Applied Control Theory For Embedded Systems

Applied Control Theory For Embedded Systems Applied Control Theory for Embedded Systems Bridging Theory and Practice Embedded systems the tiny computers powering everything from smartphones to automobiles often require precise and responsive control over physical processes This is where applied control theory plays a crucial role It bridges the gap between theoretical understanding of system dynamics and the practical implementation of control algorithms within the resourceconstrained environment of an embedded system This article delves into the key aspects of applying control theory in this context explaining the principles and challenges involved Understanding the Fundamentals Control theory at its core is about influencing the behavior of a system to achieve a desired outcome Imagine a thermostat controlling room temperature it measures the current temperature feedback compares it to the setpoint desired temperature and adjusts the heatingcooling system control action accordingly This simple example encapsulates the fundamental components of a control system Plant The system to be controlled eg a motor a chemical reactor a robotic arm Controller The algorithm that calculates the control action based on feedback Actuator The device that applies the control action to the plant eg a valve a motor driver Sensor The device that measures the plants state and provides feedback to the controller eg a temperature sensor a position encoder The controller utilizes a control algorithm often based on mathematical models of the plants dynamics These models describe how the plant responds to changes in its inputs Accurate modeling is critical for effective control design However in embedded systems model complexity must be carefully balanced against computational constraints Common Control Algorithms in Embedded Systems Several control algorithms are particularly wellsuited for embedded systems due to their computational efficiency and robustness 2 PID Control ProportionalIntegralDerivative This ubiquitous algorithm is widely used due to its simplicity and effectiveness It calculates the control signal based on the error difference between the setpoint and measured value its integral accumulated error and its derivative rate of change of the error PID controllers are easily tuned and adaptable to a wide range of systems However they require careful tuning to avoid instability or poor performance StateSpace Control This more advanced technique uses a mathematical representation of the systems state its internal variables to design the controller It allows for more sophisticated control strategies including optimal control and robust control which are less sensitive to model uncertainties However statespace methods are computationally more demanding and require a deeper understanding of linear algebra Model Predictive Control MPC MPC predicts the future behavior of the plant based on a model and optimizes the control actions to minimize a cost function over a prediction horizon This allows for handling constraints and anticipating future disturbances However MPC is computationally intensive requiring efficient algorithms and powerful processors for real time implementation in embedded systems Fuzzy Logic Control This approach uses fuzzy sets and fuzzy rules to represent the systems behavior and control actions It is particularly useful for systems with complex and imprecisely defined dynamics making it suitable for handling uncertainties and nonlinearities Its inherent

robustness makes it wellsuited for embedded systems Challenges in Implementing Control Theory on Embedded Systems Implementing control algorithms in embedded systems presents unique challenges Resource Constraints Embedded systems typically have limited processing power memory and energy resources This necessitates the use of efficient algorithms and optimized code Simplified control algorithms or reduced sampling rates might be necessary to meet realtime constraints RealTime Requirements Many control applications require realtime performance meaning the control actions must be computed and executed within strict time deadlines Missed deadlines can lead to instability or system failure Careful scheduling and resource allocation are crucial Noise and Disturbances Sensors and actuators are prone to noise and disturbances which 3 can affect the accuracy and performance of the control system Robust control techniques are necessary to mitigate these effects HardwareSoftware Codesign Effective control system design often requires close interaction between hardware and software engineers The choice of hardware components microcontroller sensors actuators significantly impacts the performance and feasibility of the control algorithm Design Considerations for Embedded Systems Successful implementation of control theory in embedded systems requires careful consideration of several factors Sampling Rate The frequency at which the controller receives sensor data and updates the control action A higher sampling rate improves responsiveness but increases computational load Quantization Effects The conversion of continuous signals to discrete values in digital systems can introduce quantization errors affecting control accuracy Antialiasing Filtering Filtering techniques are crucial to eliminate highfrequency noise that can alias into the control loop causing instability Software Development Tools Selecting appropriate realtime operating systems RTOS and development environments is essential for efficient and reliable code generation Conclusion Key Takeaways Applying control theory to embedded systems offers the potential for highly precise and responsive control of physical processes However it requires careful consideration of resource constraints realtime requirements and the unique challenges posed by the embedded environment Choosing appropriate control algorithms employing efficient implementation techniques and conducting thorough testing are all essential steps towards successful implementation Frequently Asked Questions FAQs 1 What programming languages are commonly used for embedded control systems C and C are dominant due to their efficiency and closetohardware access However languages like Python are gaining traction for prototyping and higherlevel tasks 2 How do I choose the right control algorithm for my embedded system The choice depends on the complexity of the plant the desired performance and the available resources Start 4 with simpler algorithms like PID and move to more advanced methods if necessary 3 What is the role of an RTOS in embedded control systems An RTOS RealTime Operating System provides scheduling and resource management capabilities ensuring timely execution of control tasks and preventing missed deadlines 4 How can I deal with sensor noise in my embedded control system Employ filtering techniques eg moving average Kalman filter to reduce noise and consider robust control methods to lessen the impact of uncertainties 5 What are some common debugging techniques for embedded control systems Utilize debugging tools like oscilloscopes logic analyzers and debuggers to monitor signals identify errors and validate the control algorithms performance Careful logging and data analysis are also invaluable

Embedded System DesignSoftware Engineering for Embedded SystemsEmbedded System DesignSoftware Engineering for

Embedded SystemsEmbedded Systems SecurityEmbedded Systems ArchitectureAn Embedded Software PrimerSoftware Engineering for Embedded SystemsDesign Patterns for Embedded Systems in CDesign Principles for Embedded SystemsReal-Time Concepts for Embedded SystemsComponent-Based Software Development for Embedded SystemsC++ in Embedded SystemsMaking Embedded SystemsIntroduction to Embedded SystemsIntelligence for Embedded SystemsElectronics for Embedded SystemsEmbedded and Real Time System Development: A Software Engineering PerspectiveEmbedded System ApplicationsLanguages for Embedded Systems and their Applications Peter Marwedel Robert Oshana Peter Marwedel Robert Oshana David Kleidermacher Daniele Lacamera David E. Simon Robert Oshana Bruce Powel Douglass KCS Murti Qing Li Colin Atkinson Amar Mahmutbegovi□ Elecia White Manuel Jiménez Cesare Alippi Ahmet Bindal Mohammad Ayoub Khan Jean-Claude Baron Martin Radetzki

Embedded System Design Software Engineering for Embedded Systems Embedded System Design Software Engineering for Embedded Systems Embedded Systems Security Embedded Systems Architecture An Embedded Software Primer Software Engineering for Embedded Systems Design Patterns for Embedded Systems in C Design Principles for Embedded Systems Real-Time Concepts for Embedded Systems Component-Based Software Development for Embedded Systems C++ in Embedded Systems Making Embedded Systems Introduction to Embedded Systems Intelligence for Embedded Systems Electronics for Embedded Systems Embedded and Real Time System Development: A Software Engineering Perspective Embedded System Applications Languages for Embedded Systems and their Applications *Peter Marwedel Robert Oshana Peter Marwedel Robert Oshana David Kleidermacher Daniele Lacamera David E. Simon Robert Oshana Bruce Powel Douglass KCS Murti Qing Li Colin Atkinson Amar Mahmutbegovi□ Elecia White Manuel Jiménez Cesare Alippi Ahmet Bindal Mohammad Ayoub Khan Jean-Claude Baron Martin Radetzki*

until the late 1980s information processing was associated with large mainframe computers and huge tape drives during the 1990s this trend shifted toward information processing with personal computers or pcs the trend toward miniaturization continues and in the future the majority of information processing systems will be small mobile computers many of which will be embedded into larger products and interfaced to the physical environment hence these kinds of systems are called embedded systems embedded systems together with their physical environment are called cyber physical systems examples include systems such as transportation and fabrication equipment it is expected that the total market volume of embedded systems will be significantly larger than that of traditional information processing systems such as pcs and mainframes embedded systems share a number of common characteristics for example they must be dependable efficient meet real time constraints and require customized user interfaces instead of generic keyboard and mouse interfaces therefore it makes sense to consider common principles of embedded system design embedded system design starts with an introduction into the area and a survey of specification models and languages for embedded and cyber physical systems it provides a brief overview of hardware devices used for such systems and presents the essentials of system software for embedded systems like real time operating systems the book also discusses evaluation and validation techniques for embedded systems furthermore the book presents an overview of techniques for mapping applications to execution platforms due to the importance of resource efficiency the book also contains a selected set of

optimization techniques for embedded systems including special compilation techniques the book closes with a brief survey on testing embedded system design can be used as a text book for courses on embedded systems and as a source which provides pointers to relevant material in the area for phd students and teachers it assumes a basic knowledge of information processing hardware and software courseware related to this book is available at ls12 cs tu dortmund de marwedel

this expert guide gives you the techniques and technologies in software engineering to optimally design and implement your embedded system written by experts with a solutions focus this encyclopedic reference gives you an indispensable aid to tackling the day to day problems when using software engineering methods to develop your embedded systems with this book you will learn the principles of good architecture for an embedded system design practices to help make your embedded project successful details on principles that are often a part of embedded systems including digital signal processing safety critical principles and development processes techniques for setting up a performance engineering strategy for your embedded system software how to develop user interfaces for embedded systems strategies for testing and deploying your embedded system and ensuring quality development processes practical techniques for optimizing embedded software for performance memory and power advanced guidelines for developing multicore software for embedded systems how to develop embedded software for networking storage and automotive segments how to manage the embedded development process includes contributions from frank schirrmeister shelly gretlein bruce douglass erich styger gary stringham jean labrosse jim trudeau mike brogioli mark pitchford catalin dan udma markus levy pete wilson whit waldo inga harris xinxin yang srinivasa addepalli andrew mckay mark kraeling and robert oshana road map of key problems issues and references to their solution in the text review of core methods in the context of how to apply them examples demonstrating timeless implementation details short and to the point case studies show how key ideas can be implemented the rationale for choices made and design guidelines and trade offs

a unique feature of this open access textbook is to provide a comprehensive introduction to the fundamental knowledge in embedded systems with applications in cyber physical systems and the internet of things it starts with an introduction to the field and a survey of specification models and languages for embedded and cyber physical systems it provides a brief overview of hardware devices used for such systems and presents the essentials of system software for embedded systems including real time operating systems the author also discusses evaluation and validation techniques for embedded systems and provides an overview of techniques for mapping applications to execution platforms including multi core platforms embedded systems have to operate under tight constraints and hence the book also contains a selected set of optimization techniques including software optimization techniques the book closes with a brief survey on testing this fourth edition has been updated and revised to reflect new trends and technologies such as the importance of cyber physical systems cps and the internet of things iot the evolution of single core processors to multi core processors and the increased importance of energy efficiency and thermal issues

software engineering for embedded systems methods practical techniques and applications second edition provides the

techniques and technologies in software engineering to optimally design and implement an embedded system written by experts with a solution focus this encyclopedic reference gives an indispensable aid on how to tackle the day to day problems encountered when using software engineering methods to develop embedded systems new sections cover peripheral programming internet of things security and cryptography networking and packet processing and hands on labs users will learn about the principles of good architecture for an embedded system design practices details on principles and much more provides a roadmap of key problems issues and references to their solution in the text reviews core methods and how to apply them contains examples that demonstrate timeless implementation details users case studies to show how key ideas can be implemented the rationale for choices made and design guidelines and trade offs

the ultimate resource for making embedded systems reliable safe and secure embedded systems security provides a broad understanding of security principles concerns and technologies proven techniques for the efficient development of safe and secure embedded software a study of the system architectures operating systems and hypervisors networking storage and cryptographic issues that must be considered when designing secure embedded systems nuggets of practical advice and numerous case studies throughout written by leading authorities in the field with 65 years of embedded security experience one of the original developers of the world s only common criteria eal 6 security certified software product and a lead designer of nsa certified cryptographic systems this book is indispensable for embedded systems and security professionals new and experienced an important contribution to the understanding of the security of embedded systems the kleidermachers are experts in their field as the internet of things becomes reality this book helps business and technology management as well as engineers understand the importance of security from scratch this book with its examples and key points can help bring more secure robust systems to the market dr joerg borchert vice president chip card security infineon technologies north america corp president and chairman trusted computing group embedded systems security provides real world examples of risk and exploitation most importantly the book offers clear insight into methods used to counter vulnerabilities to build true native security into technology adriel desautels president and cto netragard llc security of embedded systems is more important than ever the growth in networking is just one reason however many embedded systems developers have insufficient knowledge of how to achieve security in their systems david kleidermacher a world renowned expert in this field shares in this book his knowledge and long experience with other engineers a very important book at the right time prof dr ing matthias sturm leipzig university of applied sciences chairman embedded world conference steering board gain an understanding of the operating systems microprocessors and network security critical issues that must be considered when designing secure embedded systems contains nuggets of practical and simple advice on critical issues highlighted throughout the text short and to the point real case studies included to demonstrate embedded systems security in practice

learn embedded systems development with practical design patterns essential workflows and memory safe techniques to build secure reliable and energy efficient devices key features tackle real world challenges in embedded development from boot up to distributed iot systems apply memory management peripheral integration and power optimization techniques build robust secure and scalable solutions with practical guidance on rtos and task scheduling book descriptionembedded

systems are self contained devices with a dedicated purpose we come across a variety of fields of applications for embedded systems in industries such as automotive telecommunications healthcare and consumer electronics just to name a few embedded systems architecture begins with a bird s eye view of embedded development and how it differs from the other systems that you may be familiar with you will first be guided to set up an optimal development environment then move on to software tools and methodologies to improve the work flow you will explore the boot up mechanisms and the memory management strategies typical of a real time embedded system through the analysis of the programming interface of the reference microcontroller you ll look at the implementation of the features and the device drivers next you ll learn about the techniques used to reduce power consumption then you will be introduced to the technologies protocols and security aspects related to integrating the system into iot solutions by the end of the book you will have explored various aspects of embedded architecture including task synchronization in a multi threading environment and the safety models adopted by modern real time operating systems what you will learn participate in the design and definition phase of an embedded product get to grips with writing code for arm cortex m microcontrollers build an embedded development lab and optimize the workflow write memory safe code understand the architecture behind the communication interfaces understand the design and development patterns for connected and distributed devices in the iot master multitask parallel execution patterns and real time operating systems who this book is for this book is for software developers and designers seeking a practical introduction to embedded programming as well as early career embedded engineers wanting to deepen their understanding of architecture workflows and real world system design readers interested in stm32 memory and power management rtos and iot solutions will benefit most from this comprehensive guide

simon introduces the broad range of applications for embedded software and then reviews each major issue facing developers offering practical solutions techniques and good habits that apply no matter which processor real time operating systems methodology or application is used

this expert guide gives you the techniques and technologies in software engineering to optimally design and implement your embedded system written by experts with a solutions focus this encyclopedic reference gives you an indispensable aid to tackling the day to day problems when using software engineering methods to develop your embedded systems with this book you will learn the principles of good architecture for an embedded system design practices to help make your embedded project successful details on principles that are often a part of embedded systems including digital signal processing safety critical principles and development processes techniques for setting up a performance engineering strategy for your embedded system software how to develop user interfaces for embedded systems strategies for testing and deploying your embedded system and ensuring quality development processes practical techniques for optimizing embedded software for performance memory and power advanced guidelines for developing multicore software for embedded systems how to develop embedded software for networking storage and automotive segments how to manage the embedded development process includes contributions from frank schirrmeister shelly gretlein bruce douglass erich styger gary stringham jean labrosse jim trudeau mike brogioli mark pitchford catalin dan udma markus levy pete wilson whit waldo inga harris xinxin yang srinivasa addepalli andrew mckay mark kraeling and robert oshana road map of key

problems issues and references to their solution in the text review of core methods in the context of how to apply them examples demonstrating timeless implementation details short and to the point case studies show how key ideas can be implemented the rationale for choices made and design guidelines and trade offs

a recent survey stated that 52 of embedded projects are late by 4 5 months this book can help get those projects in on time with design patterns the author carefully takes into account the special concerns found in designing and developing embedded applications specifically concurrency communication speed and memory usage patterns are given in uml unified modeling language with examples including ansi c for direct and practical application to c code a basic c knowledge is a prerequisite for the book while uml notation and terminology is included general c programming books do not include discussion of the contraints found within embedded system design the practical examples give the reader an understanding of the use of uml and oo object oriented designs in a resource limited environment also included are two chapters on state machines the beauty of this book is that it can help you today design patterns within these pages are immediately applicable to your project addresses embedded system design concerns such as concurrency communication and memory usage examples contain ansi c for ease of use with c programming code

the book is designed to serve as a textbook for courses offered to graduate and undergraduate students enrolled in electronics and electrical engineering and computer science this book attempts to bridge the gap between electronics and computer science students providing complementary knowledge that is essential for designing an embedded system the book covers key concepts tailored for embedded system design in one place the topics covered in this book are models and architectures executable specific languages systemc unified modeling language real time systems real time operating systems networked embedded systems embedded processor architectures and platforms that are secured and energy efficient a major segment of embedded systems needs hard real time requirements this textbook includes real time concepts including algorithms and real time operating system standards like posix threads embedded systems are mostly distributed and networked for deterministic responses the book covers how to design networked embedded systems with appropriate protocols for real time requirements each chapter contains 2 3 solved case studies and 10 real world problems as exercises to provide detailed coverage and essential pedagogical tools that make this an ideal textbook for students enrolled in electrical and electronics engineering and computer science programs

a very good balance between the theory and practice of real time embedded system designs jun ichiro itojun hagino ph d research laboratory internet initiative japan inc ietf ipv6 operations working group v6ops co chair a cl

embedded systems are ubiquitous they appear in cell phones microwave ovens refrigerators consumer electronics cars and jets some of these embedded s tems are safety or security critical such as in medical equipment nuclear plants and x by wire control systems in naval ground and aerospace transportation hicles with the continuing shift from hardware to software embedded systems are increasingly dominated by embedded software embedded software is complex its engineering inherently involves a mul disciplinary interplay with the physics of the embedding system or environment

embedded software also comes in ever larger quantity and diversity the next generation of premium automobiles will carry around one gigabyte of binary code the proposed us ddx submarine is e ectively a oating embedded so ware system comprising 30 billion lines of code written in over 100 programming languages embedded software is expensive cost estimates are quoted at around us 15 30 per line from commencement to shipping in the defense realm costs can range up to 100 while for highly critical applications such as the space shuttle the cost per line approximates 1 000 in view of the exponential increase in complexity the projected costs of future embedded software are staggering

go beyond c by applying modern c in embedded systems to enhance code readability maintainability and scalability key features bridge the gap between c and modern c for embedded systems through practical examples learn how to save memory and cut down on runtime computing using compile time computation techniques improve your software design skills by applying patterns to solve common problems in embedded systems using c purchase of the print or kindle book includes a free pdf ebook book description transitioning from c can be daunting with concerns about performance overhead added complexity and unfamiliar tooling addressing these challenges amar mahmutbegovic an advocate for modern c in embedded development shows you how to harness zero cost abstractions compile time checks and powerful modern c capabilities to preserve performance while achieving safer cleaner code this book bridges the gap between traditional c and advanced c helping you retain the efficiency c developers demand while unlocking the safety and expressiveness of modern c starting with a modern development environment setup including a docker container for seamless example replication you ll overcome the hurdles of using the c standard library in memory constrained settings and get acquainted with the embedded template library etl as an alternative the book walks you through essential c concepts before exploring advanced topics such as templates strong typing error handling compile time computation and raii through practical examples you ll implement a sequencer write a type safe hal and apply patterns like command state and observer to solve common embedded development problems by the end of this book you ll have learned how to apply modern c to develop robust modular firmware with performance matching or exceeding hand coded c solutions what you will learn debunk myths and misconceptions about using c in embedded systems set up build automation tailored for c in constrained environments leverage strong typing to improve type safety apply modern c techniques such as resource acquisition is initialization raii use domain specific language dsl with a practical example using boost sml implement software development best practices including the solid principle in embedded development who this book is for this book is for embedded developers who primarily use c and want to adopt a modern c approach it introduces fundamental c concepts making it suitable for beginners while also assuming basic familiarity to fully leverage advanced features like compile time computation even those with prior c experience will discover new ways to apply modern best practices to write more efficient and maintainable embedded applications

eager to develop embedded systems these systems don t tolerate inefficiency so you may need a more disciplined approach to programming this easy to read book helps you cultivate a host of good development practices based on classic software design patterns as well as new patterns unique to embedded programming you not only learn system architecture but also specific techniques for dealing with system constraints and manufacturing requirements written by an expert who

s created embedded systems ranging from urban surveillance and dna scanners to children s toys making embedded systems is ideal for intermediate and experienced programmers no matter what platform you use develop an architecture that makes your software robust and maintainable understand how to make your code smaller your processor seem faster and your system use less power learn how to explore sensors motors communications and other i o devices explore tasks that are complicated on embedded systems such as updating the software and using fixed point math to implement complex algorithms

this textbook serves as an introduction to the subject of embedded systems design using microcontrollers as core components it develops concepts from the ground up covering the development of embedded systems technology architectural and organizational aspects of controllers and systems processor models and peripheral devices since microprocessor based embedded systems tightly blend hardware and software components in a single application the book also introduces the subjects of data representation formats data operations and programming styles the practical component of the book is tailored around the architecture of a widely used texas instrument s microcontroller the msp430 and a companion web site offers for download an experimenter s kit and lab manual along with powerpoint slides and solutions for instructors

addressing current issues of which any engineer or computer scientist should be aware this monograph is a response to the need to adopt a new computational paradigm as the methodological basis for designing pervasive embedded systems with sensor capabilities the requirements of this paradigm are to control complexity to limit cost and energy consumption and to provide adaptation and cognition abilities allowing the embedded system to interact proactively with the real world the quest for such intelligence requires the formalization of a new generation of intelligent systems able to exploit advances in digital architectures and in sensing technologies the book sheds light on the theory behind intelligence for embedded systems with specific focus on robustness the robustness of a computational flow and its evaluation intelligence how to mimic the adaptation and cognition abilities of the human brain the capacity to learn in non stationary and evolving environments by detecting changes and reacting accordingly and a new paradigm that by accepting results that are correct in probability allows the complexity of the embedded application the be kept under control theories concepts and methods are provided to motivate researchers in this exciting and timely interdisciplinary area applications such as porting a neural network from a high precision platform to a digital embedded system and evaluatin g its robustness level are described examples show how the methodology introduced can be adopted in the case of cyber physical systems to manage the interaction between embedded devices and physical world researchers and graduate students in computer science and various engineering related disciplines will find the methods and approaches propounded in intelligence for embedded systems of great interest the book will also be an important resource for practitioners working on embedded systems and applications

this book provides semester length coverage of electronics for embedded systems covering most common analog and digital circuit related issues encountered while designing embedded system hardware it is written for students and young

professionals who have basic circuit theory background and want to learn more about passive circuits diode and bipolar transistor circuits the state of the art cmos logic family and its interface with older logic families such as ttl sensors and sensor physics operational amplifier circuits to condition sensor signals data converters and various circuits used in electro mechanical device control in embedded systems the book also provides numerous hardware design examples by integrating the topics learned in earlier chapters the last chapter extensively reviews the combinational and sequential logic design principles to be able to design the digital part of embedded system hardware

nowadays embedded and real time systems contain complex software the complexity of embedded systems is increasing and the amount and variety of software in the embedded products are growing this creates a big challenge for embedded and real time software development processes and there is a need to develop separate metrics and benchmarks embedded and real time system development a software engineering perspective concepts methods and principles presents practical as well as conceptual knowledge of the latest tools techniques and methodologies of embedded software engineering and real time systems each chapter includes an in depth investigation regarding the actual or potential role of software engineering tools in the context of the embedded system and real time system the book presents state of the art and future perspectives with industry experts researchers and academicians sharing ideas and experiences including surrounding frontier technologies breakthroughs innovative solutions and applications the book is organized into four parts embedded software development process design patterns and development methodology modelling framework and performance analysis power management and deployment with altogether 12 chapters the book is aiming at i undergraduate students and postgraduate students conducting research in the areas of embedded software engineering and real time systems ii researchers at universities and other institutions working in these fields and iii practitioners in the r d departments of embedded system it can be used as an advanced reference for a course taught at the postgraduate level in embedded software engineering and real time systems

embedded systems take over complex control and data processing tasks in diverse application elds such as automotive avionics consumer products and telec munications they are the primary driver for improving overall system safety ef ciency and comfort the demand for further improvement in these aspects can only be satis ed by designing embedded systems of increasing complexity which in turn necessitates the development of new system design methodologies based on speci cation design and veri cation languages the objective of the book at hand is to provide researchers and designers with an overview of current research trends results and application experiences in c puter languages for embedded systems the book builds upon the most relevant contributions to the 2008 conference forum on design languages fdl the p mier international conference specializing in this eld these contributions have been selected based on the results of reviews provided by leading experts from search and industry in many cases the authors have improved their original work by adding breadth depth or explanation

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