✓ | SPARK, ARM | ≈ 4k | ✓ |
19 POK [POK 2015] | 2009 - 2013 | PowerPC, SPARC, x86 | ✓ | C, ASM | ≈ 7k | ✓ |
20 AIR/AIR II [AIR 2015] | 2007 - 2011 | SPARC | ? | C, ASM | ? | ✓ |

? means we do not find any literature to show the evidence.

This is a processor, a hardware implementation of separation kernel.
In order to provide safety/security critical solutions, various ISAs are supported by separation kernels, in particular ARM, SPARC, and PowerPC. Multicore processors are increasingly deployed in safety/security critical systems to fulfill the demand of processing power in integrated systems. Therefore, multicore processors are supported by most of separation kernels regardless of in industry and academia.

The LOC of separation kernels that we can find in the literature is less than ten thousand. Most of implementations adopt microkernels as the foundation and shift out the complex services into system partitions. For the sake of portability and efficiency, separation kernels in particulars are written in the C programming language embedded with pieces of ASM. Moreover, separation kernels in academia are usually delivered in open-source projects.

With the trend of integrating applications on one computing platform (e.g., IMA), native interference provided by separation kernels is often not powerful for application development. The embedded hypervisor is currently a mainstream form of separation kernels in industry and academia. Virtual machine management provides a straightforward approach for the spatial separation of resources. Moreover, embedded hypervisors virtualize general-purpose operating systems (e.g., Linux) in partitions and permit the deployment of legacy applications.

### 2.3. Critical Properties and Standards

Traditionally, critical properties of high-assurance systems are safety, security, real-time, and fault-tolerance [McLean and Heitmeyer 1995; Rushby 1994]. Different from the classical categories of critical properties, NEAT are well known properties considered in separation kernels, which stands for “Non-bypassable, Evaluatable, Always invoked and Tamper” proof [Vanfleet et al. 2005; OpenGroup 2003]. However these intuitive concepts are not easy to formalize nor to provide direct proofs. Instead, separation kernels are normally verified by formally showing that they provide the right functionalities for MILS systems according to the following critical properties [Jim et al. 2006; Vanflelt et al. 2005; Rushby 2000], which is called DIDT in this survey.

- **Data Separation**: Also known as ‘Data Isolation”, each partition is deployed as a separated resource. Applications in one partition can neither modify applications and private data in other partitions nor control private devices and actuators in other partitions.

- **Information Flow Security**: Also known as “Control of Information Flow”, information flow between partitions is defined from a source partition, which is authenticated, to a set of receivers as well authenticated; additionally, the source is authenticated to the receivers.

- **Temporal Separation**: it allows partitions to share physical resources across different time periods. A resource is assigned to one component for a slice of time, then sanitized and assigned to another component. Services received from shared resources by applications in one partition cannot be affected by other partitions.

- **Damage Limitation**: damage is contained by restraining failures from propagating from one partition to others.

The properties of data separation, information flow security, and damage limitation are all spatial properties. They are collectively called “spatial separation” properties. Data separation requires memory address spaces/data of one partition to be independent of any other partition in the system. Information flow security is a variation of data separation. Pure data separation is not pragmatic, therefore separation kernels define authorized channels between partitions to provide inter-partition communication. Pure data isolation is permitted to be violated only through these channels. Damage limitation is achieved by other three properties since the damage to applications in one partition are limited.

Due to criticality of high-assurance systems, there are mandatory verification and validation (V&V) activities in their design and analysis process to ensure that the systems fully meet their functional requirements. Several specifications have been created to standardize activities in V&V processes by international organizations. CC [National Security Agency 2012], which is also the international standard ISO/IEC 15408, and SKPP [National Security Agency 2007] are usually ap-
Table II. Critical Properties and Standards

| Property        | Standards                      | Spatial Separation | Temporal Separation |
|-----------------|--------------------------------|--------------------|---------------------|
| Safety          | DO-178B/C, ARINC 653, IEC 61508, EN 50128 | ✓                  | ✓                  |
| Security        | CC, SKPP                        | ✓                  | ✓                  |
| Real-time       | ARINC 653                       | ×                  | ×                  |
| Fault-tolerance | ARINC 653                       | ✓                  | ×                  |

✓ means a DIDT property contributes to improve the assurance of a traditional critical property.

Fig. 3. Application Schema of Formal Methods on Separation Kernels.

2.4. Application Schema of Formal Methods

In software engineering, formal methods provide a set of mathematically based techniques and tools to specify, develop, and verify software systems [Clarke and Wing 1996; Bowen and Hinchey 2006]. We depict an application schema of formal methods on separation kernels in Fig. 3, in which the artefacts and techniques are identified.

Formal specification uses languages with a rigorous syntax and semantics to give a precise description of the system and its desired properties. Informal requirements may be translated into properties of the system specification. The system specification would further have formal description of system behavior, which is translated from the informal design. Formal specification can be used to validate the completeness and accuracy of the system requirements and to guide subsequent development activities. Formal specification may be refined to high-level, low-level,
Table III. Common Criteria Evaluation Levels and Requirements of Formal Methods

| Common Criteria | Requirement | Functional Specification | High-Level Design | Low-Level Design | Implementation |
|-----------------|-------------|--------------------------|-------------------|------------------|----------------|
| EAL 1 – 4       |            |                          |                   |                  |                |
| EAL 5           | ✓           |                          |                   | ✓                |                 |
| EAL 6           | ✓           |                          |                   | ✓                | ✓              |
| EAL 7           | ✓           | ✓                        | ✓                 | ✓                | ✓              |

Formal methods level of software artefacts: ◯: informal; ●: semiformal; ●: formal

and implementation models step by step and furthermore be used for formal synthesis of implementations.

— Formal verification is the act to ensure the correctness of intended systems with respect to a certain formal specification or property. One approach of formal verification is model checking, which systematically and exhaustively explores the mathematical model to check satisfaction of properties. Another one is theorem proving, whose first step is to generate a collection of proof obligations from the system and its specifications. The truth of the proof obligations implies the conformance of the system to its specification. The second step is to discharge the proof obligations in an interactive or automated manner.

— There are two approaches to formal verification of separation kernels at the implementation level: theorem proving the implementation model by abstraction from source/binary code, and software model checking [Jhala and Majumdar 2009].

Many security and safety standards currently mandate the use of formal methods to certify correctness of separation kernels. The Common Criteria defines clear treatment of software artefacts for different evaluation levels, which is shown in Table III. The evaluation through CC defines Evaluation Assurance Levels (EAL) from EAL 1 to EAL 7 (formally verified, designed and tested). The EAL 7 mandates formal verification of the low-level design model using mathematical models and theorem proving. As a specific profile of CC, SKPP mandates formal methods on separation kernels too. DO-178C has a formal methods supplement (DO-333) to address formal methods to complement testing. IEC 61508 defines functional safety and methods for electronic systems. Certification of Safety Integrity Level (SIL) 4 in this standard highly recommend the use of formal methods.

3. TAXONOMY OF APPLYING FORMAL METHODS ON SEPARATION KERNELS

We first propose a taxonomy of applying formal methods on separation kernels in this section. The taxonomy is to group together related work that share common objectives and characteristics to yield clear category formation and easier comparative analysis. Then, we overview the related work using the proposed taxonomy.

3.1. Taxonomy

The taxonomy is designed based on the analytical framework and is shown in Fig. 4. Level 0 is the root element. Level 1 of the taxonomy is designed according to the application schema of formal methods on separation kernels (see Fig. 3). Level 2 is designed considering the functionalities in the reference architecture (see Fig. 2), critical properties, and implementations. The subcategories of “Formal Specification and Model of SKs” are designed by considering functionalities in the reference architecture. The subcategories of “Formalization of Critical Properties” and “Formal Verification of SKs” are designed using the critical properties of separation kernels. Since the “damage limitation” property is enforced indirectly by the other three properties, there is no related work of formalization and formal verification of this property, and we omit it in our taxonomy. From the implementations of separation kernels (see Table I), we could see that they are almost developed using the C programming language. Thus, beside binary code we only consider code abstraction from the C language in the category “Code Abstraction of SKs”. We discuss research works on each category in the following subsections.
3.2. Formal Specification and Model of SKs (Category 1)

This subsection overviews research works about formal description of functionalities of separation kernels. Except kernel interface and policies in Fig. 2, we group research works of other functionalities into the category “functional specification and model”.

3.2.1. Policy Model (Category 1-a). A formal policy is a kind of formal specification to describe what the system allows and prohibits. Formal policies of separation kernels actually define the security/safety requirements and can be categorized according to the critical properties. The policies are usually configured during system built-time and loaded during initialization of separation kernels.

Data separation policy defines strict data separation that does not allow data exchange between partitions. These policies include memory separation, device separation, etc. For instance, ARINC 653 defines a set of partitions and a static memory allocation policy for them [Aeronautical Radio, Inc. 2010].

The inter-partition flow policy (IPFP) [Levin et al. 2007] is a sort of information flow policy for separation kernels on MILS. Separation kernels map exported resources (e.g., communication objects) into partitions by a function \( resource\_map : resource \rightarrow partition \). IPFP is expressed abstractly in a partition flow matrix \( partition\_flow : partition \times partition \rightarrow mode \), whose entries indicate the mode of the flow. The mode indicates the direction of the flow, e.g. “Write” and “Read”. Resources from a partition are addressed equivalently with respect to IPFP. One partition can be allowed to access all resources in another partition. Another type of IPFP is port and channel based information flow used in ARINC 653. Partitioned information flow policy (PIFP) [Levin et al. 2010] extends IPFP in SKPP with two different granularities of requirements: partitions and subjects/resources. This abstraction allows subjects from a partition to have different access privileges to resources allocated in the same partition or even in a different partition.

Fault policy is a type of damage limitation policy. A typical fault policy for separation kernels is the health monitoring (HM) in ARINC 653. The HM reports and responds to hardware, kernel, and application faults and failures. ARINC 653 supports HM by providing a set of hierarchical HM configuration tables and application level error handlers. Scheduling policy is a type of temporal separation policy. A typical scheduling policy for separation kernels is the partition time window configuration in ARINC 653. The scheduling specified in ARINC 653 is a two-level scheduling. The partition scheduling is a fixed, cycle based scheduling and is strictly deterministic over time. This cyclic scheduling consists of a major time frame (MTF) that is split into partition time windows (PTW). Each PTW has an offset and a duration, which is associated to a given partition.

3.2.2. Functional Specification and Model (Category 1-b). We overview a set of formal specifications and models of separation kernels here. Refinement is often applied to create concrete models from abstract specifications in a step-wise manner. We categorize research works according to specification languages used, i.e. system/software specification languages, formal languages in theorem provers, and architecture description languages.
Using system/software specification languages. A specification language is a high-level language other than a programming language for system analysis and design and to produce executable code. Many specification approaches use algebraic or model-theoretic structures to model systems step by step by refinement. In the following we describe related work using software specification languages, such as Z notation, B method, and Alley, to construct formal specifications of separation kernels.

Craig [2007] concerns entirely with the specification, design, and refinement of operating system kernels in Z [Abrial et al. 1980], one of which is a separation kernel. Refinement goes down to a level where source code in programming languages (e.g., C and Ada) can be extracted from Z specification. The specification and proofs are done by hand on paper. This work is upgraded in [Velykis and Freitas 2010] by taking into account separation kernel requirements in [Rushby 1981] and SKPP [National Security Agency 2007]. Craig’s original specification is augmented using Z notation [Jim and Jim 1996] mechanizing it using the Z/Eves theorem prover. As a consequent, syntax errors, missing invariants and new security properties to guarantee correct operations are found.

The B Method [Abrial 1996] has been used to formally specify a secure partitioning kernel (SPK) in [André 2009]. The high-level specification constitutes a complete architectural design of the system and is simulated and validated in ProB [Leuschel and Butler 2003]. The PIFP policy is refined to a level from which C code can be automatically generated. Finally, an open source micro kernel, i.e., PREX, is adopted to integrate the PIFP implementation. Major functionalities of the OS-K separation kernel [Kawamorita et al. 2010], such as partition management, inter-partition communication, access control, are also designed in the B method. Proof obligations are generated and checked using the B4free tool. Almost the whole totality of the 2,700 proof obligations comprising the verification are automatically proven using B4free.

Aiming at least privilege separation kernel (LPSK), Phelps et al. [2008] develop a formal security policy model and a top-level specification in Alloy [Jackson 2012]. They utilize the Alloy Analyzer to verify the consistency of the specification. The top-level specification is a refinement of the PIFP policy model and uses state transitions to model two separation subsystems of LPSK, system initialization and the system during runtime. In [Martin et al. 2000; Martin et al. 2002], three levels of abstraction and refinement are used to formally develop the MASK separation kernel in SPECWARE, which is an environment for formal specification and development. The abstract specification refines the MASK policies and concerns the communication among Cells using strands, which is a flow of instructions that are executed when a message is inserted into the strand of a cell. It is refined to the kernel specification primarily concerning the data structure. Finally, the bottom layer specification is manually translated into C source code. For the purpose of information flow security of the Xenon hypervisor [McDermott and Freitas 2008], Freitas and McDermott [2011] use Circus to formally model the hypercall interface behaviour of Xenon. Circus [Oliveira et al. 2009] is a combination of Z, CSP and the refinement calculus. The whole model covers a subset of the hypercall interface and is over 4,500 pages of Circus.

Using theorem provers. Theorem provers (e.g. Isabelle/HOL, Coq) generally have a small logical kernel, provide powerful expressive languages for specification, and support reasoning about higher-order logic. They have been applied for formal verification of operating system kernels, such as seL4 [Klein et al. 2009; Klein et al. 2014] and CertiKOS [Gu et al. 2015]. Inspired by successful application of theorem provers on general-purpose microkernels, they are adopted on kernels in recent years.

The formal verification of the seL4 microkernel has been done using Isabelle/HOL [Nipkow et al. 2002]. The Isabelle/HOL specification of seL4 is extended in [Murray et al. 2013] to formally verify information flow security of seL4. In order to act as a separation kernel, seL4 is minimally extended by a static partition-based scheduler implementing a static round-robin scheduling between partitions, which are assigned fixed execution time slices. They also make small changes in the kernel APIs and add the security policy. Aiming at a precise model of PikeOS and a precise formulation
of the PikeOS security policy, the EURO-MILS project [EUROMILS 2015] creates a generic specification of separation kernels – Controlled Interruptible Separation Kernel (CISK) [Verbeek et al. 2014] in Isabelle/HOL. This specification contains several facets that are useful to implement separation kernels, such as interrupts, context switches between domains, and control. The specification is rich in detail, making it suitable for formal verification of realistic and industrial systems. Sanán et al. [2014] construct in Isabelle/HOL the functional and security model of a generic partitioning separation microkernel from a reference specification based on European Space Agency’s IMA for Space project [Windsor et al. 2011]. The specification uses ARINC 653 for the functional requirements and SKPP for the security requirements. Aiming at implementations, the specification covers hardware virtualization, CPU timer, and memory management too. Zhao et al. [2016b] present a top-level specification of ARINC 653 compliant separation kernels in Isabelle/HOL, in which partition management, partition scheduling and communication services of ARINC 653 are considered.

The Coq specification of CertiKOS in [Gu et al. 2015] is modified to disable all explicit inter-process communication and thus formed as a separation kernel without information flow among processes [Costanzo et al. 2016]. Alves-Foss et al. [2002] use the concept of virtual machine for separation and provide a formal model of a multi-partition systems (MPS) by ACL2 [Kaufmann et al. 2013]. Several different models of MPS are presented, including a two-partition system without communication between partitions and an n-partition system with restricted communication.

Using architecture description languages (ADLs). In general, ADLs concentrate on system level and are not fine-grained enough to formally specify separation kernels. However, formal models of separation kernels in ADLs could support model-driven development of applications. In [Singhoff and Plantec 2007], AADL (Architecture Analysis and Design Language) and Cheddar [Singhoff et al. 2004] are applied to model an ARINC 653 hierarchical scheduler and to analyze the schedulability of applications represented by AADL specifications, respectively.

3.2.3. Interface Specification (Category 1-c). The kernel interface defines operating system services provided to applications. Formalization of the kernel interface could support formally modeling and verification of application software on top of separation kernels.

Formalization and verification of ARINC 653 has been conducted in recent years, such as a formal specification considering the architecture of ARINC 653 systems [Oliveira Gomes 2012], modeling ARINC 653 for IMA applications [Wang et al. 2011; Delange et al. 2010], and verification of application software on top of ARINC 653 [de la Cámara et al. 2011]. Zhao et al. [2015] have formalized the system functionality and all of the 57 services specified in ARINC 653 Part 1 using Event-B [Abrial and Hallerstede 2007]. They use the refinement structure in Event-B to formalize ARINC 653 step by step and a semi-automatic translation from service requirements of ARINC 653 into the low level specification.

The formal API specification of PikeOS in Isabelle/HOL has been provided aiming at the certification of PikeOS up to CC EAL6 evaluation [Verbeek et al. 2015]. Their specification is based on CISK [Verbeek et al. 2014], which is instantiated to PikeOS API in detail. The formal API specification covers inter-partition communication, memory, file provider, port, and event.

3.3. Formalization of Critical Properties (Category 2)

Formal specification and model of separation kernels are verified with respect to critical properties. This subsection overviews the formal definition of critical properties and their sub-properties.

3.3.1. Data Separation (Category 2-a). Data separation requires resources of a partition to be independent from resources from other partitions. Pure data separation is too strong since it does not permit communications among partitions. This property is relaxed in MASK [Martin et al. 2000; Martin et al. 2002] and GWV [Matthew et al. 2003]. In the project of Mathematically Analyzed Separation Kernel (MASK) [Martin et al. 2000; Martin et al. 2002], communication between processes is regulated based on a separation policy, which is comprised of two separation axioms: a communication policy and an anonymous policy. The communication policy states that if a cell y
is modified as the result of performing a step on a cell $x$, then there is an allowed communication between $x$ and $y$. The second policy requires that the execution of an action in a cell $x$ modifies the state of the cell $y$, then any modification in $y$ has to depend only on $x$ and $y$. Based on the MASK data separation, Matthew et al. [2003] propose the GWV property to model a separation kernel that enforces partitioning on applications running on mono-processors systems. The GWV property requires that the execution of a machine step modifying any arbitrary memory segment follows a mapping from the set of memory areas bound to the current partition and that are allowed to interact that memory segment. Matthew et al. [2003] also define the exfiltration and infiltration properties for memory segments of partitions, which are special cases of the GWV property. The exfiltration and infiltration properties are similar to the communication policy and the second property of MASK respectively. Heitmeyer et al. [2008] apply the two axioms of MASK on the ED (Embedded device) separation kernel and define the no-exfiltration and no-infiltration properties for CC certification.

The GWV property has been accepted in industry [GreenHills 2008; Greve et al. 2004; Greve 2010] and formalized using the PVS theorem prove in [Rushby 2004]. The original GWV is weakened by allowing to connect memory areas belonging to the same partition in [Alves-foss and Taylor 2004]. It is also extended by the concept of subject and adding a restriction considering partition names in [Tverdyshev 2011]. A subject is an element operating on memory areas of a partition. The GWV property has been applied in formal analysis for the INTEGRITY-178B separation kernel [Richards 2010] and AAMP7 Microprocessor [Greve et al. 2004; Wilding et al. 2010].

Data separation of separation kernels at the hardware level is the separation of the system’s memory. In [Baumann et al. 2011], the memory separation of the PikeOS separation kernel is defined as “All memory accesses in the kernel preserve an initial disjoint partitioning of memory, and obey a security policy where a thread is only allowed to access memory from its assigned partition.” It is preserved by a set of assertions for function contracts.

3.3.2. Information Flow Security (Category 2-b). Information flow security deals with the problem of preventing improper release and modification of information in complex systems. Traditionally, language-based information flow security [Sabelfeld and Myers 2003] defines security policies of computer programs and ensures the data confidentiality by preventing information leakage from High variables to Low ones. Language-based information flow security is often not applicable for system-level security, because (1) in many cases it is impossible to classify High and Low variables; (2) data confidentiality is a weak property and is not enough for system-level security; and (3) language-based IFS is not able to deal with intransitive policies straightforwardly. Therefore, state-event based noninterference [Rushby 1992; von Oheimb 2004], which can deal with data confidentiality and secrecy of events together, is usually adopted in formal verification of separation kernels and microkernels [Murray et al. 2012]. We focus on state-event based properties in this paper.

The concept of noninterference was introduced in [Goguen and Meseguer 1982] for the purpose of the specification and analysis of security policies. The system is configured by a set of domains and the allowed information flow between them are specified by an information flow policy $\sim$, such that $u \sim v$ if information is allowed to flow from the domain $u$ to the domain $v$. The intuitive meaning of noninterference is that a security domain $u$ cannot interfere with a domain $v$ if no action performed by $u$ can affect the observation of $v$ to the system. Transitive noninterference is too strong and not able to model channel-control policies. Thus, intransitive noninterference is introduced in [Rushby 1992] as a declassification of transitive one. Based on noninterference in [Rushby 1992], von Oheimb [2004] proposes new notions, nonleakage and no-influence. Nonleakage is a state-event representation of language-based information flow security for arbitrary multi-domain policies. No-influence is the combination of nonleakage and intransitive noninterference. Intransitive noninterference and its new forms are usually chosen to formally verify information flow security of general purpose operating systems [Murray et al. 2012] and separation kernels [Murray et al. 2013]. Due to the scheduler in kernels, Murray et al. [2012] define special cases of nonleakage and noninfluence for operating systems. Properties of information flow security have been formally
verified on seL4 [Murray et al. 2013], PROSPER [Dam et al. 2013], PikeOS [Verbeek et al. 2015], mCertiKOS [Costanzo et al. 2016], and ARINC 653 [Zhao et al. 2016b].

The standard proof of the noninterference property is discharged by examining a set of unwinding conditions [Rushby 1992] on individual execution steps of the system. The unwinding theorem states if the system is output consistent, step consistent and locally respects the policy →, the system is secure for →. The three conditions are called unwinding conditions. The unwinding theorem simplifies the security proofs by decomposing the global properties into unwinding conditions on each execution step.

3.3.3. Temporal Separation (Category 2-c). Temporal separation usually includes sanitization/period processing and correct scheduling. Heitmeyer et al. [2008] define a sanitization property (called Temporal Separation) on the ED separation kernel. The property ensures that the data areas of a partition are cleaned when the system is switched to process data in other partitions. As for period processing, time partitioning used in formal verification of DEOS scheduler [Penix et al. 2000; Penix et al. 2005; Ha et al. 2004; Cofer and Rangarajan 2002] ensures that the access to CPU time budget by a partition cannot be affected by the execution of other partitions. Properties of correct scheduling are various according to different scheduling policies such as in [Asberg et al. 2011].

3.4. Formal Verification of SKs (Category 3)

This subsection overviews research works about formal verification of separation kernels. We categorize the works by critical properties.

3.4.1. Data Separation Verification (Category 3-a). For the purpose of CC evaluation, Heitmeyer et al. [2006; 2008] provide a pragmatic solution to verify data separation of the ED separation kernel at the source code level. The kernel contains 3,000 lines of C and assembly code. To simplify the verification, the code is annotated in advance using Hoare and Floyd pre-post conditions. A top-level state machine is formally verified by data separation in TAME, which is a front end to the PVS theorem prover. Then the source code is partitioned and demonstrated to conform to the state machine by refinement. The effort of code verification is remarkably reduced since more than 90 percent of the source code is not corresponding to any behavior defined by the top-level state machine.

The AAMP7 microprocessors in Rockwell Collins is a hardware implementation of separation kernels. Their design is proven mathematically using the ACL2 theorem prover to achieve CC EAL 7 evaluation [Greve et al. 2004; Wilding et al. 2010]. The intrinsic partitioning in AAMP7 is an instantiation of the GWV property [Matthew et al. 2003]. An abstract model meeting the GWV policy and a low-level model corresponding to the AAMP7 microcode are created, and the refinement between them is also proved.

The INTEGRITY-178B separation kernel is formally analysed to obtain the EAL 6+ CC certification [Richards 2010]. They adopt GWV [Greve 2004] as the security policy and create three levels of specification, i.e., functional specification, high-level and low-level design, in ACL2. The functional specification is a formalization for the interfaces. The other two are semiformal representations of the system at different abstract levels. The low-level design has direct correspondence with the implementation, which simplifies the “code-to-spec” analysis during CC certification.

Tverdyshev [2011] presents a modular approach in Isabelle/HOL to the formal verification of the GWV property on the two layers of PikeOS. In the microkernel model, tasks and threads correspond to subjects and partitions in GWV respectively. A GWV segment is instantiated as a physical memory address. They add “partitions” to the model of the separation kernel to separate tasks and physical address. Memory separation of the PikeOS separation kernel has been formally verified on the source code level [Baumann et al. 2011] by breaking down high-level, non-functional requirements into functional properties of memory manager that can be presented as a set of assertions.

3.4.2. Information Flow Security Verification (Category 3-b). In the formal verification of the seL4 micro-kernel, to prove information flow security Murray et al. [2012] adopt the notions of nonleak-
age and noninfluence [von Oheimb 2004] and define their variations for OS kernels. The properties are formally verified on a revised specification of seL4 [Murray et al. 2013]. Because the properties are preserved by refinement, it is possible to first prove the information flow security property on the abstract model and then conclude that it holds for seL4’s C source code due to the refinement relation. The verification applies to the total 8,830 lines of C code of the kernel implementation.

Dam et al. [2013] have formally verified information flow security of a simple ARM-based separation kernel – PROSPER at the binary code level using HOL4. They construct the top level specification, which satisfies noninterference, and a real model, which consists of two partitions being executed on two independent machines targeting an ARMv7 processor, and connected by an explicit communication channel. They use the bisimulation proof method to show that user observable traces of the specification are the same as those of the real model. The approach avoids reliance on the correctness of a C compiler and can transparently verify C code mixing with assembly.

Explicit inter-process communication of mCertiKOS is disabled to form a strict separation kernel in which information flow among processes is not allowed. The noninterference property is verified in [Costanzo et al. 2016]. They use language-based information flow security and a well-designed observation function to express security at different abstract levels. A simulation preserves state indistinguishability between high and low levels. They develop a fully-formalized Coq proof to guarantee security of the assembly execution of mCertiKOS.

Noninterference has also been formally verified on the PikeOS API specification [Verbeek et al. 2015] and a top-level specification of ARINC 653 separation kernel [Zhao et al. 2016b] using unwinding conditions.

3.4.3. Temporal Separation Verification (Category 3-c). Here, we discuss research works about formal verification of two-level scheduler which implements the partition scheduling in separation kernels.

The Honeywell DEOS is a real-time operating system supporting flexible separation. Model checking and theorem proving approaches have been applied to the DEOS scheduler to check temporal separation [Penix et al. 2000; Penix et al. 2005; Ha et al. 2004]. A major part of C++ source code of the DEOS scheduler is first translated into Promela, which is the input language for the Spin model checker [Penix et al. 2000; Penix et al. 2005]. Time partitioning is represented as a liveness property. The verification techniques are augmented in [Cofer and Rangarajan 2002] by verifying the absence of a livelock, which means that time is not elapsing in any cycle that does not contain a system tick event. Due to its size and complexity, state space explosion makes only possible to check one single configuration in each analysis. Thus, they turn to theorem proving approach and use PVS to analyze the scheduler [Ha et al. 2004]. To model the scheduler and the execution timeline in DEOS the authors use discrete time state-transition systems. Additionally, Time partitioning is expressed as a number of predicates that are proven to be true for any reachable states.

The Real-Time Specification for Java (RTSJ) is modified implementing a two-level scheduler. The first scheduling level is a priority scheduler to dispatch applications, while the second belongs to the applications [Zerzelidis and Wellings 2006; Zerzelidis and Wellings 2010]. The verification of this two level scheduler is carry out using time automata in UPPAAL. From a total of five verified properties, three of them concern the model correctness and others are liveness and deadlock free properties. In [Asberg et al. 2011], a hierarchical scheduler for VxWorks has been modelled using task automata (timed automata with tasks) [Fersman et al. 2007] and automatically checked using the Times tool. They specify nine properties of the scheduler in TCTL (Timed Computation Tree Logic).

3.5. Code Abstraction of SKs (Category 4)

Formal verification of separation kernels down to their implementation or the binary code requires to provide a formal model for the semantics of the programming language or for the Instruction Set Architecture (ISA) of the target architecture, respectively. In this subsection, we overview the formal semantics and code abstraction of the C programming language and binary code.
3.5.1. Formal Semantics and Code Abstraction for C Language (Category 4-a). It is not until the end of the 1990’s that semantics covering a subset of C, large enough to make the verification of complex and large programs possible, have appeared. Norrish [1998] brings in Cholera – an operational semantics for C89 including the C type system. Cholera has been recently leveraged to construct the tools CParser and Autocorres [Greenaway et al. 2012], which have been applied in the seL4 microkernel [Klein et al. 2009; Klein et al. 2010] and separation kernel [Murray et al. 2013] to abstract the implementation model from the seL4 source code.

Papaspyrou [2001] develops a denotational semantics of C90, which is based on monads implemented in Haskell, and covers a large subset of C90. In the formal verification of the Nova hypervisor [Tews et al. 2008], they provide a denotational semantics for C++ which includes all the C++ primitive datatypes. As part of the Verisoft project [Alkassar et al. 2008], C0 which is a subset of the C language is formalized in Isabell/HOL. Blazy and Leroy [2009] develop Clight as part of the CompCert project [Leroy 2009]. Clight accepts most of the C types and operators, although it does not support the use of control flow instruction goto and blocks. Ellison and Rosu [2012] provide an executable semantics for C99 standard in the K-framework, which supports LTL model checking, and like the semantic model in [Papaspyrou 2001], it is not mechanized. They provide a semantic model for almost all of the C functionalities. In the CH2O project, Krebbers and Wiedijk [2015] provide a small step operational semantics and executable semantics model for C11 using the Coq theorem prover. The semantic model is non-deterministic covering almost the totality of the C standard. The executable semantics is used for validation purposes.

3.5.2. Formal Semantics and Code Abstraction for Binary Code (Category 4-b). Related work in this area includes formalization of some of the most popular architectures such as Intel x86, ARM, and MIPS. Here we cover only those mechanized formal semantics that can be used in the binary code verification of separation kernels.

For the Intel architecture, Goel et al. [2014] build in the model checker ACL2 an executable semantics for the x86-64 architecture, providing a framework able to both formally analyze and simulate non-deterministic machine code programs intended to run on 64 bits Intel processors. Sarkar et al. [2009] provide in HOL4 an axiomatic and operational semantics for the Intel multiprocessor architecture, including not only semantics for the set of instructions implemented by the architecture, but also a total order axiomatic semantic model of the memory, and machine registers.

On ARM architectures, the work in [Fox and Myreen 2010] covers ARM v7 including support for Thumb-2 instructions through a monadic encoding of the architecture operations. Validation is performed throughout random generation of instructions, and the execution of the instruction on a development board and in the semantic model. Recently, ARM v8 ISA is also modeled in [Flur et al. 2016]. The ARM v7 ISA model has been used in formal verification of seL4 [Klein et al. 2014] and PROSPER [Dam et al. 2013] at the binary code level.

Within the CompCert project [Leroy 2009], a subset of 90 instructions of the PowerPC ISA is modelled using the Coq theorem-prover. This semantics is extended using the HOL4 theorem-prover in [Alglave et al. 2009] with an axiomatic memory model for multiprocessor. An x86 machine model derived from CompCert’s model has been applied in formal verification of mCertiKOS [Costanzo et al. 2016].

It is worth to mentioning the L3 language, introduced in [Fox 2015] aiming to support a generic framework for the specification of ISAs, and the reasoning on machine code programs. Through specifying a next-step function for a subset of instructions for a given ISA, and a definition of the state, the framework is able to generate high-level functions in HOL4 for machine code programs, and a set of theorems proving the correctness of the generated function w.r.t. the input machine code and the L3 specification for the ISA.

3.6. Code Synthesis of SKs (Category 5)

Formal synthesis [Jüllig 1993] translates formal, validated specifications into provably correct target code. Automated formal software synthesis gives a high degree of confidence that the generated
code is correct with respect to the specification. Automatic code synthesis of operating systems can improve customizability [Denys et al. 2002] and optimize the performance at run-time [Massalin 1992]. It is time consuming and error prone when manually porting or configuring the operating systems on different target architectures, and this issue can be addressed by automatic generation of application-specific operating systems [Gauthier et al. 2001]. But to the best of our knowledge, there are no research works on automatic code synthesis for separation kernels. The challenges are that the source code should be very efficient and usually embedded with assembly code. Actually, separation kernels in industries are always verified by the post-development approach, i.e., formal models are abstracted from the implementations of separation kernels and formally verified to provide the required proofs for critical properties.

4. ANALYSIS AND DISCUSSION

In this section, we analyze and discuss related work from the perspective of implementations, formal specification and model, critical properties, formal verification, and code abstraction and synthesis. Then, we give an overall comparison.

4.1. Implementations

We have surveyed twenty implementations of separation kernels from industry and academia in Table I. Here, we compare their objectives, standard certifications/compliance, and formal methods applications in Table IV. The “objective” column presents the critical properties that implementations concern. Although separation kernels contribute to improve fault-tolerance of systems, fault-tolerance is usually considered at system levels. Therefore, we do not compare this property in the table.

By comparing these implementations, we have the following findings.

— Traditionally, two kinds of separation kernels have been used to assure safety and security of critical systems. For instance, VxWorks 653 was used to ensure safety-critical systems and VxWorks MILS to ensure security-critical systems. Nevertheless, a new direction in this field is to unify safety and security into a single separation kernel. For instance, recent separation micro-kernel implementations such as PikeOS and XtratuM are designed to support both solutions [Zhao et al. 2016b].

— The realtime property is mostly considered on separation kernels for safety-critical systems. Due to the integration of safety and security, this property has been considered with security-critical systems.

— Industrial implementations aim at highest assurance levels of different security/safety certification, in particular CC and DO-178B. Open-source/academic implementations have emerged in recent years. However, many of them do not have certification evidence now. Some of the open-source separation kernels are compliant with the ARINC 653 standard.

— From the aspect of formal methods application, formal specification and verification have been enforced on separation kernels in academia at source code and binary code levels. The objective of formal methods on industrial implementations is security/safety certification.

4.2. Formal Specification and Model

We compare the research works of separation kernels on formal specification and model in Tables V and VI in the ascending order of time. In Table V, we compare the formal languages they have used, the size of the specification, and whether refinement is used. In Table VI, we compare the functionalities in the reference architecture that are formalized by the research works. We calculate a total score for each functionality to identify its importance in the formal specification and model of separation kernels.

A formal specification language has a mathematically defined syntax and semantics to give precise description of the artefacts used with formal methods. In the application of formal methods on separation kernels, numerous specification languages are used (see Table V), such as Classical B,
### Table IV. Comparison of Separation Kernel Implementations

| No | Name                                      | Objective | Certification/Compliance | Formal Methods |
|----|-------------------------------------------|-----------|--------------------------|----------------|
|    |                                           | Security | Safety | Realtime | DO-178B Level B, IEC 61508 SIL 3, EN 50128 SIL 4, ARINC 653 |                      |
| 1  | PikeOS [SYSGO 2015]                       | ✓         | ✓      | ✓        | ✓              |                  |
| 2  | VxWorks 653 [WindRiver 2015a]             | ×         | ✓      | ✓        | ✓              | ?                |
| 3  | VxWorks MILS [WindRiver 2015b]            | ✓         | ×      | ×        | ✓              | ?                |
| 4  | INTEGRITY-178B [GreenHills 2015a]        | ✓         | ✓      | ✓        | DO-178B Level A, CC EAL 6+SKPP, ARINC 653 | ✓                |
| 5  | INTEGRITY Multvisor [GreenHills 2015b]    | ✓         | ×      | ×        | ?              | ?                |
| 6  | LynxSecure [Lynx 2015b]                   | ✓         | ✓      | ✓        | CC EAL 7, DO-178B Level A | ?                |
| 7  | LynxOS-178 [Lynx 2015a]                   | ×         | ✓      | ✓        | DO-178B Level A, ARINC 653 | ?                |
| 8  | DDC-I Deos [DDC-I 2015]                   | ×         | ✓      | ✓        | DO-178B Level A, ARINC 653 | ?                |
| 9  | AAMP7** [Collins 2015]                    | ✓         | ✓      | ✓        | N/A            | CC EAL 7        | ✓                |
| 10 | ED [Hemmeyer et al. 2006;2008]            | ✓         | ×      | ×        |                  |                  |
| 11 | ARLx hypervisor [Genesys 2015]            | ✓         | ✓      | ×        | DO-178B Level A, MILS EAL, IEC 61508 | ?                |

#### Academic Implementations

| No | Name                                      | Objective | Certification/Compliance | Formal Methods |
|----|-------------------------------------------|-----------|--------------------------|----------------|
| 12 | sel4 [Murray et al. 2012;2013]            | ✓         | ×                        | ×              | ✓              |
| 13 | OKL4 Microvisor [Systems 2015]            | ✓         | ×                        | ×              | ✓              |
| 14 | XtratuM [XtratuM 2013]                    | ✓         | ✓                        | ×              | ✓              |
| 15 | PROSPER [PROSPER 2015]                   | ✓         | ×                        | ×              | ✓              |
| 16 | Xenon [Freitas and McDermott 2011]        | ✓         | ×                        | ×              | ✓              |
| 17 | Quest-V [QuestOS 2015]                   | ✓         | ×                        | ×              | ✓              |
| 18 | Muen [Muen 2015]                          | ✓         | ×                        | ×              | X              |
| 19 | POK [POK 2015]                            | ×         | ✓                        | ✓              | X              |
| 20 | AIR/AIR II [AIR 2015]                     | ✓         | ✓                        | ✓              | ARINC 653      | X              |

? means we do not find any literature to show the evidence.

**This is a processor, a hardware implementation of separation kernel.

### Table V. Comparison of Separation Kernel Specification - Part 1

| Specification/Model | Formal Language | Size of Specification | Refinement |
|---------------------|-----------------|-----------------------|------------|
| MASK [Martin et al. 2000;2002] | SPECWARE | ? | ✓ |
| MPS [Alves-Foss et al. 2002] | ACL2 | ≈ 2500 LOC | ✓ |
| Craig [Craig 2007] | Z | ≈ 100 pages | ✓ |
| ARINC Scheduler [Smaillot and Planetc 2007] | AADL | ? | X |
| LFSK [Phipps et al. 2008] | Alloy | ? | ✓ |
| SPK [Andre 2009] | Classical B | ? | ✓ |
| OS-K [Kawamoto 2010] | Classical B | ? | ✓ |
| Verified Software [Velykis and Freitas 2010] | Z | ≈ 50 pages | ✓ |
| Xenon [Freitas and McDermott 2011] | Circus | ≈ 4500 pages | ✓ |
| sel4 [Murray et al. 2013] | Isabel/HOL | 4970 LOC | ✓ |
| CISK [Verbeek et al. 2014] | Isabel/HOL | ≈ 300 LOC | ✓ |
| XtratuM [Sanan et al. 2014] | Isabel/HOL | 6000 LOC | ✓ |
| ARINC 653 Standard [Zhao et al. 2015] | Event-B | ≈ 2700 LOC | ✓ |
| PikeOS API [Verbeek et al. 2015] | Isabel/HOL | > 4000 LOC | X |
| ARINC 653 Separation Kernel [Zhao et al. 2016b] | Isabel/HOL | ≈ 1000 LOC | X |

? means there is no evidence in the literature.
Event-B, Z notation, Isabelle/HOL, ACL2, and model-driven architecture languages (e.g., AADL). Specification languages are often used for system analysis, requirement analysis, and systems design at a much higher level, where expressiveness and refinement [Roever and Engelhardt 2008] are the major considerations for separation kernels. Specification languages used for separation kernels often support set theory and first-order logic as the fundamental data types. Refinement is often used to create concrete models from abstract specifications in a step-wise manner.

On the other hand, for the purpose of formal verification at low level or source code level, specification languages used to specify separation kernels are focused on first-order or high-order logic languages, such as Isabelle/HOL, ACL2, PVS, and HOL4. Verification tools for these formalisms must have powerful engines for formal reasoning, supporting automatic theorem proving or providing proof assistants with a high degree of automation. Wiedijk [2006] presents a detailed comparison of seventeen theorem provers and the ability of their formal notations.

We have proposed a reference architecture for separation kernels in Fig. 2, in which we classify the functionalities into common and optional components. In Table VI, we count a total score for each functionality according to the level of abstraction at which they are formalized in research works. The importance of each functionality in the formal specification of separation kernels is thus shown by the total score. We divide the “policies” from “functionalities” in accordance with the taxonomy in subsection 3.1. From Table VI, we could see that common components have higher...
scores than optional components. It is in accordance with the classification of common and optional components in the reference architecture. An exception is the “hardware interface” which is at low level and necessary in implementations. However, it is usually omitted in formal specifications at abstract level. Most of research works only consider the concept of “partition” and do not provide specification of “partition management”, because they use the “partition” as a mechanism to separate resources and do not manage the life cycle of partitions. Although it is an optional component in the reference architecture, process management is often specified in research works because processes are importance resources in partitions. The PIFP policy is the most adopted policy of separation kernels in research works due to the fine-grained controls on partitions, resources, and subjects.

A notable observation is that different specification languages are used in the literature, but Isabel-l/HOL has become recently more popular than other formalisms. The first reason is its successful, large scale application in full formal verification of the seL4 microkernel at source code level. Second, there is a big community of experts working actively on its development, with frequent updates. Finally but not less important, it has a powerful development environment with many tools supporting automation. A detailed discussion about applying Isabelle/HOL in certification processes of separation kernels is in [Blasum et al. 2015].

4.3. Critical Properties

In Subsection 3.3, we have presented a set of critical properties, their sub-properties, and their formal definition. We sketch out their relationship in Fig. 5. The evidence of the relationship are from the literature as shown in Table VII.

GWV and MASK are the two major groups of data separation properties. GWV is inspired by properties in MASK and the relationship of these two groups of properties is discussed in [Matthew et al. 2003]. The infiltration, exfiltration, and mediation properties are actually instances of the GWV separation property. The first two are actually similar to the two properties of MASK. The properties of GWV are applied on the ED separation kernel and redefined as ED no-infiltration and ED no-
Table VII. Evidence of Relationship of Critical Properties

| Literature                          | Labels of Relationship |
|------------------------------------|------------------------|
| [Matthew et al. 2003]              | (1 - 6)                |
| [Heitmeyer et al. 2008; Heitmeyer et al. 2006] | (7, 8)                |
| [Ramirez et al. 2013]              | (9, 10)                |
| [Alves-foss and Taylor 2004]       | (11, 12)               |
| [von Oheimb 2004]                  | (13 - 15)              |
| [Rushby 1992]                      | (14)                   |
| [Murray et al. 2012]               | (16 - 20)              |
| [Murray et al. 2013]               | (23 - 25)              |
| Zhao et al. 2016b                   | (26)                   |

exfiltration [Heitmeyer et al. 2008; Heitmeyer et al. 2006]. Rushby’s noninterference and its variants constitute the major group of information flow security. The definition and formal comparison of noninterference, nonleakage and noninfluence are studied in [von Oheimb 2004; Murray et al. 2012; Zhao et al. 2016b]. The three unwinding conditions (see Subsection 3.3.2) imply noninterference by the unwinding theorem [Rushby 1992]. Noninfluence [von Oheimb 2004] is proposed based on noninterference and considers both data confidentiality and secrecy of events. It is a stronger property and implies noninterference and nonleakage. These properties have been instantiated in seL4 [Murray et al. 2012; Murray et al. 2013] and in ARINC 653 separation kernels [Zhao et al. 2016b] by extending the scheduler. Different definitions and formal comparison of noninterference are available in [van der Meyden and Zhang 2010].

The GWV property proposed in Rockwell Collins is adopted in industry as the security policy for CC certifications, such as AAMP7 microprocessor [Wilding et al. 2010], INTEGRITY-178B [Richards 2010], and PikeOS [Tverdyshev 2011]. Meanwhile, noninterference is mostly applied in academia, such as in formal verification of seL4 [Murray et al. 2012; Murray et al. 2013], PROSPER [Dam et al. 2013], and mCertiKOS [Costanzo et al. 2016]. A notable work is [Ramirez et al. 2014] in which they formally compare GWV and Rushby’s noninterference and present a mapping between the elements of the two models. The conclusion is that GWV is stronger than Rushby’s noninterference. A similar conclusion is in [Alves-foss and Taylor 2004], where they state that GWV is at least as strong as general noninterference and in addition it also provides intransitive noninterference.

Temporal separation has not attracted much attention in the literature and we therefore cannot find a large number of works focusing on the verification of temporal separation. It is however worth mentioning the work [Penix et al. 2000; Penix et al. 2005; Cofer and Rangarajan 2002] where time partitioning is verified in the DEOS kernel.

4.4. Formal Verification

In order to summarize formal verification of separation kernels, we compare the research works in Tables VIII and IX focusing on the verification targets, verified properties and sub-properties, language used, sizes of specification and proofs, verification approaches and tools, and their cost. The verification targets are artefacts of formal methods in Fig. 3, i.e. specification, high-level model, low-level model, and implementation model of source code and binary code. In Table VIII, we refine the model into high-level design and low-level design models according to the levels of formal methods application in CC certification.

The purpose of formal verification of separation kernels in industry is mainly safety/security certification, in particular CC security certification, such as INTEGRITY-178, PikeOS, AAMP7, and ED. The highest assurance level of CC certification (EAL 7) requires comprehensive security analysis using formal representations of the security model, functional specification, high-level design, and low-level design of separation kernels as well as formal proofs of correspondence among them. The implementation is not necessary for formal analysis. Therefore, it is possible to observe from Table VIII that formal verification of industrial separation kernels is often conducted on the low-level design model but not the implementation. However, in academia it often reaches the levels of source and binary code for the purpose of full formal verification. On the other hand, formal
## Table VIII. Comparison of Separation Kernel Verification - Part 1

| Verified Kernel | Verification Target | Verified Properties | Verified Sub-properties |
|----------------|---------------------|---------------------|-------------------------|
| ED [Heitmeyer et al. 2006; Heitmeyer et al. 2008] | Implementation model (source code) | Data separation, Temporal separation | No-infiltration, No-exfiltration, Kernel integrity, Separation of control |
| AAMP7 [Greve et al. 2004; Wilding et al. 2010] | Low-level model | Data separation | GWV |
| INTEGRITY-178B [Richards 2010] | Low-level model | Data separation | GWV |
| PikeOS [Baumann et al. 2011] [Tvendyshev 2011] [Verbeek et al. 2015] | High-level model, Implementation model (source code) | Data separation, Information flow security | Memory separation, GWV, Noninterference |
| sel4 [Murray et al. 2012; Murray et al. 2013] | Implementation model (source code) | Information flow security | Noninfluence, Noninterference, Nonleakage |
| PROSPER [Dam et al. 2013] | Implementation model (binary code) | Data separation, Information flow security | No-infiltration, No-exfiltration, Noninterference |
| XtratuM [Sanán et al. 2014] | Low-level model | Information flow security | Noninterference |
| mCertiKOS [Costanzo et al. 2016] | Implementation model (source code) | Information flow security | Noninterference |
| ARINC 653 [Zhao et al. 2016b] | Specification | Information flow security | Noninfluence, Noninterference, Nonleakage |
| DEOS [Penix et al. 2000; Penix et al. 2005; Coler and Rangarajan 2002; Ha et al. 2004] | Implementation model (source code) | Temporal separation | Time partitioning |
| A VxWorks scheduler [Asberg et al. 2011] | Low-level model | Temporal separation | Correctness of Scheduling |
| RTSJ scheduler [Zerzelidis and Wellings 2006; Zerzelidis and Wellings 2010] | Low-level model | Temporal separation | Correctness of Scheduling |

Verification of separation kernels usually consider data separation and information flow security other than temporal separation since CC certification of separation kernels demands a security policy model of spatial separation. From the aspect of critical properties, formal verification in industry prefers data separation, in particular the GWV property, whilst Rushby’s noninterference is preferred in academia. We find that in recent five years, research works of formal verification have mostly focused on the noninterference.

Almost all of research works of formal verification on spatial separation have used theorem proving and refinement approaches. The reasons are as follows.

— The methodology of formal verification using theorem proving and refinement is compliant with CC EAL 7 certification. Security proof of separation kernels is produced by the methodology. However, model checking only produces the verification result, e.g., correct or counterexamples.

— Separation kernels for safety and security critical systems often requires formal verification on low-level design or even source code. Despite the relatively small size of separation kernels, the model checking technique does not scale well to verify such complex systems due to the state space explosion problem. However, the theorem proving approach is applicable and full verification of separation kernels is therefore possible.

— Critical properties of separation kernels (e.g., GWV and information flow security) are difficult to be represented using temporal logic. A notable recent work is that noninterference can be classified as a sort of hyperproperties [Clarkson and Schneider 2010] and formulated by HyperLTL [Clarkson et al. 2014]. However, HyperLTL model checkers currently do not scale up to 1,000 states and are not applicable even at the abstract level of separation kernels.
Table IX. Comparision of Separation Kernel Verification - Part 2

| Verified Kernel | Formal Language | Size | Verification Approach | Tools | Cost |
|-----------------|-----------------|------|-----------------------|-------|------|
| ED [Heitmeyer et al. 2006; Heitmeyer et al. 2008] | TAME | 368 LOC of TAME spec. | R, TP | TAME, PVS theorem prover | 11 weeks |
| AAMP7 [Grove et al. 2004; Wilding et al. 2010] | ACL2 | 3,000 LOC of ACL2 definitions | R, TP | ACL2 theorem prover | ? |
| INTEGRITY-17/8B [Richards 2010] | ACL2 | ? | R, TP | ACL2 theorem prover | ? |
| PikeOS [Baumann et al. 2011; Tverdyshev 2011; Verbeek et al. 2015] | Annotated C code, Isabelle/HOL | ? | TP, MC | VCC, Isabelle proof assistant | ? |
| seL4 [Murray et al. 2012; Murray et al. 2013] | Isabelle/HOL | 4,970 LOC of spec., 27,756 LoC of proof | R, TP | Isabelle proof assistant | 51 person-months |
| PROSPER [Dam et al. 2013] | HOL4 | 21k LOC | R, TP | HOL proof assistant | ? |
| XtratuM [Sanán et al. 2014] | Isabelle/HOL | 6,000 LOC of spec | R, TP | Isabelle proof assistant | 12 person-months |
| mCertiKOS [Costanzo et al. 2016] | Coq | 6,285 LOC of proof | R, TP | Coq proof assistant | ? |
| ARINC 653 [Zhao et al. 2016b] | Isabelle/HOL | 1,000 LOC of spec, 7,000 LoC of proof | TP | Isabelle proof assistant | 8 person-months |
| DEOS [Penix et al. 2000; Penix et al. 2005; Cofer and Rangarajan 2002; Ha et al. 2004] | Promela, PVS | 1,000 LOC of PVS | TP, MC | PVS theorem prover, SPIN | ? |
| A VxWorks scheduler [Asberg et al. 2011] | Task automata, TCTL | ? | MC | Times tool | ? |
| RTOS scheduler [Zerzelidis and Wellings 2006; Zerzelidis and Wellings 2010] | Timed automata | ? | MC | UPPAAL | ? |

Verification Approach: theorem proving (TP), model checking (MC), refinement (R)
?: means there is no evidence in the literature

On the other hand, temporal separation verification often uses model checking rather than theorem proving. *time* is hard to express using first order or high order logics, which are the mathematical artefacts used in theorem provers. However, it is possible to conveniently express *time* using temporal logics, e.g., the timed automata in UPPAAL tools. A major obstacle of this approach is that the size and complexity of separation kernels limit the approach to analyze only one configuration at a time. Honeywell has addressed this issue and turned into using the PVS theorem prover to formally verify DEOS [Ha et al. 2004].

From the aspect of the cost for formal verification, there are not many evidences in the literature. From the result of seL4 [Klein et al. 2009; Murray et al. 2013], we could see that enormous manpower is often needed for formal verification of separation kernels reaching at the source code level. A possible approach to this issue is provided in [Heitmeyer et al. 2008], where manual proof is enforced at abstract level and pre- and post-conditions annotated in the source code are used to automatically verify the conformance between the specification and the source code.

4.5. Code Abstraction

Table X summarises state of the art for mechanized formal semantics of the C language. The table shows the formal language used, the version of the C language the semantics formalizes, whether the formal semantics is executable, and what separation kernels they have been applied on, if any. We include a field indicating whether a semantics is executable or not since executing the semantics is a desirable property for simulation purposes. Similarly, Table XI comprises state of the art ISAs.
Table X. Comparison of Formal Semantics of C

| Specification            | Formal Language | C Subset | Executable | Applied Kernel       |
|--------------------------|-----------------|----------|------------|----------------------|
| Cholera [Norrish 1998]   | Isabelle/HOL    | C89      |            | CParser, seL4        |
| Papaspyrou [2001]        | Haskell          | C90      | ✓          |                      |
| Tews et al. [2008]       | PVS             | ?        |            | Nova Hypervisor      |
| CO [Alkassar et al. 2008]| Isabelle/HOL    | C89      |            |                      |
| Clight [Blazy and Leroy 2009] | Coq         | C90      | ✓          |                      |
| Ellison and Rosu [2012]  | K-framework     | C99      | ✓          |                      |
| CH₂O [Krebbers and Wiedijk 2015] | Coq      | C11      | ✓          |                      |

?: means there is no evidence in the literature

Table XI. Comparison of Formal Semantics of ISA

| Specification            | Formal Language | ISA     | Executable | Multicore | Applied Kernel       |
|--------------------------|-----------------|---------|------------|-----------|----------------------|
| Goel et al. [2014]       | ACT2            | x86-64  | ✓          | ✓         |                      |
| Sarkar et al. [2009]     | HOL4            | x86-CC  | ✓          | ✓         |                      |
| CertiKOS [Costanzo et al. 2016] | Coq      | x86     | ✓          | ✓         | CertiKOS             |
| Fox and Myreen [2010]    | HOL4            | ARMv7   | ✓          |           | seL4, PROSPER        |
| Plur et al. [2016]       | Lem             | ARMv8   | ✓          | ✓         |                      |
| CompCert [Leroy 2009]    | Coq             | Power-PC| ✓          |           |                      |

The table shows the formal method used, the target architecture, whether it supports multicore, whether the semantics is executable, and what separation kernels they have been applied on, if any.

Verification of separation kernels at source code and binary code level requires two fundamental tasks: to capture the language or ISA behaviour and to prove that the provided semantic model is correct. Due to the complexity of the C language, it is difficult to capture its whole semantics. Moreover, separation kernels are usually developed using C embedded with assembly. When it is formally verified at source code level, the kernel implementation is possible to be re-structured to make it compliant with the provided semantic model, such as in the seL4 microkernel verification [Klein et al. 2014]. This raises a new discussion about the validity of the new version of the kernel. However, although the modified kernel may not have the same behaviour as the original one, by the verification of functional correctness, which is carried out on the modified kernel, we obtain an implementation with the same functionality as the original kernel, and preserving the desirable set of safety and security properties.

Concerning the correctness of the C and ISA model, the technique most commonly used is the validation of the provided semantic model w.r.t. the programming language or ISA. A validation framework automatically executes single instructions, or sequences of them, in the semantic model and in the real architecture, and it compares the results of both execution to check whether they are correct. In case some mismatch is found, it is possible to refine the semantic model to correct a possible error on it. The validation of hundreds of thousands of instructions will provide enough confidence about the correctness of the semantic model.

4.6. Overall Comparison

We give an overall comparison of formal methods application on separation kernels in this subsection. We compare the related work on aspects of the target of formal methods application, development processes covered by the formal methods used according to CC, verification approaches, estimated EAL in CC according to Table III, and scale of formal methods application in Table XII. In addition to the normative definitions of EALs, the CC standard defines the possibility of intermediate levels of security when a requirement is evaluated at a higher level than that required by the target level. The addition of the symbol “+” represents this kind of evaluation. Formal verification of ED, PikeOS, and PROSPER does not have low-level design. They either prove the conformance...
Table XII. Overall Comparison

| Related Work                  | Target | Formal Methods on CC Process | Approach | EAL | Scale |
|-------------------------------|--------|------------------------------|----------|-----|-------|
|                              |        | R | F | H | L | I |       |       |
| GWV [Matthew et al. 2003]    | Properties | ✓ | ✗ | ✗ | ✗ | ✗ | TP | 4+ | +   |
| Noninterference [Rustley 1992; von Oheimb 2004; Murray et al. 2012] | Properties | ✓ | ✗ | ✗ | ✗ | ✗ | TP | 4+ | ++ |
| MASK [Martin et al. 2000; Martin et al. 2002] | Low-level model | ✓ | ✓ | ✓ | ✓ | ✗ | R, TP | ? | ? |
| MPS [Alves-Foss et al. 2002] | High-level model | ✓ | ✓ | ✓ | ✗ | R | 5+ | ++ |
| An ARINC Scheduler [Singhoff and Plantec 2007] | Specification | ✓ | ✓ | ✗ | ✗ | ✗ | MC | 4+ | ? |
| Craig [Craig 2007]            | High-level model | ✓ | ✓ | ✓ | ✓ | R, TP | 5+ | ++ |
| IPSK [Phillips et al. 2008]  | Specification | ✓ | ✓ | ✓ | ✗ | TP | 4+ | ? |
| SPK [André 2009]             | High-level model | ✓ | ✓ | ✓ | ✓ | R, TP, CG | 5+ | ? |
| OS-K [Kawamorita et al. 2010] | High-level model | ✓ | ✓ | ✓ | ✗ | R, TP, MC | 5+ | ? |
| Verified Software [Velykis and Freitas 2010] | High-level model | ✓ | ✓ | ✗ | ✗ | R, TP | 5+ | ++ |
| Xenon [Freitas and McDermott 2011] | High-level model | ✓ | ✓ | ✓ | ✗ | R, TP | 5+ | ++ |
| CSK [Verbeek et al. 2014]    | High-level model | ✓ | ✓ | ✓ | ✗ | R, TP | 5+ | ++ |
| ARINC 653 Standard [Zhao et al. 2015] | High-level model | ✓ | ✓ | ✓ | µ | R, TP | 5+ | ++ |
| ED [Heitmeyer et al. 2006; Heitmeyer et al. 2008] | Implementation model (source code) | ✓ | ✓ | ✓ | µ | R, TP | 7 | ++ " |
| AAMP7 [Greve et al. 2004; Wilding et al. 2010] | Low-level model | ✓ | ✓ | ✓ | R, TP | 7 | ++ " |
| INTEGRITY-178B [Richards 2010] | Low-level model | ✓ | ✓ | ✓ | ✓ | R, TP | 6+ | ? |
| PikeOS [Baumann et al. 2011; Tverdyshev 2011; Verbeek et al. 2015] | High-level model, Implementation model (source code) | ✓ | ✓ | ✗ | ✓ | R, TP, MC | 6+ | ++ |
| seL4 [Murray et al. 2013]    | Implementation model (source code) | ✓ | ✓ | ✓ | ✓ | R, TP, CA | 7+ | ++++ |
| PROSPER [Dani et al. 2015]   | Implementation model (binary code) | ✓ | ✓ | ✓ | ✓ | R, TP, CA | 7+ | +++ |
| XratoM [Sanán et al. 2014]   | High-level model | ✓ | ✓ | ✓ | ✓ | R, TP | 5+ | ++ |
| mCertiKOS [Costanzo et al. 2016] | Implementation model (source code) | ✓ | ✓ | ✓ | ✓ | R, TP, CA | 7+ | +++ |
| ARINC 653 [Zhao et al. 2016b] | Specification | ✓ | ✓ | ✓ | µ | R, TP | 5+ | ? |
| DEOS [Penix et al. 2000; Penix et al. 2005; Ha et al. 2004] | Implementation model (source code) | ✓ | ✓ | ✓ | µ | R, TP, MC | 7 | ? |
| A VxWorks scheduler [Asberg et al. 2011] | High-level model | ✓ | ✓ | ✓ | ✓ | R, TP, MC | 5+ | ? |
| RTSJ scheduler [Zerzdalis and Wellings 2006; Zerzdalis and Wellings 2010] | High-level model | ✓ | ✓ | ✓ | ✓ | MC | 5+ | ? |

**Approach:** Refinement (R), Theorem Proving (TP), Model Checking (MC), Code Abstraction (CA), Code Generation (CG)

**Formal methods on CC process:** Requirement (R), Functional specification (F), High-level design (H), Low-level design (L), Implementation (I)

**Scale:** + (<1k LOC), ++ (1k ~ 10k LOC), +++ (10k ~ 100k LOC), ++++ (>100k LOC). The LOC includes the specification and proof

*a,b,c* Only LOC of specification is available.

between the high-level design and the implementation or use software model checking to analyze the implementation.

The highest assurance level of CC (EAL 7) requires formal methods application on the low-level design but not on the implementation. Aiming at security/safety of separation kernels as far as possible, a few research works have provided formal proof of refinement between the low-level design and the implementation, such as seL4 [Murray et al. 2013] and mCertiKOS [Costanzo et al. 2016]. Targeting at the source code by formal methods always means that they are applied on the implementation, which has overstepped the demand of EAL 7 in CC and estimated as EAL 7+. In ACM Journal Name, Vol. 1, No. 1, Article 1, Publication date: January 2017.
Table XII. Compared to the high cost of CC certification, formal verification on implementation is a low-cost way to provide more assurance of separation kernels as stated in [Klein et al. 2009]. Few work provides an estimation of time and cost of formal methods application on separation kernels. Thus, we cannot clearly compare them. A notable viewpoint is that the industry rules-of-thumb for CC EAL 6 certification is of $1k/LOC, although it provides less assurance than formal verification [Klein et al. 2014].

5. CHALLENGES AND FUTURE DIRECTIONS

We now discuss the remaining challenges in formal methods application on separation kernels and possible research directions that may be taken by future work.

5.1. Eliminating Specification Bottleneck

In formal methods, formal specification is a bottleneck in functional verification [Beckert and Hahnle 2014]. Therefore, simpler verification methods are often used in practice including (1) lightweight verification methods for finding bugs, (2) combining verification and testing, and (3) verifying generic and uniform properties. Due to high assurance of separation kernels and formal methods mandated by certification, the first method is obviously not sufficient. The second is always used in practice. The third is actually suitable for separation kernels. Using generic or uniform specifications can reduce the cost to create requirement specifications. Although lightweight properties, such as buffer overflows and null-pointer exceptions, are feasible in many cases, formal verification of relational properties, e.g. noninterference, is inevitable for separation kernels. The challenges and possible directions to eliminate specification bottleneck are shown as follows.

(1) **Properties of temporal separation.** The GWV and noninterference are the major properties for data separation and information flow security that have been widely applied in industry and academia. However, properties of temporal separation have not been thoroughly studied in the literature. A set of properties to clarify temporal separation are highly desired for high-assurance separation kernels.

(2) **Formal relations among properties.** We have figured out some formal relations in Fig. 5. Others are not explored. In particular, shared resources among partitions can affect the scheduling in separation kernels. But the relationship between spatial separation and temporal separation has not been studied in the literature and is not clear yet. On the other hand, there does not exist a precise and global framework for the relationship of critical properties of separation kernels and it deserves further study.

(3) **Generic formal specification.** For the purpose of the formal development, safety/security certification, and the study of formal relations between critical properties, it is highly necessary in the future to create a generic specification of separation kernels. This specification can be used to develop implementations using refinement and be revised gradually, and thus significantly alleviate the bottleneck. It has been attempted in the EURO-MILS project to deliver a generic specification for separation kernels [Verbeek et al. 2014].

(4) **Reusability of formal specification.** Formal specification is a foundation for formal verification. Furthermore, it can also be applied to development, integration, and management of systems deployed on separation kernels [Zhao et al. 2016a]. A direction is to integrate domain knowledge into formal specification of separation kernels (e.g., [Ait-Ameur and Méry 2016; Zhao et al. 2016a]) to improve its reusability.

(5) **Flexibility of formal specification and proof.** Although reusability of the specification partially relies on the formal notation used and its supported tool, a well designed specification can evidently improve it. On the other hand, proofs should address how to deal with changes of formal model due to upgrading of separation kernels. Since re-verification is usually expensive for separation kernels, the proof change should be as small as possible when the uniform specification and design models are tailored or extended in real applications. A reusable design of the specification and its proof is a challenge for separation kernels.
5.2. Automating Full Formal Verification

Full formal verification of systems means that the verification is enforced not only on the specification but also covers all the source code and even the binary code with machine checkable proof. Formal verification at the implementation level can significantly improve the assurance of systems than other approaches, such as applying formal specification or lightweight properties over higher-level models [Andronick et al. 2012]. Full formal verification of programs had rarely been conducted and was often considered to be highly expensive [Hall 1990] before successful practices of seL4 [Klein et al. 2009], CompCert [Leroy 2009], and CertiKOS [Gu et al. 2015].

Full formal verification at the source code level is necessarily based on a set of assumptions, such as the correctness of the hardware and the compiler [Klein et al. 2009]. Whilst, formal verification at the binary code level overcomes assumptions on the correctness of the compiler. Full correctness of separation kernels by formal verification could be assured by a formal pervasive verification approach covering the hardware, compiler, and kernel itself exactly as proposed in the Verisoft XT project [Hillebrand and Paul 2007]. A major obstacle of this objective is that full formal verification of operating system kernels is usually manpower intensive, e.g., 20 person-years are invested in formal verification of seL4. We summarize a set of challenges and potential directions in automating full formal verification of separation kernels to alleviate enormous efforts as follows.

(1) **Automatic verification of critical properties.** As shown in Table IX, existing works usually apply theorem proving to verify spatial separation of separation kernels. Automatic approaches at specification and design levels can enormously alleviate manual efforts and deserves further study.

(2) **Automatic refinement checking and property preservation.** A promising way to the correctness of low-level models is refinement. However, from seL4 we could see that it is often a time-consuming work to find and prove the refinement relation between two levels of specification [Klein et al. 2009]. Automatic refinement checking is thus worth considering in formal verification of separation kernels. Zhao et al. [2016a] have illustrated high degree of automatic refinement checking using Event-B. Second, it is critical that properties could be preserved during refinement. Refinement preservation of information flow security has been discussed in [Van Der Meyden 2012]. For separation kernels, refinement preservation of critical properties needs systematical study.

(3) **Proof generation during automatic verification.** Traditional model checking approaches produce the verification result directly. For the purpose of safety and security certification, it is necessary that automatic approaches generate proofs for the correctness.

(4) **Full formal verification at C source code level.** Programming in C is not sufficient for implementing separation kernels and programmers have to manipulate hardware directly by embedding assembly code in C. The assembly code is often omitted in full formal verification (e.g., seL4 [Klein et al. 2009]) and not supported by code abstraction tools, such as CParser [Greenaway et al. 2012] which translates a large subset of C-99 code into Isabelle/HOL. Existing works have to be extended for full formal verification considering C and assembly code together.

5.3. Dealing with Multicore and Concurrency

In the domain of high-assurance systems, an increasing trend is the adoption of multicore processor to fulfil demands of higher computing power [Parkinson 2011]. The overall performance of systems is improved by concurrent execution of instructions in multicore processors. The latest version of ARINC 653 [Aeronautical Radio, Inc. 2015] specifies the functionality and system services of multicore separation kernels. As summarized in Table I, separation kernels from industry and academia mostly support multicore processors. Multicore kernels are challenging formal verification and the safety/security certification [Cohen et al. 2013]. To the best of our knowledge, there is no research work on formal verification of multicore kernels in the literature.

Separation kernels are reactive systems whose execution is triggered by system calls and in-kernel events. In general, the execution of system calls of monocore kernels are non-preemptive. It is often assumed in formal verification that kernels do not have in-kernel concurrency and the execution of functions handling events is considered to be atomic, such as in [Klein et al. 2009]. In such a case,
formal verification of critical properties could be decomposed to examine individual execution steps, i.e., atomic functions. This is the basic idea of the unwinding theorem [Rushby 1992] to reason about noninterference. However, kernels are preemptive when processing other interruptions and thus in-kernel concurrency exists in practice. On the other hand, multicore introduces more complicated concurrency in separation kernels. The complexity increases greatly due to concurrent execution among cores and the shared resources. Functions to handle events are shared-variable based parallel programs and are executed in an interleaved manner.

A promising way of conquering this issue is compositional verification [Shankar 1993; Dinsdale-Young et al. 2013]. Rely-guarantee method [Jones 1983] is a fundamental approach for compositional reasoning of parallel programs with shared variables. We outline the challenges and potential directions in formal methods application on multicore separation kernels as follows.

1. **Formalization of critical properties.** The original critical properties for separation kernels are usually defined on a state machine in which a transition is a big-step action (e.g., a system call). In the case of multicore, non-atomicity of events requires new formalization of critical properties.

2. **Specification languages in theorem provers.** Existing specification of separation kernels uses inherent functions of programming languages in theorem provers (e.g., Isabelle/HOL, Coq) to specify the atomic behavior of events. For multicore, specification languages which can express interleaved semantics and deal with complexity are required in theorem provers.

3. **Compositional reasoning of critical properties.** Although compositional reasoning of language-based information flow security has been studied [Mantel et al. 2011; Murray et al. 2016], compositional reasoning of state-event based definitions, which are usually applied on operating system kernels, should be addressed in future. Compositional reasoning of other critical properties also deserves further study. Proof systems for compositional reasoning and their automation techniques are critical.

4. **Parallel refinement.** Based on the specification languages, a refinement framework is certainly needed with considerations of concurrency and compositionality of refinement relation [Liang et al. 2014]. The critical properties of separation kernels are necessary to be preserved during parallel refinement of multicore specification.

### 5.4. Formal Development and Code Generation

Separation kernels are always formally verified by the post-hoc approach, i.e., formal verification on an existing implementation. One promise of formal methods is to develop formal models step by step and generate code automatically or manually from the model whose correctness and properties have been formally verified. The benefit of formal development for separation kernels is significant. First, the specification and the verification targets, i.e., implementations of separation kernel, are developed in tandem, the specification bottleneck can be greatly alleviated. Second, formal proofs requested by safety/security certification can be generated during refinement-based development. Third, developing source code is a time-consuming and error-prone process. Automatic code generation via certified/verified tools can alleviate many efforts to design and implementation and provide rigorous arguments to validate the generated code. For this purpose, the following challenges need to be addressed in the future.

1. **Stepwise refinement for formal development supporting multicore.** In formal verification of seL4 [Klein et al. 2009; Murray et al. 2013] and ED [Heitmeyer et al. 2008], refinement methods have been applied. Due to the post-hoc verification objective of these projects, refinement is not a technique to develop the specification in a stepwise manner, but to prove the conformance between formalizations at different levels. Therefore, they have few levels of specification and the refinement is coarse-grained. For the purpose of formal development, a stepwise refinement framework, which is able to deal with additional design elements (e.g., new events and new state variables) and concurrency, is highly desired.

2. **Verified code generation and traceability.** Formal synthesis of separation kernels is difficult since the code should be very efficient and embedded with assembly code to manipulate hardware.
Table XIII. Statistics of Challenges

| Related Work                               | Specification Bottleneck | Full Formal Verification | Multicore Concurrency | Formal Dev. |
|--------------------------------------------|--------------------------|--------------------------|-----------------------|-------------|
| GWV [Matthew et al. 2003]                  | €                        | €                        | €                     | €           |
| Noninterference [Rushby 1992; von Oheimb 2004; Murray et al. 2012] | €                        | €                        | €                     | €           |
| MASK [Martin et al. 2000; Martin et al. 2002] | €                        | €                        | €                     | €           |
| MPS [Alves-Foss et al. 2002]              | €                        | €                        | €                     | €           |
| An ARINC Scheduler [Singhoff and Plantec 2007] | €                        | €                        | €                     | €           |
| Craig [Craig 2007]                         | €                        | €                        | €                     | €           |
| LPSK [Phelps et al. 2008]                 | ʘ                        | €                        | €                     | €           |
| SPK [André 2009]                           | €                        | €                        | €                     | €           |
| OS-K [Kawamorita et al. 2010]             | €                        | €                        | €                     | €           |
| Verified Software [Velykis and Freitas 2010] | €                        | €                        | €                     | €           |
| Xenon [Freitas and McDermott 2011]        | €                        | €                        | €                     | €           |
| CISK [Verbeek et al. 2014]                | €                        | €                        | €                     | €           |
| ARINC 653 Standard [Zhao et al. 2015]     | €                        | €                        | €                     | €           |
| ED [Heitmeyer et al. 2006; Heitmeyer et al. 2008]  | ʘ                        | €                        | €                     | €           |
| AAMP7 [Greve et al. 2004; Wilding et al. 2010] | €                        | €                        | €                     | €           |
| INTEGRITY-178B [Richards 2010]            | €                        | €                        | €                     | €           |
| PikeOS [Baumann et al. 2011; Tverdyshev 2011; Ramírez et al. 2014; Verbeek et al. 2015] | €                        | €                        | €         | €           |
| seL4 [Murray et al. 2013]                 | €                        | €                        | €                     | €           |
| PROSPER [Dam et al. 2013]                 | €                        | €                        | €                     | €           |
| XtratuM [Sanan et al. 2014]               | €                        | €                        | €                     | €           |
| mcCertiKOS [Costanzo et al. 2016]         | €                        | €                        | €                     | €           |
| ARINC 653 [Zhao et al. 2016b]             | €                        | €                        | €                     | €           |
| DEOS [Penix et al. 2000; Penix et al. 2005; Ha et al. 2004]  | €                        | €                        | €         | €           |
| A VxWorks scheduler [Asberg et al. 2011]  | €                        | €                        | €                     | €           |
| RTSJ scheduler [Zerzelidis and Wellings 2006; Zerzelidis and Wellings 2010] | €                        | €                        | €         | €           |

- €: the challenge has been addressed
- ʘ: the challenge has been partially addressed
- ʘ: the authors have mentioned the challenge but failed to address it
The blank is that the literature does not mention this kind of problem.

Therefore, the machine model have to be considered in the formal synthesis. On the other hand, verified synthesis and traceability of the code to formal models are required for certifications.

5.5. Summary

We have compared typical related work which have (partially) addressed the challenges and studied the potential directions mentioned in Table XIII. From the table, we could see that the challenge of specification bottleneck has been widely considered, in particular the generality and reusability of formal specification. Full formal verification has attracted large efforts in recent years, e.g., seL4, mcCertiKOS, and PROSPER, in which full formal verification of the source code or binary code has been done. As a new trend in high-assurance systems, multicore and concurrency issues in formal verification of separation kernels have not been addressed. To the best of our knowledge, except some efforts to preemptive and interruptable OSs [Chen et al. 2016; Xu et al. 2016], there is no research work on formal verification of multicore kernels. Formal development and code genera-
tion for separation kernels has been partially considered in some research works. However, issues considering automatic code generation have not been addressed.

6. CONCLUSION
We have surveyed, categorized and comparatively analyzed major research works in formal methods application on separation kernels. Our analytical framework clarifies the scope of formal methods application on separation kernels and characterizes the separation kernels. The taxonomy and survey of research works have distilled existing efforts in this field to the current date. This survey additionally gives an overview and limitations of existing works by a detailed comparison and analysis. We also highlight the challenges and future directions. With this snapshot of the overall research landscape, we thus hope the separation kernel community can better explore various potential opportunities to further improve the safety and security of separation kernel implementations and reduce the cost of development and certification by formal methods application.

REFERENCES
Jean-Raymond Abrial. 1996. The B-Book: Assigning Programs to Meanings. Cambridge University Press.
Jean-Raymond Abrial and Stefan Hallerstede. 2007. Refinement, Decomposition, and Instantiation of Discrete Models: Application to Event-B. Fundamenta Informaticae 77, 1-2 (2007), 1–28.
Jean-Raymond Abrial, Stephen A. Schuman, and Bertrand Meyer. 1980. Specification Language. In On the Construction of Programs. Cambridge University Press, 343–410.
Aeronautical Radio, Inc. 2010. ARINC Specification 653: Avionics Application Software Standard Interface, Part 1 - Required Services. Aeronautical Radio, Inc.
Aeronautical Radio, Inc. 2013. ARINC Specification 653: Avionics Application Software Standard Interface, Part 0 - Overview of ARINC 653. Aeronautical Radio, Inc.
Aeronautical Radio, Inc. 2015. ARINC Specification 653: Avionics Application Software Standard Interface, Part 1 - Required Services. Aeronautical Radio, Inc.
Alexandra Aguiar and Fabiano Hessel. 2012. Current Techniques and Future Trends in Embedded System’s Virtualization. Software: Practice and Experience 42, 7 (July 2012), 917–944.
AIR. 2015. AIR ARINC 653 Interface in Real-time Operating Systems. http://air.di.fc.ul.pt/. (2015). Accessed: 2015-07.
Yamine Ait-Ameur and Dominique Méry. 2016. Making Explicit Domain Knowledge in Formal System Development. Science of Computer Programming 121 (June 2016), 100–127.
Burns Alan and J. Davis Robert. 2015. Mixed Criticality Systems - A Review. Technical Report. Department of Computer Science, University of York.
Jade Alglave, Anthony Fox, Samin Ishtiaq, Magnus O Myreen, Susmit Sarkar, Peter Sewell, and Francesco Zappa Nardelli. 2009. The Semantics of Power and ARM Multiprocessor Machine Code. In Proc. of DAMP’09. ACM Press, 13–24.
Eyad Alkassar, Mark A. Hillebrand, Dirk Leinenbach, Norbert W. Schirmer, and Artem Starostin. 2008. The Verisoft Approach to Systems Verification. In Proc. of VSTTE’08. Springer, 209–224.
J. Alves-Foss, B. Rinker, M. Benke, J. Marshall, P. O’Connel, and C. Taylor. 2002. Formal Modelling of Security Policies for Multi-partition Systems. Technical Report.
Jim Alves-foss and Carol Taylor. 2004. An Analysis of the GWV Security Policy. In Proc. of ACL2’04.
Stanley R Ames Jr, Morrie Gasser, and Roger R Schell. 1983. Security Kernel Design and Implementation: An Introduction. Computer 16, 7 (July 1983), 14–22.
Passos André. 2009. Assessing the Formal Development of a Secure Partitioning Kernel with the B Method. In Proc. of ADCSS’09.
June Andrénick, Ross Jeffery, Gerwin Klein, Rafal Kolanski, Mark Staples, He Zhang, and Liming Zhu. 2012. Large-scale Formal Verification in Practice: A Process Perspective. In Proc. of ICSE’12. IEEE Press, 1002–1011.
Mikael Asberg, Paul Pettersson, and Thomas Nolte. 2011. Modelling, Verification and Synthesis of Two-Tier Hierarchical Fixed-Priority Preemptive Scheduling. In Proc. of ERTS’11. IEEE Press, 172–181.
James Barhorst, Todd Belote, Pam Blinns, Jon Hoffman, James Paunicka, Prakash Sarathy, John Scoredos, Peter Stanfill, Douglas Stuart, and Russell Urzi. 2009. A Research Agenda for Mixed-Criticality Systems. Cyber-Physical Systems Week (2009).
Christoph Baumann, Thorsten Borner, Holger Blasum, and Sergey Tverdyshev. 2011. Proving Memory Separation in a Microkernel by Code Level Verification. In Proc. of ISORCW’11. IEEE Press, 25–32.
Bernhard Beckert and Reiner Hahne. 2014. Reasoning and Verification: State of the Art and Current Trends. IEEE Intelligent Systems 29, 1 (January – February 2014), 20–29.
Holger Blasum, Sergey Tverdyshev, Bruno Langenstein, Werner Stephan, Abderrahmane Feliachi, Yakoub Nemouchi, Burkhan Wolff, Cyril Proch, Freek Verbeek, and Julien Schmaltz. 2015. EURO-MILS: Used Formal Methods. Technical Report. EURO-MILS Project.

Sandrine Blazy and Xavier Leroy. 2009. Mechanized Semantics for the Clight Subset of the C language. *Journal of Automated Reasoning* 43, 3 (October 2009), 263–288.

Jonathan P Bowen and Michael G Hinchey. 2006. Ten Commandments of Formal Methods... Ten Years Later. *Computer* 39, 1 (January 2006), 40–48.

Hao Chen, Xiongnan (Newman) Wu, Zhong Shao, Joshua Lockerman, and Ronghui Gu. 2016. Toward Compositional Verification of Interruptible OS Kernels and Device Drivers. In *Proc. of PLDI’16*. ACM Press, 431–447.

Edmund M Clarke and Jeannette M Wing. 1996. Formal Methods: State of the Art and Future Directions. *Comput. Surveys* 28, 4 (December 1996), 626–643.

Michael R Clarkson and Bernd Finkbeiner, Masoud Koleini, Kristopher K Micinski, Markus N Rabe, and César Sánchez. 2014. Temporal Logics for Hyperproperties. In *Proc. of POST’14*. Springer, 265–284.

Michael R. Clarkson and Fred B. Schneider. 2010. Hyperproperties. *Journal of Computer Security* 18, 6 (September 2010), 1157–1210.

Darren D Cofer and Murali Rangarajan. 2002. Formal Modeling and Analysis of Advanced Scheduling Features in an Avionics RTOS. In *Proceedings of the 2nd International Conference on Embedded Software*. Springer, Grenoble, France, 138–152.

Ernie Cohen, Wolfgang Paul, and Sabine Schmaltz. 2013. Theory of Multi Core Hypervisor Verification. In *Proc. of SOFSEM’13*. Springer, 1–27.

Rockwell Collins. 2015. Advanced Architecture MicroProcessor 7 Government Microprocessor (AAMP7G). https://www.rockwellcollins.com/Data/Products/InformationAssurance/Cryptography/AAMP7G_Microprocessor.aspx. (2015). Accessed: 2015-07.

David Costanzo, Zhong Shao, and Ronghui Gu. 2016. End-to-end Verification of Information-flow Security for C and Assembly Programs. In *Proc. of PLDI’16*. ACM Press, 648–664.

Iain Craig. 2007. *Formal Refinement for Operating System Kernels*. Springer.

D-MILS. 2014. *Analysis of State of the Art in Compositional Reasoning for Functional, Safety and Security Formal Verification*. Technical Report.

Mads Dam, Roberto Guanciale, Narges Khakpour, Hamed Nemati, and Oliver Schwarz. 2013. Formal Verification of Information Flow Security for a Simple ARM-based Separation Kernel. In *Proc. of CCS’13*. ACM Press, 223–234.

DDC-I. 2015. Deos safety-critical RTOS. http://www.ddci.com/products_deos.php. (2015). Accessed: 2015-07.

Pedro de la Cámara, J Raúl Castro, María del Mar Gallardo, and Pedro Merino. 2011. Verification Support for ARINC-653-based Avionics Software. *Software Testing, Verification and Reliability* 21, 4 (December 2011), 267–298.

Julien Delange, Laurent Pautet, and Fabrice Kordon. 2010. Modeling and Validation of ARINC653 Architectures. In *Proc. of ERTS’10*. 1 – 8.

Christian Esposito, Ricardo Barbosa, and Nuno Silva. 2013. Safety-critical Standards for Verification and Validation. In *Innovative Technologies for Dependable OTS-Based Critical Systems*. Springer, 41–53.

Thoms Dinsdale-Young, Lars Birkedal, Philippa Gardner, Matthew Parkinson, and Hongseok Yang. 2013. Views: Compositional Reasoning for Concurrent Programs. In *Proc. of POPL’13*. ACM Press, 287–300.

Anthony Fox and Magnus O Myreen. 2010. A Trustworthy Monadic Formalization of the ARMv7 Instruction Set Architecture. In *Innovative Technologies for Dependable OTS-Based Critical Systems*. Springer, 41–53.

Elena Fersman, Pavel Krcal, Paul Pettersson, and Wang Yi. 2007. Task Automata: Schedulability, Decidability and Undecidability. *Information and Computation* 205, 8 (August 2007), 1149–1172.

Shaked Flur, Kathryn E. Gray, Christopher Pulte, Susmit Sarkar, Ali Sezgin, Luc Maranget, Will Deacon, and Peter Sewell. 2016. Modelling the ARMv8 Architecture, Operationally: Concurrency and ISA. In *Proc. of POPL’16*. ACM Press, 608–621.

Anthony Fox. 2015. Improved Tool Support for Machine-Code Decompilation in HOL4. In *Proc. of ITP’15*. Springer, 187–202.

Anthony Fox and Magnus O Myreen. 2010. A Trustworthy Monadic Formalization of the ARMv7 Instruction Set Architecture. In *Proceedings of 1st International Conference on Interactive Theorem Proving*. Springer, Edinburgh, UK, 243–258.
Gerwin Klein, June Andronick, Kevin Elphinstone, Toby Murray, Thomas Sewell, Rafal Kolanski, and Gernot Heiser. 2014. Comprehensive Formal Verification of an OS Microkernel. ACM Transactions on Computer Systems 32, 1 (February 2014), 2:1–2:70.

Gerwin Klein, Kevin Elphinstone, Gernot Heiser, June Andronick, David Cock, Philip Derrin, Dhammika Elkaduwe, Kai Engelhardt, Rafal Kolanski, Michael Norrish, and others. 2009. seL4: Formal Verification of an OS Kernel. In Proc. of SOSP’09. ACM Press, 207–220.

Robbert Krebbers and Freek Wiedijk. 2015. A Typed C11 Semantics for Interactive Theorem Proving. In Proc. of CPP’15. ACM, 15–27.

Butler Lampson, Martin Abadi, Michael Burrows, and Edward Wobber. 1992. Authentication in Distributed Systems: Theory and Practice. ACM Transactions on Computer Systems 10, 4 (November 1992), 265–310.

Bernhard Leiner, Martin Schlager, Roman Obermaisser, and Bernhard Huber. 2007. A Comparison of Partitioning Operating Systems for Integrated Systems. In Proc. of SAFECOMP’07. Springer, 342–355.

Xavier Leroy. 2009. Formal Verification of A Realistic Compiler. Commun. ACM 52, 7 (July 2009), 107–115.

Michael Leuschel and Michael Butler. 2003. ProB: A Model Checker for B. In Proc. of FME’03. Springer, 855–874.

Timothy E. Levin, Cynthia E. Irvine, Clark Weissman, and Thuy D. Nguyen. 2007. Analysis of Three Multilevel Security Architectures. In Proc. of CSAW’07. ACM Press, 37–46.

Timothy E. Levin, Thuy D. Nguyen, and Cynthia E. Irvine. 2010. Separation Kernel Protection Profile Revisited: Choices and Rationale. Technical Report. DTIC.

W. B. Martin, P. D. White, and F. S. Taylor. 2002. Creating High Confidence in a Separation Kernel. Automated Software Engineering 9, 3 (August 2002), 263–284.

W. Martin, P. White, F. S. Taylor, and A. Goldberg. 2000. Formal Construction of the Mathematically Analyzed Separation Kernel. In Proc. of ASE’00. IEEE Press, 133–141.

Henry Massalin. 1992. Synthesis: An Efficient Implementation of Fundamental Operating System Services. Ph.D. Dissertation. Department of Computer Science, Columbia University.

National Security Agency 2007. U.S. Government Protection Profile for Separation Kernels in Environments Requiring High Robustness. National Security Agency.

National Security Agency 2012. Common criteria for information technology security evaluation (3.1 r4 ed.). National Security Agency.

Tobias Nipkow, Markus Wenzel, and Lawrence Paulson. 2002. Isabelle/HOL: A Proof Assistant for Higher-order Logic. Springer-Verlag.

M. Norrish. 1998. C Formalized in HOL. Technical Report 517D. University of Cambridge.

Artur Oliveira Gomes. 2012. Formal Specification of the ARINC 653 Architecture Using Circus. Master’s thesis. Department of Computer Science, University of York.

ACM Journal Name, Vol. 1, No. 1, Article 1, Publication date: January 2017.
OpenGroup. 2003. *Protection Profile for Partitioning Kernels in Environments Requiring Augmented High Robustness*. Technical Report. The Open Group.

Nikolaos S. Papaspyrou. 2001. Denotational Semantics of ANSI C. *Computer Standards & Interfaces* 23, 3 (July 2001), 169–185.

Paul Parkinson. 2011. Safety, Security and Multicore. In *Proc. of SSS’09*. Springer, 215–232.

Gordon R Parr and R Edwards. 1999. Integrated Modular Avionics. *Air & Space Europe* 1, 2 (1999), 72–75.

Karger Paul. 2005. Multi-level Security Requirements for Hypervisors. In *Proc. of ACSAC’05*. IEEE Press, 277 – 275.

John Penix, Willem Visser, Eric Engstrom, Aaron Larson, and Nicholas Weininger. 2000. Verification of time partitioning in the DEOS scheduler kernel. In *Proc. of ICSE’00*. ACM Press, 488–497.

John Penix, Willem Visser, Seunghoon Park, Corina Pasareanu, Eric Engstrom, Aaron Larson, and Nicholas Weininger. 2005. Verifying Time Partitioning in the DEOS Scheduling Kernel. *Formal Methods in System Design* 26, 2 (March 2005), 103–135.

David Phelps, Mikhail Auguston, and Timothy E. Levin. 2008. Formal Models of a Least Privilege Separation Kernel in Alloy. Technical Report. DTIC Document.

POK. 2015. POK: A Partitioned Operating System. http://pok.tuxfamily.org/. (2015). Accessed: 2015-07.

PROSPER. 2015. PROSPER Hypervisor. http://prosper.sics.se/. (2015). Accessed: 2015-07.

Kriithi Ramamritham and John A Stankovic. 1994. Scheduling Algorithms and Operating Systems Support for Real-time Systems. *Proc. IEEE* 82, 1 (January 1994), 55–67.

Adrian Garcia Ramirez, Julien Schmalz, Freek Verbeek, Bruno Langenstein, and Holger Blasum. 2014. On Two Models of Noninterference: Rushby and Greve, Wilding, and Vanfleet. In *Proc. of SAFECOM’14*. Springer, 246–261.

Raymond J. Richards. 2010. Modeling and Security Analysis of a Commercial Real-Time Operating System Kernel. In *Design and Verification of Microprocessor Systems for High-Assurance Applications*. Springer, 301–322.

Reiner Sailer, Trent Jaeger, Enriquillo Valdez, Ramon Caceres, Ronald Perez, Stefan Berger, John Linwood Griffin, and Leendert Van Doorn. 2005a. Building a MAC-based Security Architecture for the Xen Open-source Hypervisor. In *Proc. of ACSAC’05*. IEEE Press, 276 – 285.

Reiner Sailer, Enriquillo Valdez, Trent Jaeger, Ronald Perez, Leendert Van Doorn, John Linwood Griffin, Stefan Berger, Leendert Doorn, John Linwood, and Griffin Stefan Berger. 2005b. sHype: Secure Hypervisor Approach to Trusted Virtualized Systems. Technical Report RC23511. IBM.

Andrei Sabelfeld and Andrew C. Myers. 2003. Language-based Information-flow Security. *IEEE Journal on Selected Areas in Communications* 21, 1 (January 2003), 5–19.

F. Singhoff, J. Legrand, L. Nana, and L. Marcé. 2004. Cheddar: A Flexible Real Time Scheduling Framework. In *Proc. of SIGAda’04*. ACM Press, 1–8.

Frank Singhoff and Alain Plantec. 2007. AADL Modeling and Analysis of Hierarchical Schedulers. In *Proc. of SIGAda’07*. ACM Press, 41–50.
SYSGO. 2015. SYSGO PikeOS Hypervisor. https://www.sysgo.com/products/pikeos-rtos-and-virtualization-concept/. (2015). Accessed: 2015-07.

Cog Systems. 2015. OKL4 Microvisor. http://cog.systems/products/okl4-microvisor.shtml. (2015). Accessed: 2015-07.

Hendrik Tews, Tjark Weber, Marcus Volp, Erik Poll, Mark van Eekelen, and Peter van Rossum. 2008. Nova Micro-Hypervisor Verification. Technical Report. Radboud University Nijmegen, The Netherlands.

Sergey Tverdyshev. 2011. Extending the GWV Security Policy and Its Modular Application to a Separation Kernel. In Proc. of NFM’11. Springer, 391–405.

Ron Van Der Meyden. 2012. Architectural Refinement and Notions of Intransitive Noninterference. Formal Aspects of Computing 24, 4 (July 2012), 769–792.

Ron van der Meyden and Chenyi Zhang. 2010. A Comparison of Semantic Models for Noninterference. Theoretical Computer Science 411, 47 (October 2010), 4123–4147.

Steven H VanderLeest. 2010. ARINC 653 Hypervisor. In Proc. of DASC’10. IEEE Press, 5.E.2–1 – 5.E.2–20.

Steven H VanderLeest, David Greve, and Paul Skentzos. 2013. A Safe & Secure ARINC 653 Hypervisor. In Proc. of DASC’13. IEEE Press, 7.B.4–1 – 7.B.4–17.

W Mark Vanfleet, Jahn A Luke, R William Beckwith, Carol Taylor, Ben Calloni, and Gordon Uchenick. 2005. MILS: Architecture for High-assurance Embedded Computing. CrossTalk 18, 8 (2005), 12–16.

Andrius Velkyis and Leo Freitas. 2010. Formal Modelling of Separation Kernel Components. In Proc. of ICTAC’10. Springer, 230–244.

Freek Verbeek, Oto Havle, Julien Schmaltz, Sergey Tverdyshev, Holger Blasum, Bruno Langenstein, Werner Stephan, Burkhard Wolff, and Yakoub Nemouchi. 2015. Formal API Specification of the PikeOS Separation Kernel. In Proc. of NFM’15. Springer, 375–389.

Freek Verbeek, Sergey Tverdyshev, Oto Havle, Holger Blasum, Bruno Langenstein, Werner Stephan, Yakoub Nemouchi, Abderrahmane Feliachi, Burkhart Wolff, and Julien Schmaltz. 2014. Formal Specification of a Generic Separation Kernel. Archive of Formal Proofs (2014).

David van Oheimb. 2004. Information Flow Control Revisited: Noninfluence= Noninterference+ Nonleakage. In Proc. of ESORICS’04. Springer, 225–243.

Ying Wang, Dianfu Ma, Yongwang Zhao, Lu Zou, and Xianqi Zhao. 2011. An AADL-based Modeling Method for ARINC653-based Avionics Software. In Proc. of COMPSAC’11. IEEE Press, 224–229.

Richard West, Ye Li, Eric Missimer, and Matthew Danish. 2016. A Virtualized Separation Kernel for Mixed-Criticality Systems. ACM Transactions on Computer Systems 34, 3 (June 2016), 8:1–8:41.

Freek Wiedijk. 2006. The Seventeen Provers of the World. Lecture Notes in Computer Science, Vol. 3600. Springer-Verlag.

Matthew M Wilding, David A Greve, Raymond J Richards, and David S Hardin. 2010. Formal Verification of Partition Management for the AAMP7G Microprocessor. In Design and Verification of Microprocessor Systems for High-Assurance Applications. Springer, 175–191.

WindRiver. 2015a. Wind River VxWorks 653 Platform. http://www.windriver.com/products/vxworks/certification-profiles/. (2015). Accessed: 2015-07.

WindRiver. 2015b. Wind River VxWorks MILS Platform. http://www.windriver.com/products/vxworks/certification-profiles/. (2015). Accessed: 2015-07.

William Wulf, Ellis Cohen, William Corwin, Anita Jones, Roy Levin, Charles Pierson, and Fred Pollack. 1974. Hydra: The Kernel of a Multiprocessor Operating System. Commun. ACM 17, 6 (June 1974), 337–345.

XtratuM. 2015. XtratuM Hypervisor. http://www.xtratum.org/. (2015). Accessed: 2015-07.

2016. A Practical Verification Framework for Preemptive OS Kernels. In Proc. of CAV’16. Springer, 59–79.

Alexandros Zerzelidis and Andy Wellings. 2006. Getting more flexible scheduling in the rtsj. In Proc. of ISORC’06. IEEE Press, 8.

Yongwang Zhao, David Sanán, Fuyuan Zhang, and Yang Liu. 2016a. Formal Specification and Analysis of Partitioning Operating Systems by Integrating Ontology and Refinement. IEEE Transactions on Industrial Informatics 12, 4 (August 2016), 1321 – 1331.

Yongwang Zhao, David Sanán, Fuyuan Zhang, and Yang Liu. 2016b. Reasoning About Information Flow Security of Separation Kernels with Channel-Based Communication. In Proc. of TACAS’16. Springer, 791–810.

ACM Journal Name, Vol. 1, No. 1, Article 1, Publication date: January 2017.
Yongwang Zhao, Zhibin Yang, and Dianfu Ma. 2016c. A Survey on Formal Specification and Verification of Separation Kernels. *Frontiers of Computer Science* (2016). To appear (submitted in May, 2014).

Yongwang Zhao, Zhibin Yang, and David Sanan. 2015. Event-based Formalization of Safety-critical Operating System Standards: An Experience Report on ARINC 653 using Event-B. In *Proc. of ISSRE’15*. IEEE Press, 281 – 292.