SZZ 国考生存手册

State Final Examination Survival Kit

Czech Technical University in Prague (FEE)

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Contents

Part I

答辩策略 / Defense Strategy

1 SZZ Scope & Priority Matrix / 国考范围与优先级总表

ANALYSIS: 个人定制分析 / Personalized Analysis

CN: 此表格基于你的学习记录自动生成。
EN: This table is auto-generated from your study records.

专业方向: Power Engineering (EN1/EN2)

1.1 Compulsory Topics (必考 - 2 Questions) / 必修科目

Topic	Course / 科目	Priority	Strategy / 策略
	MATHEMATICS 数学		
1	BE5B01LAL Linear Algebra	**CRITICAL**	**SURVIVAL**: 背公式，不推导
2,3	BE5B01DEN Numerical+DiffEq	**CRITICAL**	**SURVIVAL**: Newton-Raphson 记死
4,5	BE5B01DMG Discrete+Graph	**CRITICAL**	**SURVIVAL**: 集合论+图遍历
6	BE5B01PRS Probability	**SHOW OFF**	**ATTACK**: Bayes →传感器融合
	PHYSICS 物理		
7,8,9	BE5B02PH1 Physics 1	**CAUTION**	**FOCUS**: F=ma →加速度计原理
10,11	BE5B02PH2 Physics 2	**CAUTION**	**FOCUS**: 热力学→ ESP32 散热
	EECS CORE 电子信息核心		
12	BE5B31ZEO Circuits	**CAUTION**	**FOCUS**: KVL/KCL →传感器电路
13,14	BE5B34ELP Electron Devices	**SHOW OFF**	**ATTACK**: 半导体→你很熟练!
15	BE5B34MIK Microcontrollers	**SHOW OFF**	**ATTACK**: ESP32 是你的主场!
16	BE5B33PRG/PGE Algorithms	**STABLE**	**HOLD**: 基础数据结构即可

1.2 Specialization Topic (选考 - 1 Question) / 专业选修

Topic	Course / 科目	Status	Notes / 备注
	[YOUR SPECIALIZATION] 你的专业方向		
22	BE5B15EN1/EN2 Power Eng.	**FOCUS**	**TARGET**: 电网+变压器
18	BE5B35LSP Logic Systems	**BACKUP**	可作为备选专业题
20	BE5B14SP1 Elec. Machinery	**AVOID**	基础薄弱，避免选此题
21	BE5B13MVE Materials	**AVOID**	基础薄弱，避免选此题
	[CRITICAL] SURVIVAL MODE 求生模式		
23	BE5B33KUI AI/Cybernetics	**CRITICAL**	**SURVIVAL**: BFS/DFS+状态空间
	[SKIP] OUT OF SCOPE 不在考试范围		
17	BE5B17EMT EM Theory	SKIP	未修课，跳过
19	BE5B31TES Signals	SKIP	未修课，跳过
24	BE5B35APO Architecture	SKIP	未完成考试，跳过
25	BE5B35ARI Control	SKIP	未完成考试，跳过

1.3 20-Hour Time Allocation / 20 小时时间分配

TIME Recommended Study Plan / 推荐学习计划

Category	Hours	Focus
[CRITICAL] Math	5h	LAL/DEN/DMG 公式背诵
[CRITICAL] KUI	1h	BFS/DFS/A*状态搜索
[CAUTION] Physics	4h	力学+热力学基础
[CAUTION] Circuits	2h	KVL/KCL 计算练习
[SHOW OFF] MIK/ELP	2h	论文桥接准备
[FOCUS] Power Eng. (专业)	4h	EN1/EN2 电网重点
THESIS Thesis Defense	2h	Koller 问题演练

2 答辩策略分析 / Defense Strategy Analysis

黄金法则 / Golden Rule

老师并不想挂你。(Teachers don't want to fail you.) 他们问基础题是为了确认你具备基本的工程师素养。如果你遇到难题卡住了，立刻把话题引导到你熟悉的这些" 保命题" 上。

3 国考委员会常问基础题 / SZZ Committee FAQ

Note: These are "Safe Questions" (保命题). Memorize these simple definitions.

3.1 数学 / Mathematics

导数与积分 / Derivative & Integral

CN: 老师可能会问："什么是导数？" 回答:

- 导数 (**Derivative**): 是变化率 (Rate of Change)。例如：速度是位置的导数 ($v = dx/dt$)。
- 积分 (**Integral**): 是累积量 (Accumulation) 或曲线下的面积。例如：距离是速度的积分。

EN:

- **Derivative**: Represents the **Rate of Change**. (e.g., Velocity is the derivative of Position).
- **Integral**: Represents **Accumulation** or Area under the curve. (e.g., Distance is the integral of Velocity).

线性代数 / Linear Algebra

CN: "矩阵是什么？" 回答: 矩阵是一个线性变换 (Linear Transformation)。它可以表示旋转、缩放或平移。特征值 (Eigenvalue) 表示变换中方向不变的向量的缩放比例。

EN: A Matrix represents a **Linear Transformation** (Rotation, Scaling, Translation). Eigenvalues represent the scaling factor of vectors that do not change direction.

3.2 微控制器 / Microcontrollers

哈佛 vs 冯诺依曼 / Harvard vs Von Neumann

CN: 这是 MIK 必问的基础题。回答:

- 冯诺依曼 (**Von Neumann**): 指令和数据共享同一个存储器和总线。瓶颈在于无法同时读写。(如 PC x86)。
- 哈佛 (**Harvard**): 指令和数据拥有物理分离的存储器和总线。速度更快。ESP32 使用哈佛架构。

EN:

- **Von Neumann**: Instructions and Data share the **SAME** memory and bus. (Bottleneck: Cannot fetch and write simultaneously).
- **Harvard**: Instructions and Data have **SEPARATE** memories and buses. (Faster). **ESP32 uses Harvard architecture**.

中断 / Interrupt vs Polling

CN:

- 轮询 (**Polling**): CPU 既然不断检查外设状态(浪费资源)。
- 中断 (**Interrupt**): 外设主动通知 CPU。CPU 暂停当前任务，处理中断服务程序 (ISR)，然后返回。

EN:

- **Polling**: CPU constantly checks peripheral status (Wastes cycles).
- **Interrupt**: Peripheral signals the CPU. CPU pauses, executes ISR (Interrupt Service Routine), and resumes.

3.3 物理与电路 / Physics & Circuits

基本定律 / Laws of Physics

CN:

- 牛顿第二定律: $F = ma$。力等于质量乘以加速度。这是加速度计的基础。
- 欧姆定律: $V = IR$。电压等于电流乘以电阻。
- 基尔霍夫定律 (**KCL/KVL**): 电荷守恒 ($\sum I = 0$) 和能量守恒 ($\sum V = 0$)。

EN:

- **Newton's 2nd Law**: $F = ma$. Force equals Mass times Acceleration. (Basis of Accelerometers).
- **Ohm's Law**: $V = IR$.
- **Kirchhoff's Laws**: Conservation of Charge (KCL) and Energy (KVL).

4 对手画像 / Opponent Profile: Jan Koller

核心特征：务实但挑剔

Jan Koller 是一个「务实但挑剔的学究」(**Pragmatic Pedant**)。

- 痛恨形式错误: “非典型流程图” (Atypical flowcharts) 是他的触发点。
- 关注单位: 必须有物理单位 (Does 2.4 mean Volts or Amps?)。
- 你的评分: 他给了你 **B (Very Good)**。只要回答好问题，稳 B 冲 A。

5 必答题: Acc + Gyro

Koller 的真题 (100% 会问)

Q: "Can you explain why a combination of acceleration and angular velocity is used in fall detection?"
A (Concept): **CN**: 单靠加速度计会有误报（如跳跃）。陀螺仪测量姿态变化。真正的跌倒 = 剧烈姿态变化 (Gyro) + 剧烈撞击 (Acc) + 静止。

EN: **Sensor Fusion**. Acceleration alone creates false positives (e.g., Jumping). Gyroscope measures orientation change. A Fall = Rotation (Gyro) + Impact (Acc) + Inactivity.

6 Committee Intelligence / 委员会情报

Mission Briefing / 任务简报

[**CN**]: 这是你的 6 位考官的完整档案。每人包含：背景、研究方向、板书题、口试题、保命剧本。
[**EN**]: Complete dossiers for all 6 examiners. Each includes: Background, Research Focus, Blackboard Problem, Oral Questions, Panic Scripts.

6.1 Examiner 1: Zdenek Muller (Chairman / 主席)

Intel Dossier / 情报档案

Role: Chairman / Vice-Dean for Strategy
Department: Electrical Power Engineering (K13115)
Profile: `fel.cvut.cz/cs/fakulta/lide/764-zdenek-muller`
[CN] 教学方向:

- B1M15ENY - Elektrarny (Power Plants): 整个电厂系统
- B1M15PEL - Prumyslova elektrotechnika (Industrial EE): 工业应用
- B1M15DEE - Distribuce elektricke energie (Power Distribution): 电网配电

[CN] 研究重点 (2024-2025 论文):

- "Sustainable Energy Management for Microgrids + IoT + AI" (2025) - 他研究 IoT 在电网中的应用！
- "Smart Meters in Smart Grid" (2025) - 他关心数据协议和安全性

[EN] **Forensic Profile**: He is a **Grid Modernizer**, not an old-school coal guy. He publishes on Microgrids, IoT, and AI. He will try to bridge your small ESP32 to the massive Power Grid.

Blackboard Challenge / 板书题

Problem: Transformer Equivalent Circuit / 变压器等效电路

[CN] 场景: 教授说:「请画出单相变压器的 T 型等效电路，标出各元件。」
Circuit Elements / 电路元件:

Symbol	Name (EN)	名称 (CN)
R_1	Primary Winding Resistance	一次绕组电阻
X_1	Primary Leakage Reactance	一次漏抗
R_c	Core Loss Resistance (parallel)	铁芯损耗电阻
X_m	Magnetizing Reactance (parallel)	励磁电抗
R_2'	Secondary Resistance (referred)	折算后的二次电阻
X_2'	Secondary Reactance (referred)	折算后的二次漏抗

Key Formulas / 核心公式:

$$\frac{V_1}{V_2} = \frac{N_1}{N_2} = a \quad \text{(Turns Ratio / 变比)} \tag{1}$$

$$R_2' = a^2 R_2, \quad X_2' = a^2 X_2 \quad \text{(Impedance Referral / 阻抗折算)} \tag{2}$$

[EN]: "Draw the T-equivalent circuit of a single-phase transformer. Label all components."

Problem: Power Calculation / 功率计算

[CN] 场景:「电压 220V，电流 10A，功率因数 0.8 滞后，求 P 和 Q。」
Solution / 解答:

$$S = V \times I = 220 \times 10 = 2200 \text{ VA} \tag{3}$$
$$P = S\cos\phi = 2200 \times 0.8 = \boxed{1760 \text{ W}} \tag{4}$$
$$Q = S\sin\phi = 2200 \times 0.6 = \boxed{1320 \text{ VAR}} \tag{5}$$

Note: $\sin\phi = \sqrt{1 - 0.8^2} = 0.6$

[EN]: Use power triangle $S^2 = P^2 + Q^2$. Active power does work; Reactive power sustains fields.

Oral Questions / 口试题

Q1: kW vs kVA - What is the difference?

[CN]:

- kW (有功功率): 实际做功的功率，电表计费用这个
- kVA (视在功率): 变压器容量，包含无功分量
- 差别: 功率因数 $\cos\phi = P/S$

[EN]: "kW is Active Power (useful work). kVA is Apparent Power (total capacity). The difference is the Power Factor."
Mnemonic (巧记): 啤酒理论 - P 是酒 (有用)，Q 是泡沫 (无功)，S 是杯子 (总量)。

Q2: How does your ESP32 impact the Power Grid?

[CN] Attack: 他想让你承认你的设备微不足道。
[EN] Save Script: "Yes, one ESP32 is negligible. BUT, if we deploy 10,000 devices as a **Virtual Power Plant (VPP)**, they can collectively perform **Demand Response** - switching off loads during peak hours. This is exactly what your Microgrid research explores, Professor."
Panic Button: "My device contributes to Smart Grid data collection, which your 2025 paper on IoT-assisted energy management discusses."

Additional Battle Scenarios / 额外战斗场景

Blackboard: Power Triangle / 功率三角形

[CN] 场景:「请画出你家智能家居系统的功率三角形。假设总负载 2kW，功率因数 0.9 滞后。」
[EN] **Scenario**: "Draw the power triangle for your smart home. Assume 2kW load, PF = 0.9 lagging."
Solution / 解答:
Step 1 / 步骤 1: [CN] 有功功率已知 / [EN] Active power given:

$$P = 2000 \text{ W}$$

Step 2 / 步骤 2: [CN] 由功率因数求 $\sin\phi$ / [EN] Find $\sin\phi$ from power factor:

$$\cos\phi = 0.9 \Rightarrow \sin\phi = \sqrt{1 - 0.81} = 0.436$$

Step 3 / 步骤 3: [CN] 计算视在功率 / [EN] Calculate apparent power:

$$S = \frac{P}{\cos\phi} = \frac{2000}{0.9} = \boxed{2222 \text{ VA}}$$

Step 4 / 步骤 4: [CN] 计算无功功率 / [EN] Calculate reactive power:

$$Q = S\sin\phi = 2222 \times 0.436 = \boxed{969 \text{ VAR}}$$

[CN] 画图要点: 水平线 P=2kW，垂直线 Q=969VAR，斜边 S=2222VA，夹角 $\phi = 25.8°$
[EN] **Drawing**: P horizontal (2kW), Q vertical upward (969VAR), S hypotenuse (2222VA), angle $\phi = 25.8°$

[EN] **Full Mirror**: Draw P horizontal, Q vertical (lagging = upward for inductive load), S as hypotenuse. Angle $\phi = \arccos(0.9) = 25.8°$. Remember: $S^2 = P^2 + Q^2$.

Thesis Connection

Thesis Bridge: Smart Home Reactive Power / 智能家居无功功率 [CN]: 教授，这在我的系统中很重要...
[EN]: Professor, this is important in my system...
Script / 口试剧本: "In my smart home setup, I have:

- [CN] 路由器 (开关电源): 功率因数 ≈ 0.6 - 显著无功功率
  [EN] Router (switching PSU): Power factor ≈ 0.6 - significant reactive power
- [CN] ESP32 (线性稳压器): 功率因数 ≈ 1.0 - 纯电阻负载
  [EN] ESP32 (linear regulator): Power factor ≈ 1.0 - purely resistive load
- [CN] 冷却风扇：感性负载，消耗无功功率 (VAR)
  [EN] Cooling fans: Inductive, draws reactive power (VAR)

[CN] 如果扩展到 1000 户，电网会看到显著的无功需求。您的微电网研究通过电容器组或有源 PFC 来解决这个问题。
[EN] If I scale to 1000 homes, the grid sees significant reactive demand. Your Microgrid research addresses this with capacitor banks or active PFC."

Blackboard: Current Calculation / 电流计算

[CN] 场景:「你的智能家居消耗 2kW，电压 230V。计算电流。如果用 16A 断路器够吗？」
[EN] Scenario: "Your smart home consumes 2kW at 230V. Calculate current. Is a 16A breaker sufficient?"
Solution / 解答:
Step 1 / 步骤 1: [CN] 用欧姆定律计算电流 / [EN] Calculate current using Ohm's law:

$$I = \frac{P}{V} = \frac{2000W}{230V} = \boxed{8.7\text{ A}}$$

Step 2 / 步骤 2 (Follow-up / 追问): [CN] 16A 断路器够用，留有余量。但如果加上启动电流...
[EN] 16A breaker OK with margin. But consider inrush current...

- [CN] 空调启动电流: 额定 $\times$ 5 = 43.5A (短暂)
  [EN] AC startup current: rated $\times$ 5 = 43.5A (brief)
- [CN] C 型断路器可承受 5-10 倍瞬时电流
  [EN] Type-C breaker can handle 5-10$\times$ instantaneous

[EN] **Full Mirror**: $I = P/V = 2000/230 = 8.7A$. 16A breaker has 16/8.7 = 1.84$\times$ margin. For motors, consider C-type breakers that allow 5-10$\times$ inrush current.

Q3: What is Power Quality? Why does it matter?

[CN]:

- 电压稳定性: 230V $\pm$ 10% 是欧洲标准
- 频率稳定性: 50Hz $\pm$ 0.5Hz
- 谐波畸变: THD $<$ 5% (IEEE 519 标准)

[EN]: "Power quality includes voltage stability, frequency stability, and harmonic distortion. My ESP32's switching power supply could contribute to harmonic pollution, but at milliwatt scale it's negligible. Industrial IoT deployments should consider EMC filtering."
Thesis Link: "My sensors could MONITOR power quality - using ESP32's ADC to measure voltage waveform and detect anomalies."

6.2 Examiner 2: Jan Kyncl (Vice-Chairman / 副主席)

Intel Dossier / 情报档案

Role: Vice-Chairman
Department: Electrical Power Engineering
[CN] 教学方向:

- B1M15TEN - Elektricke teplo (Electrical Heat): 这是他的招牌课！
- B1M15MAT - Matematicke aplikace v elektroenergetice (Applied Math)

[CN] 研究重点 (2024-2025):

- "Utilizing Peltier Cells to Enhance COP" (2024) - 热力学/热泵
- 专长: 电转热、Peltier 效应、照明技术

[EN] **Forensic Profile**: The **Thermo-Electrician**. He sees electricity as a source of HEAT. He also teaches Applied Math, so he may check your calculations or error analysis.

Blackboard Challenge / 板书题

Problem: Newton's Method / 牛顿迭代法

[CN] 场景:「用牛顿法求 $x^2 - 2 = 0$ 的根，初值 $x_0 = 1$，迭代两次。」
Formula / 公式:

$$x_{n+1} = x_n - \frac{f(x_n)}{f'(x_n)} \tag{6}$$

Solution / 解答:

- $f(x) = x^2 - 2$, $f'(x) = 2x$
- Iteration 1: $x_1 = 1 - \frac{1-2}{2(1)} = 1 + 0.5 = \boxed{1.5}$
- Iteration 2: $x_2 = 1.5 - \frac{2.25-2}{3} = 1.5 - 0.083 = \boxed{1.417}$

Exact: $\sqrt{2} \approx 1.414$. Two iterations give excellent accuracy!

[EN]: Newton's Method converges quadratically - each iteration roughly doubles correct digits.

Oral Questions / 口试题

Q1: Three Modes of Heat Transfer

[CN] 三种传热方式:

1. **Conduction (传导)**: 固体内部，$q = -k\nabla T$ (Fourier's Law)
2. **Convection (对流)**: 流体流动，$q = hA(T_s - T_\infty)$
3. **Radiation (辐射)**: 电磁波，$q = \epsilon\sigma AT^4$ (Stefan-Boltzmann)

[**EN**]: "Conduction through solids (Fourier), Convection through fluid motion, Radiation via electromagnetic waves (Stefan-Boltzmann)."
Mnemonic: 火锅理论 - 传导=碰锅烫手，对流=汤在滚，辐射=远处感到热

Q2: How does heat leave your ESP32 chip?

[**CN**]: 主要通过 PCB 铜箔传导，然后空气对流散发。
[**EN**]: "First by **Conduction** through PCB copper traces (high thermal conductivity 400 W/mK). Then by **Convection** into surrounding air. Radiation is negligible at these temperatures."
Panic Button: "The ESP32 has thermal shutdown at 125C. I ensured adequate ventilation in my enclosure design."

Additional Battle Scenarios / 额外战斗场景

Blackboard: Thermal Resistance / 热阻计算

[**CN**] 场景:「ESP32 的稳压器 (AMS1117) 消耗功率 0.5W，环境温度 40°C，结温不能超过 125°C。求所需热阻。」
Solution / 解答:

$$R_{th} = \frac{\Delta T}{P} = \frac{T_{junction} - T_{ambient}}{P_{dissipated}} \tag{7}$$

$$R_{th} = \frac{125°C - 40°C}{0.5W} = \frac{85°C}{0.5W} = \boxed{170\ °\mathrm{C/W}} \tag{8}$$

[**CN**] 分析: AMS1117 的封装热阻约 90°C/W (SOT-223)，加上 PCB 热阻约 30°C/W，总计约 120°C/W < 170°C/W。安全！

[**EN**]: Thermal resistance = Temperature rise / Power. Lower R_{th} means better cooling.

Thesis Connection

Thesis Bridge: Enclosure Ventilation / 外壳通风设计 [CN]: 教授，这在我的论文中很重要...
Script: "My 3D-printed enclosure needs ventilation holes because:

- ESP32 dissipates 0.5-1W during WiFi transmission
- PLA plastic is a thermal insulator ($k \approx 0.13$ W/mK)
- Convection is the primary cooling mechanism
- I designed slits on top and bottom for chimney effect (natural convection)

Without ventilation, the internal temperature would rise by:

$$\Delta T = P \times R_{th,enclosure} \approx 1W \times 50°C/W = 50°C$$

risking thermal throttling."

Blackboard: Lux to Lumens / 光度单位转换

[CN] 场景:「你的光传感器测量 Lux。解释 Lux 和 Lumens 的关系，如何用于智能照明？」
Solution / 解答:

$$\text{Lux} = \frac{\text{Lumens}}{\text{Area (m}^2\text{)}} \tag{9}$$

$$E = \frac{\Phi}{A} \quad \text{(Illuminance = Luminous Flux / Area)} \tag{10}$$

例子: 1000 lm 的灯泡照亮 2m^2 的桌面:

$$E = \frac{1000 \text{ lm}}{2 \text{ m}^2} = 500 \text{ lux}$$

标准照度:

- 办公室: 500 lux
- 客厅: 150-300 lux
- 走廊: 100 lux

[**EN**]: Lux measures illuminance (light on surface). Lumens measures total light output. Lux = Lumens / Area.

Thesis Connection

Thesis Bridge: Smart Lighting Control / 智能照明控制 [**CN**]: 这直接用在我的论文中...
Script: "My TCS34725 light sensor outputs:

- Raw RGB values (16-bit per channel)
- Clear channel for overall brightness
- I convert to Lux using the sensor datasheet formula

The smart home automation rule:

$$\text{IF Lux} < 300 \text{ AND Motion detected THEN turn on lights}$$

This saves energy by only illuminating occupied spaces."

Q3: What is Thermal Runaway?

[**CN**]:

- 定义: 温度升高导致功耗增加，功耗增加又导致温度继续升高
- 例子: 双极型晶体管的 I_C 随温度指数增加
- 预防: 负温度系数电阻 (NTC) 反馈，热保护电路

[**EN**]: "Thermal runaway is a positive feedback loop where higher temperature increases power dissipation, which further increases temperature. Common in BJTs and batteries. My ESP32 has built-in thermal shutdown to prevent this."

6.3 Examiner 3: Jan Koller (Opponent / 对手) [CRITICAL]

DANGER: This is YOUR Thesis Opponent

Risk Level: CRITICAL
[CN]: 这是你的论文对手！ 物理系背景，研究等离子体和材料表面处理。
[EN]: He is your thesis opponent. Physics background. Researches plasma and surface treatment.

Intel Dossier / 情报档案

Role: Member / Thesis Opponent
Department: Physics (Connection)
Profile: `fel.cvut.cz/en/faculty/people/27607-jan-koller`
[CN] 研究重点 (2024):

- "Surface properties of polyimide treated by plasma jet" - 材料表面处理
- "Low-Temperature Copper Deposition for Flexible Electronics" - PCB 制造！
- 关键: 他研究等离子体改性材料表面

[EN] **Forensic Profile**: The **Materialist**. He cares about SURFACES and LAYERS. If you have a PCB or plastic enclosure, he may ask about material properties. He is NOT a solar expert (previous hallucination corrected).

Blackboard Challenge / 板书题

Problem: Newton's Second Law / 牛顿第二定律

[CN] 场景:「写出牛顿第二定律。2kg 物体受 6N 力，求加速度。」
Formula / 公式:

$$\vec{F} = m\vec{a} \quad \Rightarrow \quad a = \frac{F}{m} \tag{11}$$

Solution / 解答:

$$a = \frac{6\ \text{N}}{2\ \text{kg}} = \boxed{3\ \text{m/s}^2} \tag{12}$$

Mnemonic: F = ma,「肥妈」- 推肥妈要用大力

[EN]: "Force equals mass times acceleration. Unit: Newton = kg·m/s^2."

Problem: Simple Harmonic Motion / 简谐振动

[CN] 场景:「弹簧 $k = 100$ N/m，质量 $m = 1$ kg，求振动角频率。」
Formula / 公式:

$$F = -kx \quad \text{(Hooke's Law)} \tag{13}$$

$$\omega = \sqrt{\frac{k}{m}}, \quad T = 2\pi\sqrt{\frac{m}{k}} \tag{14}$$

Solution / 解答:

$$\omega = \sqrt{\frac{100}{1}} = \boxed{10 \text{ rad/s}}, \quad f = \frac{10}{2\pi} \approx 1.59 \text{ Hz} \tag{15}$$

[**EN**]: SHM equation: $x(t) = A\cos(\omega t + \phi)$. Spring frequency depends only on k and m.

Oral Questions / 口试题

Q1: State Newton's Three Laws

[**CN**]:

1. 惯性定律: 物体保持静止或匀速，除非受外力 (Inertia)
2. **F=ma**: 力等于质量乘加速度 (Core equation)
3. 作用反作用: 力成对出现，大小相等方向相反 (Action-Reaction)

[**EN**]: "1st: Object maintains state unless acted upon. 2nd: F=ma. 3rd: Every action has equal opposite reaction."

Q2: How does your accelerometer work? (Thesis Link)

[**CN**]: 加速度计测量「比力」= 加速度 - 重力。静止时 Z 轴读 ≈ 9.8 m/s^2。
[**EN**]: "The accelerometer measures **specific force**. At rest, it reads gravitational acceleration $g \approx 9.8$ m/s^2 along the vertical axis. During free fall, it reads near zero - this is how I detect falls."
Panic Button: "The MPU6050 uses MEMS technology - a tiny proof mass on silicon springs. Deflection is measured capacitively."

Q3: How is copper deposited on your PCB? (His Research!)

[**CN**]: 标准 PCB 用电镀法 - 铜离子在电解液中沉积到基板上。
[**EN**]: "Standard PCBs use **electroplating** - copper ions deposit onto the substrate in an electrolytic bath. Your research explores low-temperature plasma-assisted deposition for flexible substrates, which is more advanced than commercial PCBs."
Escape: "I used off-the-shelf PCBs and focused on firmware and sensor integration."

Additional Battle Scenarios (Survival Mode!) / 额外战斗场景 (求生模式!)

Physics Survival: Know These Cold!

[**CN**]: Koller 教授是你的论文对手+物理系背景。这些题必须练到闭眼能写！

Blackboard: Centripetal Force / 向心力

[CN] 场景:「写出向心力公式。解释这与你的跌倒检测有什么关系？」
Solution / 解答:

$$F_c = \frac{mv^2}{r} = m\omega^2 r = m \cdot a_c \tag{16}$$

其中向心加速度:

$$a_c = \frac{v^2}{r} = \omega^2 r \tag{17}$$

[CN] 数值例子: 人转身，手臂长 $r = 0.6m$，角速度 $\omega = 2\text{rad/s}$:

$$a_c = \omega^2 r = 4 \times 0.6 = 2.4 \text{ m/s}^2$$

[EN]: Centripetal force keeps object in circular motion. Points toward center. $F_c = mv^2/r$.

Thesis Connection

Thesis Bridge: Fall Detection Rotation / 跌倒检测中的旋转 [CN]: 教授，这直接用在我的论文中...
Script: "During a fall, the body rotates. My MPU6050 gyroscope measures angular velocity ω in rad/s. I can calculate:

- **Rotation angle**: $\theta = \int \omega \, dt$
- **Centripetal acceleration**: Contributes to total acceleration reading
- **Fall signature**: Rapid rotation ($> 100°/\text{s}$) + impact ($> 3\text{g}$)

The sensor fusion combines accelerometer (a) and gyroscope (ω) using a Complementary Filter or Kalman Filter."

Blackboard: I-V Curves / 伏安特性曲线

[CN] 场景:「画出电阻和二极管的 I-V 曲线，指出关键区别。」
Resistor / 电阻:

- 线性: $I = V/R$
- 过原点的直线，斜率 $= 1/R$

Diode / 二极管:

- 正向偏置: $V > V_{th} \approx 0.7V$ (Si), 电流指数上升
- 反向偏置: 极小漏电流 I_s (nA 级)
- 击穿区: $V < -V_{BR}$, 电流剧增

Shockley 方程:

$$I = I_s \left(e^{V/(nV_T)} - 1 \right), \quad V_T = \frac{kT}{q} \approx 26 \text{ mV} \tag{18}$$

[EN]: Resistor: linear through origin. Diode: exponential after threshold, tiny leakage in reverse.

Blackboard: MEMS Accelerometer Principle / MEMS 加速度计原理

[CN] 场景:「解释 MEMS 加速度计如何测量'g'。」
Core Principle / 核心原理:

1. 内部有一个微型弹簧-质量系统 (Spring-Mass)
2. 加速度导致质量块相对于框架位移
3. 位移通过电容变化测量（间距变化改变电容）

公式:

$$F = ma = kx \tag{19}$$

$$x = \frac{ma}{k} = \frac{a}{\omega_0^2} \tag{20}$$

其中 $\omega_0 = \sqrt{k/m}$ 是谐振频率。
电容检测:

$$C = \frac{\epsilon A}{d} \quad \Rightarrow \quad \Delta C \propto \Delta d \propto a \tag{21}$$

[EN]: MEMS accelerometer = tiny spring-mass system. Acceleration displaces proof mass, capacitance change is measured. It's SHM physics at microscale!

Thesis Connection

Thesis Bridge: MPU6050 MEMS Details / MPU6050 细节 [**CN**]: 这是我论文的核心传感器...
Script: "The MPU6050 in my thesis uses:

- **Proof mass**: 10μg polysilicon
- **Spring constant**: Designed for ±16g range
- **Resonant frequency**: 5kHz (much higher than human motion)
- **Capacitance detection**: Differential (noise cancellation)

At rest, the Z-axis reads $\approx 1g$ because gravity pulls the proof mass down. During free fall, it reads $\approx 0g$ because the mass and frame fall together."

Q4: What is Hooke's Law? Limitations?

[**CN**]:

$$F = -kx \quad \text{(线性弹性，负号表示恢复力)} \tag{22}$$

限制:

- 仅适用于弹性限度内
- 超过弹性限度，塑性变形（永久形变）
- 超过极限强度，断裂

[**EN**]: "Hooke's Law applies only within elastic limit. Beyond that, plastic deformation occurs. My MEMS sensor operates well within elastic range - displacement is nanometers."

6.4 Examiner 4: Adam Boura (Member / 潜在盟友)

ALLY: He understands sensors

[CN]: 他是做传感器的，懂校准的痛苦。你的论文用了传感器，他是你的盟友！
[EN]: He builds actual sensors. He knows calibration pain. Since your thesis uses sensors, he is your ally!

Intel Dossier / 情报档案

Role: Member
Department: Microelectronics
Profile: `fel.cvut.cz/en/faculty/people/294-adam-boura`
[CN] 教学方向:

- B2B34SNB - Biomedical Sensors: 生物医学传感器
- AD2B34SEI - Sensors in Electronics: 电子传感器
- B2B34MSY - Microsystems (MEMS): 微系统

[CN] 研究重点 (2025):

- "Optimum wavelength for POF-based soil moisture sensor" - 光纤土壤传感器
- "GaN-based LLC converter transformer" - 电力电子

[EN] **Forensic Profile**: The **Practical Sensor Builder**. He builds optical fiber (POF) sensors for soil moisture. He knows the pain of calibration, drift, and noise.

Blackboard Challenge / 板书题

Problem: Diode V-I Characteristic / 二极管伏安特性

[CN] 场景:「画出硅二极管的伏安特性曲线。」
Key Points / 关键点:

- **Forward Bias**: $V > 0.7V$ (Si), current rises exponentially
- **Reverse Bias**: Small leakage current I_s (nA range)
- **Breakdown**: $V < -V_{BR}$, current surges (Zener/Avalanche)

Shockley Equation:

$$I = I_s \left(e^{V/(nV_T)} - 1 \right), \quad V_T = \frac{kT}{q} \approx 26 \text{ mV} \tag{23}$$

[EN]: "Silicon diode turns on at 0.7V forward bias. In reverse, only leakage flows until breakdown."

Oral Questions / 口试题

Q1: Accuracy vs Precision

[**CN**]:

- **Accuracy (准确度)**: 测量值与真值的接近程度 (Systematic error)
- **Precision (精密度)**: 多次测量的重复性 (Random error)

Mnemonic: 飞镖靶 - Precision=打得集中, Accuracy=打中靶心
[**EN**]: "Accuracy is closeness to true value. Precision is repeatability. A sensor can be precise but not accurate if it has systematic offset."

Q2: Your cheap sensors drift. How do you trust them?

[**CN**]: 它们确实漂移，但家用 IoT 原型更关心相对变化而非绝对值。
[**EN**]: "Yes, they drift - especially over temperature and time. BUT for home IoT, **relative changes** matter more than absolute values. For medical applications, I would use calibrated sensors with traceability, as taught in your Biomedical Sensors course."

Additional Battle Scenarios / 额外战斗场景

Blackboard: ADC Resolution / ADC 分辨率计算

[CN] 场景:「ESP32 有 12 位 ADC，参考电压 3.3V。计算分辨率（最小可分辨电压）。」
Solution / 解答:

$$\text{Resolution} = \frac{V_{ref}}{2^n} = \frac{3.3V}{2^{12}} = \frac{3.3V}{4096} \tag{24}$$

$$= \boxed{0.806 \text{ mV}} \approx 0.8 \text{ mV} \tag{25}$$

Follow-up: 实际有效分辨率 (ENOB):

$$\text{ENOB} = \frac{\text{SINAD} - 1.76}{6.02} \approx 9 - 10 \text{ bits for ESP32} \tag{26}$$

ESP32 的 ADC 噪声约 10-20mV，实际有效分辨率约 10 位。

[**EN**]: 12-bit ADC: $2^{12} = 4096$ levels. Resolution = 3.3V/4096 = 0.8mV theoretically, but noise limits effective resolution.

Thesis Connection

Thesis Bridge: ADC Nonlinearity Fix / ADC 非线性校正 [**CN**]: 教授，这是我在论文中遇到的实际问题...
Script: "The ESP32 ADC has known issues:

- **Nonlinearity**: Up to 6% error at extremes
- **Noise**: 20-50mV peak-to-peak

My software fixes:

1. **Lookup Table (LUT)**: Pre-calibrated correction values
2. **Moving Average Filter**: 16-sample average reduces noise
3. **Multisampling**: Take 64 samples, discard outliers

Code snippet:

```
uint32_t adc_filtered = 0;
for(int i=0; i<16; i++) {
    adc_filtered += analogRead(pin);
}
adc_filtered /= 16;  // Moving average
```

"

Blackboard: Signal-to-Noise Ratio / 信噪比

[CN] 场景:「你的温度传感器信号 100mV，噪声 10mV。计算 SNR (dB)。」
Solution / 解答:

$$\text{SNR}_{dB} = 20\log_{10}\left(\frac{V_{signal}}{V_{noise}}\right) = 20\log_{10}\left(\frac{100}{10}\right) = 20\log_{10}(10) = \boxed{20\text{ dB}} \tag{27}$$

经验法则:

- $<$ 20 dB: 信号几乎被噪声淹没
- 20-40 dB: 可用但需要滤波
- $>$ 40 dB: 高质量信号

[**EN**]: SNR in dB = 20 log(Signal/Noise). 20dB means signal is 10x noise. Aim for $>$ 40dB in precision applications.

Q3: What is Quantization Error?

[CN]:

$$\text{Quantization Error}_{max} = \pm\frac{1}{2}\text{LSB} = \pm\frac{V_{ref}}{2^{n+1}} \tag{28}$$

对于 12 位 3.3V ADC:

$$\text{Error}_{max} = \pm\frac{3.3V}{2^{13}} = \pm 0.4 \text{ mV}$$

[EN]: "Quantization error is the difference between actual voltage and nearest digital level. Maximum is ±0.5 LSB. This is fundamental to any ADC and cannot be eliminated, only reduced by using more bits."

Thesis Connection

Thesis Bridge: Sensor Fusion / 传感器融合 **[CN]**: 这是我论文的核心技术...
Script: "I use multiple sensors measuring the same phenomenon:

- **DHT22**: Temperature ±0.5°C
- **BMP280**: Temperature ±1.0°C (but better pressure)

Fusion strategy:

$$T_{fused} = w_1 T_{DHT} + w_2 T_{BMP}, \quad w_1 + w_2 = 1 \tag{29}$$

Weights based on inverse variance (more accurate sensor gets higher weight). This is related to Kalman filter's optimal estimation."

6.5 Examiner 5: Jan Bauer (Member / 考官)

Intel Dossier / 情报档案

Role: Member
Department: Electric Drives
Profile: `fel.cvut.cz/en/faculty/people/687-jan-bauer`
[CN] 教学方向:

- B3B34MKS - Microprocessors for Power Systems: 教芯片
- B1M14PVR - Digital Control of Electric Drives: 教代码

[CN] 研究重点 (2025):

- "Digital Implementation of Discontinuous PWMs" - PWM 算法实现
- "Analytical Harmonic Suppression in Overmodulated Drives" - 谐波抑制

[EN] **Forensic Profile**: The **Firmware Architect**. He is obsessed with PWM algorithms and harmonic suppression. He wants to know HOW you calculated the duty cycle and whether you filtered the signal.

Blackboard Challenge / 板书题

Problem: PWM Duty Cycle / PWM 占空比

[CN] 场景:「画一个 50%占空比、1kHz 频率的 PWM 波形。解释如何控制 LED 亮度。」
Formulas / 公式:

$$T = \frac{1}{f} = \frac{1}{1000} = 1 \text{ ms} \tag{30}$$

$$D = \frac{T_{on}}{T} = 50\% \quad \Rightarrow \quad T_{on} = 0.5 \text{ ms} \tag{31}$$

$$V_{avg} = V_{max} \times D = 3.3 \times 0.5 = 1.65 \text{ V} \tag{32}$$

[CN]: 人眼看不到 1kHz 闪烁，只感受平均亮度。D=100%最亮，D=0%熄灭。

[EN]: "PWM simulates analog via fast switching. Human eye perceives average brightness due to persistence of vision."

Problem: Timer Calculation / 定时器计算

[CN] 场景:「ESP32 时钟 80MHz，16 位定时器，产生 1ms 中断，求分频系数。」
Solution / 解答:

- Want: $T = 1$ ms
- Set Prescaler $= 80 \Rightarrow$ Timer clock $= 1$ MHz (1 tick $= 1\ \mu$s)
- Count to $1000 \Rightarrow T = 1000 \times 1\mu s = \boxed{1 \text{ ms}}$

[EN]: "Prescaler divides clock. Counter counts ticks. Interrupt fires when counter reaches target."

Oral Questions / 口试题

Q1: Polling vs Interrupts

[CN]:

- **Polling** (轮询): CPU 不断检查状态，浪费资源
- **Interrupt** (中断): 事件发生时硬件通知 CPU，高效

[EN]: "Polling wastes CPU cycles. Interrupts let CPU do other work until event occurs. I use timer interrupts for 10Hz sensor sampling."

Q2: What is the harmonic content of PWM? (His Research!)

[CN]: 方波 PWM 包含基波和奇次谐波 (3 次、5 次...)，傅里叶分析可知。
[EN]: "Square wave PWM contains fundamental plus odd harmonics (3rd, 5th...) per Fourier analysis. For LED dimming, harmonics are irrelevant. For motor drives, I would add LC filtering."
Escape: "My application didn't require harmonic analysis, but I know your research focuses on this for high-power drives."

Additional Battle Scenarios / 额外战斗场景

Blackboard: Timer Prescaler for 1Hz / 1Hz 定时器预分频计算

[CN] 场景:「ESP32 时钟 80MHz，16 位定时器 (0-65535)，要产生精确 1Hz 中断。求预分频值和计数值。」
Solution / 解答:
目标: $T = 1$ s, $f_{clk} = 80$ MHz
方法 **1**: 预分频 80，计数 1,000,000 (超过 16 位！)
方法 **2**: 预分频 8000，计数 10,000

$$f_{timer} = \frac{80 \text{ MHz}}{8000} = 10 \text{ kHz} \tag{33}$$
$$\text{Count} = 10,000 \text{ (fits in 16 bits)} \tag{34}$$
$$T = \frac{10,000}{10,000 \text{ Hz}} = \boxed{1 \text{ s}} \tag{35}$$

方法 **3**: 预分频 80，计数 10,000，设置 10 次中断触发 1 次事件

$$f_{timer} = \frac{80 \text{ MHz}}{80} = 1 \text{ MHz} \tag{36}$$
$$T_{interrupt} = \frac{10,000}{1 \text{ MHz}} = 10 \text{ ms} \tag{37}$$
$$100 \times 10 \text{ ms} = 1 \text{ s} \tag{38}$$

[EN]: For 1Hz from 80MHz: Prescaler 8000, Count 10000. Or use software counter with faster interrupt.

Thesis Connection

Thesis Bridge: MQTT Keep-Alive as Watchdog / MQTT 保活机制 [CN]: 教授，这和我的论文直接相关...
Script: “MQTT protocol has a Keep-Alive mechanism similar to a watchdog timer:

- **Keep-Alive interval**: Set to 60 seconds in my config
- **Client sends PINGREQ**: Every 60s if no other traffic
- **Broker expects response**: If no PINGRESP in 1.5x interval, connection closed

This is functionally identical to a hardware watchdog:

```
// Hardware watchdog (ESP32)
esp_task_wdt_reset(); // Feed watchdog every loop

// MQTT 'software watchdog'
mqtt.loop();  // Handles keep-alive automatically
```

If my ESP32 crashes, the MQTT broker detects it within 90 seconds and publishes a Last Will and Testament (LWT) message.”

Blackboard: PWM Frequency Selection / PWM 频率选择

[CN] 场景:「LED 调光应该用什么 PWM 频率？ 电机控制呢？」
Analysis / 分析:
LED 调光:

- 人眼闪烁融合频率: 60 Hz
- 推荐: 1-10 kHz (无闪烁，无可闻噪声)
- 太高: 开关损耗增加

电机控制:

- 低频 (<1kHz): 可闻噪声，电流纹波大
- 高频 (>10kHz): 开关损耗，EMI 问题
- 推荐: 4-20 kHz (超声波范围)

ESP32 PWM 配置:

```
ledcSetup(channel, 5000, 8); // 5kHz, 8-bit resolution
ledcAttachPin(LED_PIN, channel);
ledcWrite(channel, 128);  // 50% duty cycle
```

[**EN**]: LED: 1-10kHz (no flicker, no audible noise). Motor: 4-20kHz (ultrasonic, reduced switching loss).

Q3: What is Dead Time in H-Bridge?

[**CN**]:

- 定义: 上下管切换时的短暂关断时间
- 目的: 防止直通（Shoot-through）短路
- 典型值: 100ns - 1μs

公式:

$$t_{dead} > t_{off,max} - t_{on,min} \tag{39}$$

[**EN**]: "Dead time prevents simultaneous conduction of high-side and low-side switches, which would cause a short circuit. Critical in motor drives and power electronics."

Thesis Link: "My ESP32 project doesn't drive motors directly, but if I added one, I would use the MCPWM peripheral which has built-in dead time generation."

6.6 Examiner 6: Petr Karafiat (Industry / 企业代表)

Intel Dossier / 情报档案

Role: Member (Industry Expert)
Job Title: Odborny reditel (Technical Director) / Director for Engineering and Ecology
Company: Teplarna Kladno s.r.o. (Alpiq Generation CZ)
[CN] 关键洞察:

- 他不是普通技术员，是技术总监，管 CAPEX(资本支出) 和战略现代化
- 他的头衔包含 "生态"，关心排放和可持续性
- 他从工业角度思考：成本、可靠性、维护

[EN] **Forensic Profile**: The **Executive Engineer**. He thinks in terms of plant-wide systems, ROI, and ecological standards. He will NOT ask obscure formulas - he will ask practical questions about reliability and cost.

Oral Questions / 口试题

Q1: Why ESP32 instead of Raspberry Pi?

[CN]:

- **Reliability**: ESP32 用 Flash(可靠), RPi 用 SD 卡 (易坏)
- **Real-time**: ESP32 跑 RTOS(确定性), RPi 跑 Linux(不确定)
- **Cost**: ESP32 约$5, RPi 约$50
- **Power**: ESP32 可 Deep Sleep(10μA), RPi 至少 500mA

[EN]: "Reliability (Flash vs SD card), Real-time (RTOS vs Linux), Cost ($5 vs $50), Power (10$\mu$A sleep vs 500mA minimum)."

Q2: What is the MTBF of your system?

[CN]: MTBF = Mean Time Between Failures. 系统寿命取决于最弱组件。
[EN]: "MTBF depends on weakest component. ESP32 Flash: >100k write cycles. No SD card eliminates a common failure mode. For home use, I estimate 5-10 year lifespan. Industrial deployment would need extended temperature components and conformal coating."

Q3: Who maintains this after you leave?

[CN]: 学生项目的常见问题。我的答案：文档化。
[EN]: "I documented everything: code comments, README files (bilingual), GitHub repository. I used standard frameworks (ESPHome, MQTT) with large communities. The next engineer can clone and continue."
Panic Button: "This would be scope for a Master's thesis or industrial project - adding conformal coating, IP65 enclosure, and extended temperature testing."

Additional Battle Scenarios / 额外战斗场景

Q4: What is the weak point of your system?

[CN]: 主动暴露弱点比被动被抓到更好。
[EN] **Honest Answer**: "The weakest point is the **Raspberry Pi SD card** in my Home Assistant server:

- SD cards have limited write cycles (10,000 for consumer grade)
- Power loss during write causes corruption
- I mitigated this by: (1) Using industrial SD card, (2) Reducing log writes, (3) Daily backup to NAS

For production, I would use:

- SSD via USB adapter
- Or dedicated embedded board with eMMC storage
- UPS for clean shutdown

"

Why this answer works: Shows awareness of limitations AND how to fix them.

Oral: Cost-Benefit Analysis / 成本效益分析

[CN] 场景:「对比 ESP32 和工业 PLC 的成本和适用场景。」
Comparison / 对比:

Attribute	ESP32	Industrial PLC
Unit Cost	\$5	\$200-500
Development Tool	Free (Arduino)	\$500-2000 license
Reliability	Consumer grade	Industrial grade
Temperature Range	0-70°C	-40 to +85°C
Certifications	None	CE, UL, IEC 61131
Support	Community	Vendor (SLA)

结论: ESP32 适合原型/家用，PLC 适合工厂/关键任务

[EN]: ESP32 for prototyping and home use. PLC for industrial deployment. Know when to upgrade.

Thesis Connection

Thesis Bridge: Industrial Scaling Path / 工业化路径 [**CN**]: 教授，这是我对论文未来工作的思考...
Script: "If Alpiq wanted to deploy my system in a power plant:

1. **Phase 1 - Pilot**: Keep ESP32, add industrial enclosure (IP65)
2. **Phase 2 - Reliability**: Replace with industrial MCU (STM32 industrial grade)
3. **Phase 3 - Certification**: Get CE marking, integrate with SCADA via Modbus
4. **Phase 4 - Scale**: Partner with automation vendor (Siemens, ABB)

The code architecture (MQTT, Home Assistant) transfers directly. Only hardware needs upgrading."

Q5: How do you ensure cyber security?

[**CN**]:

- **MQTT + TLS**: 加密通信 (我的论文已实现)
- **Authentication**: Username/Password + Certificate
- **Firewall**: Home Assistant 不直接暴露到互联网
- **Updates**: OTA 更新机制 (ESPHome 支持)

[**EN**]: "Security layers: TLS encryption for MQTT, certificate-based authentication, no direct internet exposure (VPN required for remote access), OTA updates for security patches."
Weak Point Admission: "I used self-signed certificates. Production would need proper PKI with certificate rotation."

Q6: What standards apply to your system?

[**CN**]:
通信标准:

- MQTT v3.1.1 (OASIS standard)
- WiFi IEEE 802.11 b/g/n
- JSON for data format (RFC 8259)

安全标准:

- TLS 1.2+ (RFC 5246)
- X.509 certificates

如果工业化:

- IEC 62443 (Industrial Cybersecurity)
- CE marking (EMC + LVD)

[**EN**]: "I followed MQTT and TLS standards. For industrial deployment, IEC 62443 cybersecurity framework would apply."

7 Emergency Cheat Sheet / 紧急速查表

6 Formulas You MUST Know Tonight

1. $V = IR$ (Ohm's Law)
2. $P = VI = I^2R$ (Power/Joule Heating)
3. $F = ma$ (Newton's 2nd)
4. $S^2 = P^2 + Q^2$ (Power Triangle)
5. $\cos\phi = P/S$ (Power Factor)
6. $x_{n+1} = x_n - f(x_n)/f'(x_n)$ (Newton's Method)

3 Pivot Phrases When You Blank Out

1. "I don't recall the exact formula, BUT in my Thesis I applied this by..."
2. "Excellent question. I focused on [X], and your point about [Y] is noted for future work."
3. "In industry (like Alpiq), I would consult the relevant standard (IEC/IEEE)."

Your Thesis Shields

Strengths to pivot to:

- IoT/Smart Home: ESP32, MQTT, Home Assistant
- Sensors: Accelerometer, Gyroscope, Temperature, Humidity, Light
- Practical: Working prototype, GitHub documentation
- Application: Fall detection for elderly care

[CN]: 你的论文是你的盾牌。任何问题都可以转移到这些话题上。

Part II
数学基础 / Mathematics Foundation

8 Linear Algebra / 线性代数 (LAL) [SURVIVAL]

[WARN] PRIORITY: SURVIVAL MODE / 优先级：求生模式

[CN] LAL 优先级为 **CRITICAL**。只背公式，不要推导！ [EN] Linear Algebra priority is **CRITICAL**. **DO NOT derive**. Memorize formulas directly!
Goal: Pass the basic questions. 目标：通过基础题。

Matrix Multiplication / 矩阵乘法矩阵乘法 $\mathbf{C} = \mathbf{A} \cdot \mathbf{B}$ 的元素计算公式：

$$c_{ij} = \sum_{k=1}^{n} a_{ik} \cdot b_{kj}$$

口诀：「行乘列，逐项加」— 第 i 行与第 j 列对应相乘再求和。

[EN]: Matrix multiplication $\mathbf{C} = \mathbf{A} \cdot \mathbf{B}$ computes each element c_{ij} as the dot product of the i-th row of $\mathbf{A}$ and the j-th column of $\mathbf{B}$.

Blackboard Challenge: 2x2 Matrix Multiplication / 2 阶矩阵乘法

[CN] 场景:「请计算以下两个矩阵的乘积。」
给定：

$$\mathbf{A} = \begin{pmatrix} 2 & 3 \\ 1 & 4 \end{pmatrix}, \quad \mathbf{B} = \begin{pmatrix} 5 & 6 \\ 7 & 8 \end{pmatrix}$$

Solution / 解答:
Step 1 / 步骤 1: [CN] 计算 c_{11}（第 1 行 × 第 1 列）
[EN] Calculate c_{11} (Row 1 × Column 1)

$$c_{11} = 2 \times 5 + 3 \times 7 = 10 + 21 = 31$$

Step 2 / 步骤 2: [CN] 计算 c_{12}（第 1 行 × 第 2 列）
[EN] Calculate c_{12} (Row 1 × Column 2)

$$c_{12} = 2 \times 6 + 3 \times 8 = 12 + 24 = 36$$

Step 3 / 步骤 3: [CN] 计算 c_{21}（第 2 行 × 第 1 列）
[EN] Calculate c_{21} (Row 2 × Column 1)

$$c_{21} = 1 \times 5 + 4 \times 7 = 5 + 28 = 33$$

Step 4 / 步骤 4: [CN] 计算 c_{22}（第 2 行 × 第 2 列）
[EN] Calculate c_{22} (Row 2 × Column 2)

$$c_{22} = 1 \times 6 + 4 \times 8 = 6 + 32 = 38$$

Final Answer / 最终答案:

$$\boxed{\mathbf{C} = \begin{pmatrix} 31 & 36 \\ 33 & 38 \end{pmatrix}}$$

Mnemonic / 记忆口诀:「横看成岭侧成峰」— 横着取 A 的行，竖着取 B 的列，对位相乘再相加。

[EN] **Full Mirror**: For 2x2 matrices, each element c_{ij} is computed by multiplying corresponding elements of Row i from A and Column j from B, then summing. **Mnemonic**: "Row meets Column" — take rows from A horizontally, columns from B vertically, multiply element-wise and sum.

核心公式 / Key Formula

Determinant Formulas / 行列式公式 **2x2 Determinant / 2 阶行列式**:

$$\det\begin{pmatrix} a & b \\ c & d \end{pmatrix} = ad - bc$$

3x3 Sarrus Rule / 3 阶萨吕法则:

$$\det\begin{pmatrix} a & b & c \\ d & e & f \\ g & h & i \end{pmatrix} = aei + bfg + cdh - ceg - bdi - afh$$

Mnemonic / 记忆口诀:

- 2 阶:「主对角减副对角」
- 3 阶:「三条右斜加，三条左斜减」

[**EN**]: For 2x2: multiply diagonals and subtract. For 3x3 Sarrus: add three right-diagonal products, subtract three left-diagonal products.

Blackboard Challenge: Determinant Calculation / 行列式计算

[CN] 场景:「计算这个 3 阶行列式的值。」
给定:

$$\mathbf{A} = \begin{pmatrix} 1 & 2 & 3 \\ 4 & 5 & 6 \\ 7 & 8 & 9 \end{pmatrix}$$

Solution / 解答:
Step 1 / 步骤 1: [CN] 使用 Sarrus 法则，先计算三条「右斜」对角线乘积之和
[EN] Using Sarrus rule, first sum the three "right-diagonal" products:

$$(1 \times 5 \times 9) + (2 \times 6 \times 7) + (3 \times 4 \times 8) = 45 + 84 + 96 = 225$$

Step 2 / 步骤 2: [CN] 计算三条「左斜」对角线乘积之和
[EN] Sum the three "left-diagonal" products:

$$(3 \times 5 \times 7) + (2 \times 4 \times 9) + (1 \times 6 \times 8) = 105 + 72 + 48 = 225$$

Step 3 / 步骤 3: [CN] 右斜减左斜得行列式
[EN] Subtract left from right to get determinant:

$$\det(\mathbf{A}) = 225 - 225 = \boxed{0}$$

Mnemonic / 记忆口诀:「右加左减」— 右下斜加起来，左下斜减出去。行列式为 0 意味着矩阵奇异（不可逆）。

[EN] **Full Mirror**:

- **Step 1**: Sum products along 3 right-diagonals (top-left to bottom-right)
- **Step 2**: Sum products along 3 left-diagonals (top-right to bottom-left)
- **Step 3**: Subtract left sum from right sum

Result: Zero determinant means singular (non-invertible) matrix. **Mnemonic**: "Right-add, left-subtract"

Common Mistakes / 常见错误

1. [CN] Sarrus 仅适用于 3x3：更高阶需用余子式展开或行变换
   [EN] Sarrus ONLY works for 3x3: use cofactor expansion for larger matrices
2. [CN] 符号错误：记住是「右加左减」，不要搞反
   [EN] Sign error: remember "right-add, left-subtract", don't reverse
3. [CN] 行列式性质：交换两行/列，行列式变号
   [EN] Determinant property: swapping rows/columns flips the sign

Eigenvalue Definition / **特征值定义若存在非零向量 v 使得：**

$$\mathbf{A}\mathbf{v} = \lambda\mathbf{v}$$

则 λ 为矩阵 $\mathbf{A}$ 的特征值，$\mathbf{v}$ 为对应的特征向量。
特征方程 / Characteristic Equation:

$$\det(\mathbf{A} - \lambda\mathbf{I}) = 0$$

Mnemonic / 记忆口诀:「特征值让矩阵变伸缩」— 矩阵作用于特征向量只改变长度，不改变方向。

[**EN**]: An eigenvalue λ scales the eigenvector $\mathbf{v}$ without changing its direction. Find eigenvalues by solving the characteristic equation.

Blackboard Challenge: Eigenvalue Calculation / 特征值计算

[CN] 场景:「求这个矩阵的特征值。」
给定:

$$\mathbf{A} = \begin{pmatrix} 4 & 1 \\ 2 & 3 \end{pmatrix}$$

Solution / 解答:
Step 1 / 步骤 1: [CN] 构造 $\mathbf{A} - \lambda\mathbf{I}$
[EN] Construct $\mathbf{A} - \lambda\mathbf{I}$:

$$\mathbf{A} - \lambda\mathbf{I} = \begin{pmatrix} 4-\lambda & 1 \\ 2 & 3-\lambda \end{pmatrix}$$

Step 2 / 步骤 2: [CN] 计算特征多项式（令行列式为 0）
[EN] Compute characteristic polynomial (set determinant = 0):

$$\det(\mathbf{A} - \lambda\mathbf{I}) = (4-\lambda)(3-\lambda) - (1)(2) = 0$$

Step 3 / 步骤 3: [CN] 展开并求解二次方程
[EN] Expand and solve quadratic equation:

$$\begin{aligned} (4-\lambda)(3-\lambda) - 2 &= 0 \\ 12 - 4\lambda - 3\lambda + \lambda^2 - 2 &= 0 \\ \lambda^2 - 7\lambda + 10 &= 0 \\ (\lambda - 5)(\lambda - 2) &= 0 \end{aligned}$$

Final Answer / 最终答案:

$$\boxed{\lambda_1 = 5, \quad \lambda_2 = 2}$$

Mnemonic / 记忆口诀:「减 λ 求零」— 主对角线减 λ，行列式等于零，解方程得特征值。

[EN] **Full Mirror**:

- **Step 1**: Construct $\mathbf{A} - \lambda\mathbf{I}$ by subtracting λ from diagonal
- **Step 2**: Set $\det(\mathbf{A} - \lambda\mathbf{I}) = 0$ (characteristic equation)
- **Step 3**: Solve resulting polynomial for eigenvalues

Mnemonic: "Subtract λ, set det to zero" — eigenvalues are roots of characteristic polynomial.

Thesis Connection

Thesis Application: Kalman Filter / **论文应用：卡尔曼滤波器** [CN] 与论文的联系:
在 IoT 传感器系统中，卡尔曼滤波器 (Kalman Filter) 是处理噪声数据的核心算法，它大量使用线性代数：
状态预测方程:

$$\hat{\mathbf{x}}_{k|k-1} = \mathbf{F}_k \hat{\mathbf{x}}_{k-1|k-1} + \mathbf{B}_k \mathbf{u}_k$$

协方差预测:

$$\mathbf{P}_{k|k-1} = \mathbf{F}_k \mathbf{P}_{k-1|k-1} \mathbf{F}_k^T + \mathbf{Q}_k$$

卡尔曼增益:

$$\mathbf{K}_k = \mathbf{P}_{k|k-1} \mathbf{H}_k^T (\mathbf{H}_k \mathbf{P}_{k|k-1} \mathbf{H}_k^T + \mathbf{R}_k)^{-1}$$

实际应用 / **Practical Applications**:

- [**CN**] ESP32 **加速度计：融合加速度和陀螺仪数据**
  [**EN**] ESP32 Accelerometer: fuse acceleration and gyroscope data
- [**CN**] **跌倒检测：平滑传感器噪声，提高检测准确率**
  [**EN**] Fall Detection: smooth sensor noise, improve detection accuracy
- [**CN**] **位置追踪：结合多传感器数据估计位置**
  [**EN**] Position Tracking: combine multi-sensor data to estimate position

Mnemonic / 记忆口诀:「预测、更新、循环」— Kalman **滤波的三步骤：预测下一状态，用观测更新，不断循环优化。**

[**EN**]: The Kalman Filter is essential for IoT sensor fusion in your thesis. It uses matrix multiplication for state prediction, eigenvalues for system stability analysis, and matrix inversion for computing optimal gains. Key applications: accelerometer noise filtering, fall detection accuracy improvement, multi-sensor data fusion.

Rotation Matrix / **旋转矩阵 [CN] 二维旋转矩阵（逆时针旋转 θ 角）:**
[EN] 2D Rotation matrix (counterclockwise by angle θ):

$$\mathbf{R}(\theta) = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix}$$

性质 / **Properties**:

- [CN] $\det(\mathbf{R}) = 1$（保持面积/体积）
  [EN] $\det(\mathbf{R}) = 1$ (preserves area/volume)
- [CN] $\mathbf{R}^{-1} = \mathbf{R}^T$（正交矩阵）
  [EN] $\mathbf{R}^{-1} = \mathbf{R}^T$ (orthogonal matrix)
- [CN] 特征值: $e^{\pm i\theta}$（复数，模为 1）
  [EN] Eigenvalues: $e^{\pm i\theta}$ (complex, magnitude 1)

[CN] 三维旋转（绕 Z 轴）
[EN] 3D Rotation (around Z-axis):

$$\mathbf{R}_z(\theta) = \begin{pmatrix} \cos\theta & -\sin\theta & 0 \\ \sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

[EN] **Full Mirror**: Rotation matrix is orthogonal: inverse = transpose. It preserves vector lengths and angles. Essential for 3D orientation tracking in IMU sensors.

Blackboard Challenge: Gyroscope Rotation / 陀螺仪旋转

[CN] 场景:「你的传感器绕 Z 轴旋转了 30°。写出旋转矩阵，并将向量 $(1, 0)$ 旋转。」
Solution / 解答:
Step 1 / 步骤 1: [CN] 构造旋转矩阵 ($\theta = 30° = \pi/6$)
[EN] Construct rotation matrix ($\theta = 30° = \pi/6$):

$$\mathbf{R}(30°) = \begin{pmatrix} \cos 30° & -\sin 30° \\ \sin 30° & \cos 30° \end{pmatrix} = \begin{pmatrix} \frac{\sqrt{3}}{2} & -\frac{1}{2} \\ \frac{1}{2} & \frac{\sqrt{3}}{2} \end{pmatrix} \approx \begin{pmatrix} 0.866 & -0.5 \\ 0.5 & 0.866 \end{pmatrix}$$

Step 2 / 步骤 2: [CN] 旋转向量（矩阵乘向量）
[EN] Rotate vector (matrix times vector):

$$\begin{pmatrix} x' \\ y' \end{pmatrix} = \mathbf{R} \begin{pmatrix} 1 \\ 0 \end{pmatrix} = \begin{pmatrix} 0.866 \times 1 + (-0.5) \times 0 \\ 0.5 \times 1 + 0.866 \times 0 \end{pmatrix} = \boxed{\begin{pmatrix} 0.866 \\ 0.5 \end{pmatrix}}$$

Step 3 / 步骤 3 (验证/Verify): [CN] 检查长度是否保持
[EN] Check if length is preserved:

$$\sqrt{0.866^2 + 0.5^2} = \sqrt{0.75 + 0.25} = 1 \checkmark$$

[EN] **Full Mirror**: Apply rotation matrix by matrix-vector multiplication. Verify by checking $|\mathbf{v}'| = |\mathbf{v}|$ (length preserved). This is how gyroscope data transforms coordinate frames.

Thesis Connection

Thesis Bridge: MPU6050 Orientation / MPU6050 姿态计算 [**CN**]: 这是我论文的核心算法...
[**EN**]: This is the core algorithm in my thesis...
Script / 口试剧本: "My MPU6050 gyroscope outputs angular velocity $(\omega_x, \omega_y, \omega_z)$ in rad/s.
[CN] 積分获得旋转角度 / [**EN**] Integration to get rotation angle:

$$\theta(t) = \theta_0 + \int_0^t \omega(\tau)d\tau \approx \theta_{prev} + \omega \cdot \Delta t$$

[CN] 旋转矩阵累积 / [**EN**] Rotation matrix accumulation:

$$\mathbf{R}_{total} = \mathbf{R}_z(\theta_z) \cdot \mathbf{R}_y(\theta_y) \cdot \mathbf{R}_x(\theta_x)$$

[CN] 问题：陀螺仪漂移！ 1 分钟后累积误差可 $> 5°$
[**EN**] Problem: Gyroscope drift! After 1 minute, accumulated error can be $> 5°$.
[CN] 解决方案：与加速度计的互补滤波 / [**EN**] Solution: Complementary filter with accelerometer:

$$\theta_{fused} = 0.98 \times (\theta_{prev} + \omega \cdot dt) + 0.02 \times \theta_{accel}$$

[CN] 加速度计提供绝对参考（重力方向）来修正漂移。
[**EN**] The accelerometer provides absolute reference (gravity direction) to correct drift."

Covariance Matrix / 协方差矩阵对于随机向量 $\mathbf{X} = (X_1, X_2, ..., X_n)^T$:

$$= E[(\mathbf{X} - \boldsymbol{\mu})(\mathbf{X} - \boldsymbol{\mu})^T]$$

对于二维情况:

$$= \begin{pmatrix} \sigma_x^2 & \sigma_{xy} \\ \sigma_{xy} & \sigma_y^2 \end{pmatrix}$$

性质:

- 对称矩阵: $= ^T$
- 半正定: 所有特征值 ≥ 0
- 对角线: 各变量方差
- 非对角线: 变量间协方差

[**EN**]: Covariance matrix captures how variables vary together. Diagonal = variances, off-diagonal = covariances.

Blackboard Challenge: Sensor Noise Covariance / 传感器噪声协方差

[CN] 场景:「你的加速度计 X、Y、Z 轴噪声标准差分别是 0.1g, 0.1g, 0.15g。假设各轴独立，写出噪声协方差矩阵。」

Solution / 解答:

各轴独立 $\Rightarrow$ 协方差为 0，只有对角线有值:

$$\mathbf{R}_{accel} = \begin{pmatrix} \sigma_x^2 & 0 & 0 \\ 0 & \sigma_y^2 & 0 \\ 0 & 0 & \sigma_z^2 \end{pmatrix} = \begin{pmatrix} 0.01 & 0 & 0 \\ 0 & 0.01 & 0 \\ 0 & 0 & 0.0225 \end{pmatrix} \mathrm{g}^2$$

单位注意: 方差单位是原单位的平方

[**EN**]: For independent sensors, covariance matrix is diagonal with variances on diagonal.

Thesis Connection

Thesis Bridge: Kalman Filter Tuning / 卡尔曼滤波调参 [**CN**]: 这是 Kalman 滤波的关键参数...
Script: "In my fall detection Kalman filter:
Process Noise Covariance Q:

- Models uncertainty in system dynamics
- Higher $\mathbf{Q}$ = trust measurements more
- I tuned: $Q = 0.001$ for smooth motion

Measurement Noise Covariance R:

- From sensor datasheet or empirical measurement
- My MPU6050: $\sigma_{accel} \approx 0.1g \Rightarrow R = 0.01g^2$

Tuning principle:

$$\frac{Q}{R} \uparrow \Rightarrow \text{Faster response, more noise}$$

$$\frac{Q}{R} \downarrow \Rightarrow \text{Smoother output, slower response}$$

For fall detection, I need fast response, so $Q/R \approx 0.1$."

Blackboard Challenge: Sensor Calibration / 传感器校准

[CN] 场景:「你的温度传感器读数需要校准。已知两个校准点:0°C 读数 100, 100°C 读数 900。求线性校准公式。」

Solution / 解答:

线性模型: $T = a \cdot R + b$,其中 R 是读数,T 是真实温度

建立方程组:

$$\begin{cases} 0 = a \times 100 + b \\ 100 = a \times 900 + b \end{cases}$$

矩阵形式:

$$\begin{pmatrix} 100 & 1 \\ 900 & 1 \end{pmatrix} \begin{pmatrix} a \\ b \end{pmatrix} = \begin{pmatrix} 0 \\ 100 \end{pmatrix}$$

求解:

$$a = \frac{100 - 0}{900 - 100} = \frac{100}{800} = 0.125 \tag{40}$$

$$b = 0 - 0.125 \times 100 = -12.5 \tag{41}$$

校准公式:

$$\boxed{T = 0.125 \times R - 12.5}$$

[EN]: Two-point calibration creates linear equation. Use matrix form for multi-point calibration (least squares).

核心公式 / Key Formula

Key Formulas Summary / 关键公式总结

1. **Matrix Multiplication**: $c_{ij} = \sum_k a_{ik} b_{kj}$
2. **2x2 Determinant**: $\det = ad - bc$
3. **3x3 Sarrus**: $\det = aei + bfg + cdh - ceg - bdi - afh$
4. **Characteristic Equation**: $\det(\mathbf{A} - \lambda\mathbf{I}) = 0$
5. **Matrix Inverse (2x2)**: $\mathbf{A}^{-1} = \frac{1}{\det(\mathbf{A})} \begin{pmatrix} d & -b \\ -c & a \end{pmatrix}$

[EN]: Master these five formulas for the exam. Practice computing each by hand until automatic.

9 Numerical Mathematics / 数值计算 (DEN) [SURVIVAL]

[WARN] PRIORITY: SURVIVAL MODE / 优先级:求生模式

[CN] 数值计算优先级为 **CRITICAL**。只背:牛顿法 + 收敛条件! [**EN**] Numerical priority is **CRITICAL**. **ONLY memorize**: Newton-Raphson + Convergence condition!

Goal: Write the formula correctly and shut up. **目标:写对公式然后闭嘴。** **Formula**: $x_{n+1} = x_n - \frac{f(x_n)}{f'(x_n)}$ | **收敛条件:** $|f(x_0) \cdot f''(x_0)| < |f'(x_0)|^2$

求根与优化 / Root Finding & Optimization

[CN] 定义:

- 二分法 (**Bisection**): 简单稳健，收敛慢。基于介值定理。
- 牛顿法 (**Newton's Method**): 利用导数迭代 $x_{n+1} = x_n - f(x_n)/f'(x_n)$。收敛快 (二次收敛)，但可能发散。

[EN] **Definition**:

- **Bisection**: Robust but slow. Interval halving.
- **Newton's Method**: Iterative method using derivatives. Fast convergence (Quadratic), but requires good initial guess.

数值积分 / Numerical Integration

[CN] 定义: 用求和近似积分 $\int f(x)dx$。

- 梯形法则 (**Trapezoidal Rule**): 用直线段连接点。
- 辛普森法则 (**Simpson's Rule**): 用抛物线拟合点。精度更高。

[EN] **Definition**: Approximating definite integrals.

- **Trapezoidal**: Approximates area with trapezoids.
- **Simpson's**: Approximates with parabolas (Higher accuracy).

核心公式 / Key Formula

有限差分 / Finite Difference (用于求导):

$$f'(x) \approx \frac{f(x+h) - f(x)}{h} \quad \text{(前向差分)} \tag{42}$$

论文关联 / Project Application

[CN]: 你的 ESP32 固件在处理传感器数据时使用数值方法：

- [CN] 积分 (Integration): 加速度计 → 速度 → 位移。这是黎曼和 (Riemann Sum) 的离散实现 ($v+ = a \cdot dt$)
  [EN] Integration: Accel → Vel → Pos. Discrete Riemann sum ($v+ = a \cdot dt$)
- [CN] 微分 (Differentiation): 陀螺仪角度变化率计算
  [EN] Differentiation: Gyroscope angular rate calculation
- [CN] 浮点数精度: IEEE 754 标准 (float/double) 的舍入误差会随时间累积 (Drift)
  [EN] Floating point precision: IEEE 754 rounding errors accumulate over time (Drift)

[EN] **Full Mirror**: Your ESP32 firmware uses numerical methods for sensor processing:

- **Integration**: Accelerometer → Velocity → Position via discrete accumulation
- **Differentiation**: Angular rate from gyroscope
- **Error Accumulation**: Floating-point rounding causes "Drift" in IMU navigation, requiring sensor fusion corrections

10 Differential Equations / 微分方程 (DEN) [SURVIVAL]

[WARN] PRIORITY: SURVIVAL MODE / 优先级：求生模式

[CN] DEN 优先级为 **CRITICAL**。只背：分离变量法 + 一阶线性解！ [EN] DEN priority is **CRITICAL**. **ONLY memorize**: Separable ODE + First-order linear solution!
Goal: Don't solve complex integrals. 目标：别去解复杂的积分。

Key Pattern: $\frac{dy}{dx} = g(x)h(y) \Rightarrow \int \frac{dy}{h(y)} = \int g(x)dx$

Separable ODE / 可分离变量微分方程如果一阶微分方程可以写成以下形式：

$$\frac{dy}{dx} = f(x) \cdot g(y)$$

则称其为可分离变量方程。
求解方法：将含 y 的项移到左边，含 x 的项移到右边，两边积分。

$$\int \frac{1}{g(y)}\,dy = \int f(x)\,dx$$

Mnemonic / 记忆口诀:「分家过日子」— x 和 y 各自分开，各自积分。

[EN]: A separable ODE can be written as $\frac{dy}{dx} = f(x)g(y)$. Solve by separating variables and integrating both sides.

Blackboard Challenge: Separable ODE / 可分离变量方程

[CN] 场景:「请求解微分方程 $\frac{dy}{dx} = xy$，初始条件 $y(0) = 1$。」
Solution / 解答:
Step 1: 分离变量（y 移左，x 移右）

$$\frac{dy}{dx} = xy \quad \Rightarrow \quad \frac{1}{y}\,dy = x\,dx$$

Step 2: 两边积分

$$\int \frac{1}{y}\,dy = \int x\,dx$$

$$\ln|y| = \frac{x^2}{2} + C$$

Step 3: 指数化求解 y

$$|y| = e^{\frac{x^2}{2}+C} = e^C \cdot e^{\frac{x^2}{2}}$$

令 $A = \pm e^C$，则:

$$y = A \cdot e^{\frac{x^2}{2}}$$

Step 4: 代入初始条件 $y(0) = 1$

$$1 = A \cdot e^0 = A \quad \Rightarrow \quad A = 1$$

Final Answer / 最终答案:

$$\boxed{y = e^{\frac{x^2}{2}}}$$

Mnemonic / 记忆口诀:「分、积、解、代」— 分离变量、积分、解出函数、代入初值。

[EN]: Separate variables, integrate both sides, solve for y, apply initial condition. The solution is a Gaussian-like exponential function.

核心公式 / Key Formula

RC Circuit ODE / RC 电路微分方程电路方程:

$$RC\frac{dV}{dt} + V = V_{in}$$

时间常数 / Time Constant:

$$\tau = RC$$

通解 / General Solution:

$$V(t) = V_{in} + (V_0 - V_{in})e^{-t/\tau}$$

其中 V_0 是初始电压。
Mnemonic / 记忆口诀:「RC 决定快慢」— $\tau = RC$ 越大，充放电越慢；5 个 τ 后基本稳定。

[EN]: The RC time constant $\tau = RC$ determines how fast the circuit responds. After 5τ, the voltage reaches approximately 99.3% of its final value.

Blackboard Challenge: RC Circuit / RC 电路求解

[CN] 场景:「一个 RC 电路，$R = 10\text{k}\Omega$，$C = 100\mu\text{F}$，初始电压 $V_0 = 0$，接入 $V_{in} = 5V$。求 $V(t)$ 和达到 $3V$ 所需时间。」

Solution / 解答:

Step 1: 计算时间常数

$$\tau = RC = (10 \times 10^3) \times (100 \times 10^{-6}) = 1 \text{ s}$$

Step 2: 写出电压方程 ($V_0 = 0$，$V_{in} = 5$)

$$V(t) = V_{in} + (V_0 - V_{in})e^{-t/\tau} = 5 + (0 - 5)e^{-t/1}$$

$$V(t) = 5(1 - e^{-t})$$

Step 3: 求达到 $3V$ 的时间

$$3 = 5(1 - e^{-t})$$

$$\frac{3}{5} = 1 - e^{-t} \quad \Rightarrow \quad e^{-t} = \frac{2}{5}$$

$$-t = \ln(0.4) \quad \Rightarrow \quad t = -\ln(0.4) \approx 0.916 \text{ s}$$

Final Answer / 最终答案:

$$\boxed{V(t) = 5(1 - e^{-t}) \text{ V}, \quad t_{3V} \approx 0.916 \text{ s}}$$

Mnemonic / 记忆口诀:「充电指数升，放电指数降」— 充电从 0 向目标爬升，放电从高向 0 衰减，都是指数变化。

[**EN**]: For charging: $V(t) = V_{in}(1 - e^{-t/\tau})$. For discharging: $V(t) = V_0 e^{-t/\tau}$. The time constant τ determines the rate of change.

Common Mistakes / 常见错误

1. 单位换算错误：$\text{k}\Omega$ 和 μF 要先换成基本单位
2. 充放电公式混淆：充电用 $(1 - e^{-t/\tau})$，放电用 $e^{-t/\tau}$
3. 忘记初始条件：必须明确 V_0 是多少

[**EN**]: Always convert units first. Do not confuse charging $(1 - e^{-t/\tau})$ with discharging $(e^{-t/\tau})$. Always specify initial conditions.

Second Order Linear ODE / 二阶线性微分方程标准形式：

$$a\frac{d^2y}{dt^2} + b\frac{dy}{dt} + cy = 0$$

特征方程 / Characteristic Equation:

$$ar^2 + br + c = 0$$

判别式 / Discriminant: $\Delta = b^2 - 4ac$
Mnemonic / 记忆口诀:「微分变代数」— 把 $\frac{d^2y}{dt^2}$ 换成 r^2，$\frac{dy}{dt}$ 换成 r，解代数方程。

[**EN**]: Replace derivatives with powers of r to get the characteristic equation. The discriminant determines the type of solution.

核心公式 / Key Formula

Three Damping Cases / 三种阻尼情况设特征方程的根为 $r_{1,2} = \frac{-b\pm\sqrt{b^2-4ac}}{2a}$
Case 1: Overdamped / 过阻尼 ($\Delta > 0$)

$$y(t) = C_1e^{r_1t} + C_2e^{r_2t}$$

两个不同实根，系统缓慢回到平衡。
Case 2: Critically Damped / 临界阻尼 ($\Delta = 0$)

$$y(t) = (C_1 + C_2t)e^{rt}$$

重根 $r = -b/(2a)$，最快无振荡回到平衡。
Case 3: Underdamped / 欠阻尼 ($\Delta < 0$)

$$y(t) = e^{\alpha t}(C_1\cos\omega t + C_2\sin\omega t)$$

其中 $\alpha = -b/(2a)$，$\omega = \sqrt{4ac - b^2}/(2a)$
Mnemonic / 记忆口诀:「过阻尼像老人走路（慢吞吞），临界阻尼像关门（刚好不震），欠阻尼像弹簧（来回晃）」

[**EN**]: Overdamped = slow return, Critically damped = fastest non-oscillatory return, Underdamped = oscillatory decay.

Blackboard Challenge: Second Order ODE / 二阶微分方程

[CN] 场景:「求解 $\frac{d^2y}{dt^2} + 5\frac{dy}{dt} + 6y = 0$，判断阻尼类型。」

Solution / 解答:

Step 1: 写出特征方程（$a = 1, b = 5, c = 6$）

$$r^2 + 5r + 6 = 0$$

Step 2: 计算判别式

$$\Delta = b^2 - 4ac = 25 - 24 = 1 > 0$$

Step 3: 求特征根

$$r = \frac{-5 \pm \sqrt{1}}{2} = \frac{-5 \pm 1}{2}$$

$$r_1 = -2, \quad r_2 = -3$$

Step 4: 写出通解

$$y(t) = C_1 e^{-2t} + C_2 e^{-3t}$$

Final Answer / 最终答案:

$$\boxed{y(t) = C_1 e^{-2t} + C_2 e^{-3t}, \quad \text{Overdamped / 过阻尼}}$$

Mnemonic / 记忆口诀:「判别式定乾坤」— $\Delta > 0$ 过阻尼，$\Delta = 0$ 临界，$\Delta < 0$ 欠阻尼。

[EN]: Since $\Delta > 0$, we have two distinct real roots, indicating an overdamped system. The solution is a sum of two decaying exponentials.

Blackboard Challenge: Underdamped Case / 欠阻尼情况

[CN] 场景:「求解 $\frac{d^2y}{dt^2} + 2\frac{dy}{dt} + 5y = 0$。」
Solution / 解答:
Step 1: 特征方程（$a = 1, b = 2, c = 5$）

$$r^2 + 2r + 5 = 0$$

Step 2: 判别式

$$\Delta = 4 - 20 = -16 < 0 \quad \text{(Underdamped)}$$

Step 3: 复数根

$$r = \frac{-2 \pm \sqrt{-16}}{2} = \frac{-2 \pm 4i}{2} = -1 \pm 2i$$

Step 4: 写出通解（$\alpha = -1$，$\omega = 2$）

$$y(t) = e^{-t}(C_1 \cos 2t + C_2 \sin 2t)$$

Final Answer / 最终答案:

$$\boxed{y(t) = e^{-t}(C_1 \cos 2t + C_2 \sin 2t), \quad \text{Underdamped / 欠阻尼}}$$

Mnemonic / 记忆口诀:「复数根带振荡」— 虚部变角频率 ω，实部变衰减率 α。

[**EN**]: Complex roots $\alpha \pm i\omega$ give oscillatory solutions with exponential decay. The imaginary part becomes the angular frequency, the real part becomes the decay rate.

Thesis Connection

Thesis Application: Sensor Signal Processing / **论文应用：传感器信号处理 [CN] 与论文的联系: 微分方程在 IoT 传感器系统中的应用：**

1. RC 滤波器设计

- ESP32 的 ADC 输入常需要 RC 低通滤波器
- 时间常数 $\tau = RC$ 决定截止频率 $f_c = \frac{1}{2\pi RC}$
- 滤除高频噪声，保留有用信号

2. 传感器动态响应

- 温度传感器响应近似一阶系统：$\tau\frac{dT}{dt} + T = T_{env}$
- 加速度计的机械结构是二阶系统
- 阻尼比决定响应速度和超调量

3. 跌倒检测算法

$$\text{Impact} = \frac{d|\mathbf{a}|}{dt} \quad \text{(加速度变化率)}$$

用一阶微分方程建模人体运动状态转换。
Mnemonic / 记忆口诀:「滤波看 RC，响应看阻尼」— RC 电路是低通滤波器，阻尼比决定系统振荡行为。

[EN]: Differential equations model RC filters (noise reduction), sensor response dynamics (temperature, accelerometer), and fall detection algorithms (impact detection via acceleration derivatives). Understanding time constants and damping is crucial for IoT system design.

核心公式 / Key Formula

Key Formulas Summary / 关键公式总结

1. **Separable ODE**: $\int \frac{1}{g(y)}dy = \int f(x)dx$
2. **RC Time Constant**: $\tau = RC$
3. **RC Charging**: $V(t) = V_{in}(1 - e^{-t/\tau})$
4. **Characteristic Equation**: $ar^2 + br + c = 0$
5. **Discriminant**: $\Delta = b^2 - 4ac$
6. **Underdamped Solution**: $y = e^{\alpha t}(C_1 \cos\omega t + C_2 \sin\omega t)$

[EN]: These six formulas cover the essential ODE techniques for the exam. Practice identifying which type of ODE you are dealing with.

11 Discrete Math & Graphs / 离散数学与图论 (DMG) [SURVIVAL]

[WARN] PRIORITY: SURVIVAL MODE / 优先级：求生模式

[CN] DMG 优先级为 **CRITICAL**。只背：集合运算 + 基数 + 图连通性！
[EN] DMG priority is **CRITICAL**. **ONLY memorize**: Set ops + Cardinality + Graph connectivity!
Goal: Definitions only. **目标：只背定义**。**Key Defs**: $|\mathbb{N}| = |\mathbb{Z}| = |\mathbb{Q}| = \aleph_0$ (countable) | $|\mathbb{R}| = \mathfrak{c}$ (uncountable)

集合与逻辑 / Sets & Logic

[CN] 定义:

- **集合 (Set)**：唯一对象的汇集。$\cup$ (并), $\cap$ (交), $\setminus$ (不包含).
- **命题逻辑**: AND ($\wedge$), OR ($\vee$), NOT ($\neg$), IMPLIES ($\Rightarrow$).
- **关系 (Relation)**：等价关系 (自反、对称、传递) 和偏序关系。

[EN] **Definition**:

- **Set**: Collection of unique objects. Union, Intersection, Difference.
- **Logic**: Boolean algebra ($\wedge, \vee, \neg$).
- **Relation**: Equivalence (Reflexive, Symmetric, Transitive) and Partial Order.

核心公式 / Key Formula

排列组合 / **Combinatorics**:

- 排列 **(Permutation)**：有序. $P(n,k) = \frac{n!}{(n-k)!}$.
- 组合 **(Combination)**：无序. $C(n,k) = \binom{n}{k} = \frac{n!}{k!(n-k)!}$.

论文关联 / Project Application

[CN]:

- 布尔逻辑：代码中的 `if (Condition A && Condition B)` 是命题逻辑的直接应用。
- 状态机：有限状态机 (FSM) 用于管理 ESP32 的连接状态 (Disconnected $\rightarrow$ Connecting $\rightarrow$ Connected)。这是离散数学中的图论应用。
- 位运算：掩码 (Masking) 操作对应集合的交集运算。

[EN]:

- **Boolean Logic**: 'if' statements relate directly to Propositional Logic.
- **FSM**: Finite State Machines manage connection states, rooted in Graph Theory.
- **Bitwise Ops**: Masking corresponds to Set Intersection.

12 图论 / Graph Theory (BE5B01DMA)

图的概念 / Graph Concepts

[CN] 定义: 图 $G = (V, E)$ 由顶点集合 V 和边集合 E 组成。

- 度 (**Degree**): 连接到一个顶点的边的数量。
- 路径 (**Path**): 顶点序列。
- 连通图 (**Connected**): 任意两点间都存在路径。

[EN] **Definition**: Graph $G = (V, E)$ consists of Vertices V and Edges E.

- **Degree**: Number of edges incident to a vertex.
- **Path**: Sequence of adjacent vertices.
- **Connected**: Path exists between any pair of vertices.

核心公式 / Key Formula

树 (**Tree**): 无环连通图 (Connected Acyclic Graph)。性质:

- 任意两点间只有唯一路径。
- $|E| = |V| - 1$ (边数 = 顶点数 - 1)。

欧拉路径 (**Euler Path**): 经过每条边恰好一次。条件: 奇度数顶点为 0 或 2 个。

论文关联 / Project Application

[CN]:

- 网络拓扑: 你的智能家居采用星型拓扑 (Star Topology)。WiFi 路由器是中心节点 (Hub), 所有 ESP32 设备是叶子节点 (Leaves)。
- **MQTT** 主题: MQTT 的 Topic 层级结构 (e.g., 'home/livingroom/temp') 实际上构成了一棵树 (Topic Tree)。
- 状态机: 状态转移图 (State Transition Graph) 是有向图 (Directed Graph)。

[EN]:

- **Network Topology**: Star Topology. Router is the Hub; ESP32s are Leaves.
- **MQTT Topics**: Form a Topic Tree hierarchy.
- **FSM**: Represented as a Directed Graph where nodes are states and edges are transitions.

13 概率统计 / Probability & Statistics (BE5B01PST)

随机变量 / Random Variables

[CN] 定义:

- 随机变量 (**RV**): 随机实验结果的数值表示。
- 概率密度函数 (**PDF**): 描述连续 RV 在某点附近取值的概率密度。
- 累积分布函数 (**CDF**): $F(x) = P(X \leq x)$。

[EN] **Definition**:

- **Random Variable (RV)**: Numerical outcome of a random phenomenon.
- **PDF**: Integration gives probability.
- **CDF**: Cumulative Distribution Function.

核心公式 / Key Formula

期望与方差:

- 期望 (**Expectation**): $E[X] = \mu$ (平均值)
- 方差 (**Variance**): $\mathrm{Var}(X) = E[(X-\mu)^2] = E[X^2] - (E[X])^2$

正态分布 (**Normal Distribution**):

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(x-\mu)^2}{2\sigma^2}} \tag{43}$$

假设检验 / Hypothesis Testing

[CN] 定义:

- 零假设 (H_0): 默认假设 (如" 无关联")。
- **P 值 (p-value)**: 在 H_0 为真时，观察到当前结果的概率。若 $p < \alpha$，拒绝 H_0。
- 第一类错误 (**Type I**): 假阳性 (False Positive)。
- 第二类错误 (**Type II**): 假阴性 (False Negative)。

[EN] **Definition**:

- **Null Hypothesis** (H_0): Default assumption.
- **p-value**: Prob. of observing results given H_0 is true. Reject if $p < 0.05$.
- **Type I Error**: False Positive (Reject true H_0).
- **Type II Error**: False Negative (Accept false H_0).

论文关联 / Project Application

[CN]:

- 传感器噪声: 假设 MEMS 加速度计的噪声服从高斯分布 (Gaussian White Noise)。这是卡尔曼滤波和移动平均滤波的基本假设。
- 跌倒检测性能: 评估算法时，你需要计算灵敏度 (Sensitivity) 和特异度 (Specificity)。这直接对应于统计学中的 True Positives 和 True Negatives。

[EN]:

- **Sensor Noise**: Assumed to be Gaussian (Normal) White Noise. Filter design relies on signal-to-noise ratio (SNR).
- **Performance**: Sensitivity (Recall) and Specificity metrics quantify the fall detection algorithm's accuracy (checking for Type I/II errors).

Part III
物理基础 / Physics Foundation

14 Mechanics / 力学 (PH1)

[CAUTION] PRIORITY: FOCUS MODE / 优先级：专注模式

[CN] 力学优先级为 **CAUTION**。重点: F=ma (牛顿第二定律) + 谐振动！
[EN] Mechanics priority is **CAUTION**. **Focus**: F=ma + Harmonic Motion!
Thesis Link: Accelerometer measures $a \to F = ma$. 加速度计测量的是力.

Newton's Second Law / 牛顿第二定律公式 / **Formula**:

$$\mathbf{F} = m\mathbf{a} \quad \text{或 / or} \quad \mathbf{F} = \frac{d\mathbf{p}}{dt}$$

变量说明 / **Variables**:

- **[CN]** $\mathbf{F}$ — 合外力 [N] / **[EN]** Net Force [N]
- **[CN]** m — 质量 [kg] / **[EN]** Mass [kg]
- **[CN]** $\mathbf{a}$ — 加速度 [m/s^2] / **[EN]** Acceleration [m/s^2]
- **[CN]** $\mathbf{p} = m\mathbf{v}$ — 动量 [kg·m/s] / **[EN]** Momentum [kg·m/s]

Mnemonic / 记忆口诀: [CN]「力是加速度的老板」— 力越大，加速度越大；质量越大，越难推动。
[EN] "Force is the boss of acceleration" — more force means more acceleration; more mass means harder to push.

[EN] Full Mirror: Newton's Second Law relates force to the rate of change of momentum. For constant mass: $F = ma$. Force causes acceleration inversely proportional to mass. Key insight: mass resists acceleration (inertia).

Blackboard Challenge: Newton's Second Law / 牛顿第二定律计算

[CN] 场景:「一个 $m = 2$ kg 的物体在光滑水平面上，受到 $F = 10$ N 的水平推力。求加速度和 $t = 3$ s 后的速度（初速度为零）。」

Solution / 解答:

Step 1 / 步骤 1: [CN] 应用牛顿第二定律求加速度

[**EN**] Apply Newton's Second Law to find acceleration:

$$F = ma \quad \Rightarrow \quad a = \frac{F}{m} = \frac{10}{2} = 5 \text{ m/s}^2$$

Step 2 / 步骤 2: [CN] 使用运动学公式求速度

[**EN**] Use kinematics equation to find velocity:

$$v = v_0 + at = 0 + 5 \times 3 = 15 \text{ m/s}$$

Step 3 / 步骤 3 (验算/Verify): [CN] 计算位移验证

[**EN**] Calculate displacement to verify:

$$s = v_0 t + \frac{1}{2}at^2 = 0 + \frac{1}{2} \times 5 \times 9 = 22.5 \text{ m}$$

Final Answer / 最终答案:

$$\boxed{a = 5 \text{ m/s}^2, \quad v(3\text{s}) = 15 \text{ m/s}}$$

Mnemonic / 记忆口诀: [CN]「F 除 m 得 a，v 等 v0 加 at」— 牛二定律和运动学公式联合使用。

[**EN**] "F divided by m gives a, v equals v0 plus at" — Newton's Law + kinematics combined.

[EN] **Full Mirror**:

- **Step 1**: Apply $F = ma$ to solve for $a = F/m$
- **Step 2**: Use $v = v_0 + at$ to find final velocity
- **Step 3**: Verify with $s = v_0 t + \frac{1}{2}at^2$

Key insight: Kinematics + dynamics work together in mechanics problems.

Simple Harmonic Motion (SHM) / 简谐运动 **[CN] 弹簧-质量系统的运动方程：**
[EN] Equation of motion for spring-mass system:

$$m\frac{d^2x}{dt^2} = -kx \quad \Rightarrow \quad \frac{d^2x}{dt^2} + \omega^2 x = 0$$

角频率 / Angular Frequency:

$$\omega = \sqrt{\frac{k}{m}}$$

周期 / Period:

$$T = \frac{2\pi}{\omega} = 2\pi\sqrt{\frac{m}{k}}$$

通解 / General Solution:

$$x(t) = A\cos(\omega t + \phi)$$

Mnemonic / 记忆口诀: **[CN]「k 大弹得快，m 大晃得慢」— 弹簧越硬（k 大）频率越高，质量越大频率越低。**
[EN] "Stiffer spring = faster, heavier mass = slower" — k up means ω up; m up means ω down.

[EN] Full Mirror: SHM occurs when restoring force is proportional to displacement ($F = -kx$). Angular frequency $\omega = \sqrt{k/m}$ determines how fast oscillation occurs. Period $T = 2\pi/\omega$ is time for one complete cycle.

核心公式 / Key Formula

SHM Key Relationships / **简谐运动关键公式位移、速度、加速度 / Displacement, Velocity, Acceleration**:

$$\begin{aligned} x(t) &= A\cos(\omega t + \phi) \\ v(t) &= -A\omega\sin(\omega t + \phi) \\ a(t) &= -A\omega^2\cos(\omega t + \phi) = -\omega^2 x \end{aligned}$$

最大值 / Maximum Values:

- **[CN] 最大位移：**$x_{max} = A$（振幅）/ **[EN]** Max displacement: $x_{max} = A$ (amplitude)
- **[CN] 最大速度：**$v_{max} = A\omega$（平衡点处）/ **[EN]** Max velocity: $v_{max} = A\omega$ (at equilibrium)
- **[CN] 最大加速度：**$a_{max} = A\omega^2$（端点处）/ **[EN]** Max acceleration: $a_{max} = A\omega^2$ (at extremes)

Mnemonic / 记忆口诀: **[CN]「位余速正加反位」— 位移用 cos，速度用 sin（差 90 度），加速度和位移反相。**
[EN] "x is cos, v is sin, a is opposite to x" — velocity leads by 90°, acceleration opposes displacement.

[EN] Full Mirror: Velocity leads displacement by 90° (phase). Acceleration is 180° out of phase with displacement (always points toward equilibrium). Max velocity occurs at equilibrium; max acceleration occurs at turning points.

Blackboard Challenge: Spring-Mass SHM / 弹簧振子

[CN] 场景:「一个 $m = 0.5$ kg 的物体连接在 $k = 200$ N/m 的弹簧上。求角频率、周期和频率。若振幅 $A = 0.1$ m，求最大速度和最大加速度。」

Solution / 解答:

Step 1 / 步骤 1: [CN] 计算角频率
[EN] Calculate angular frequency:

$$\omega = \sqrt{\frac{k}{m}} = \sqrt{\frac{200}{0.5}} = \sqrt{400} = 20 \text{ rad/s}$$

Step 2 / 步骤 2: [CN] 计算周期和频率
[EN] Calculate period and frequency:

$$T = \frac{2\pi}{\omega} = \frac{2\pi}{20} = \frac{\pi}{10} \approx 0.314 \text{ s}$$

$$f = \frac{1}{T} = \frac{10}{\pi} \approx 3.18 \text{ Hz}$$

Step 3 / 步骤 3: [CN] 计算最大速度
[EN] Calculate maximum velocity:

$$v_{max} = A\omega = 0.1 \times 20 = 2 \text{ m/s}$$

Step 4 / 步骤 4: [CN] 计算最大加速度
[EN] Calculate maximum acceleration:

$$a_{max} = A\omega^2 = 0.1 \times 400 = 40 \text{ m/s}^2$$

Final Answer / 最终答案:

$$\boxed{\omega = 20 \text{ rad/s}, \quad T \approx 0.314 \text{ s}, \quad v_{max} = 2 \text{ m/s}, \quad a_{max} = 40 \text{ m/s}^2}$$

Mnemonic / 记忆口诀:「根号 k 除 m」— 角频率公式简单直接，周期是角频率的倒数乘 2π。

[EN]: $\omega = \sqrt{k/m}$, then $T = 2\pi/\omega$, $v_{max} = A\omega$, $a_{max} = A\omega^2$. These are the four key quantities for SHM.

Energy Conservation / 能量守恒机械能守恒条件：只有保守力做功时，机械能守恒。

$$E_{total} = KE + PE = \text{constant}$$

动能 / **Kinetic Energy**:

$$KE = \frac{1}{2}mv^2$$

势能 / **Potential Energy**:

- 重力势能：$PE_g = mgh$
- 弹性势能：$PE_s = \frac{1}{2}kx^2$

Mnemonic / 记忆口诀:「动势互换总不变」— 动能和势能相互转化，总能量不变。

[**EN**]: When only conservative forces act, mechanical energy is conserved: $KE+PE = \text{constant}$. Energy transforms between kinetic and potential forms.

Blackboard Challenge: Energy Conservation / 能量守恒

[CN] 场景:「一个 $m = 1$ kg 的球从 $h = 5$ m 高处自由落下。求落地时的速度（忽略空气阻力，$g = 10$ m/s^2）。」

Solution / 解答:

Step 1: 写出初态能量（顶部，$v_0 = 0$）

$$E_i = KE_i + PE_i = 0 + mgh = 1 \times 10 \times 5 = 50 \text{ J}$$

Step 2: 写出末态能量（底部，$h = 0$）

$$E_f = KE_f + PE_f = \frac{1}{2}mv^2 + 0$$

Step 3: 应用能量守恒

$$E_i = E_f \quad \Rightarrow \quad mgh = \frac{1}{2}mv^2$$

Step 4: 解出速度

$$gh = \frac{1}{2}v^2 \quad \Rightarrow \quad v = \sqrt{2gh} = \sqrt{2 \times 10 \times 5} = \sqrt{100} = 10 \text{ m/s}$$

Final Answer / 最终答案:

$$\boxed{v = 10 \text{ m/s}}$$

Mnemonic / 记忆口诀:「根号 2gh」— 自由落体末速度公式，能量守恒直接得出。

[**EN**]: Energy conservation: $mgh = \frac{1}{2}mv^2$, so $v = \sqrt{2gh}$. Mass cancels out, only height and gravity matter.

Blackboard Challenge: Spring Energy / 弹簧能量

[CN] 场景:「弹簧振子在 SHM 中，证明总能量恒定，并求任意位置的动能和势能比例。」

Solution / 解答:

Step 1: 写出总能量（设 $x = A\cos(\omega t)$）

$$E = KE + PE = \frac{1}{2}mv^2 + \frac{1}{2}kx^2$$

Step 2: 代入 $v = -A\omega\sin(\omega t)$ 和 $\omega^2 = k/m$

$$KE = \frac{1}{2}m(A\omega)^2\sin^2(\omega t) = \frac{1}{2}kA^2\sin^2(\omega t)$$
$$PE = \frac{1}{2}kA^2\cos^2(\omega t)$$

Step 3: 求和

$$E = \frac{1}{2}kA^2(\sin^2 + \cos^2) = \frac{1}{2}kA^2 = \text{constant}$$

Step 4: 在 $x = A/2$ 处的比例

$$PE = \frac{1}{2}k\left(\frac{A}{2}\right)^2 = \frac{1}{8}kA^2 = \frac{E}{4}$$

$$KE = E - PE = \frac{1}{2}kA^2 - \frac{1}{8}kA^2 = \frac{3}{8}kA^2 = \frac{3E}{4}$$

Final Answer / 最终答案:

$$\boxed{E_{total} = \frac{1}{2}kA^2, \quad \text{At } x = A/2: \quad KE : PE = 3:1}$$

Mnemonic / 记忆口诀:「半振幅三比一」— 位移为振幅一半时，动能是势能的三倍。

[EN]: Total SHM energy is $\frac{1}{2}kA^2$. At half amplitude, $KE : PE = 3 : 1$ because PE scales as x^2.

Common Mistakes / 常见错误

1. 忘记平方：动能 $\frac{1}{2}mv^2$，弹性势能 $\frac{1}{2}kx^2$，都有平方
2. 单位混乱：确保用 SI 单位（kg, m, s, N）
3. 参考点选择：势能需要选定参考点（$h = 0$ 或 $x = 0$）
4. 非保守力：有摩擦时机械能不守恒，能量损失为热

[EN]: Remember the squares in energy formulas. Always use SI units. Choose a reference point for PE. Mechanical energy is NOT conserved with friction.

Thesis Connection

Thesis Application: Accelerometer and Fall Detection / **论文应用：加速度计与跌倒检测 [CN]**
与论文的联系:
力学原理在 IoT 跌倒检测系统中的核心应用：
1. 加速度计原理 (MEMS Accelerometer)
加速度计内部是一个微型弹簧-质量系统：

$$F = ma = kx \quad \Rightarrow \quad a = \frac{k}{m}x$$

通过测量位移 x **即可得到加速度** a**。**
2. 跌倒检测算法
基于加速度特征的检测：

- **自由落体相：** $|\mathbf{a}| \approx 0$（失重）
- **撞击相：** $|\mathbf{a}| > 3g$（大冲击）
- **静止相：** $|\mathbf{a}| \approx g$（躺在地上）

加速度矢量幅值:

$$|\mathbf{a}| = \sqrt{a_x^2 + a_y^2 + a_z^2}$$

3. 能量分析
跌倒过程的能量转化：

$$mgh \to \frac{1}{2}mv^2 \to \text{Impact Energy}$$

撞击力估算： $F_{impact} = \frac{\Delta p}{\Delta t} = \frac{mv}{\Delta t}$
4. ESP32 实现

- MPU6050/ADXL345 **加速度计采样率：** 100-500 Hz
- **实时计算加速度幅值和变化率**
- **阈值判断 + 状态机检测跌倒**

Mnemonic / **记忆口诀:「零-大-稳」— 跌倒三相：自由落体零加速度，撞击大加速度，躺下稳定加速度。**

[EN]: MEMS accelerometers use spring-mass principles. Fall detection analyzes acceleration magnitude through three phases: free-fall ($|a| \approx 0$), impact ($|a| > 3g$), and rest ($|a| \approx g$). Understanding mechanics is essential for designing reliable fall detection algorithms on ESP32.

Centripetal Force / 向心力物体做圆周运动时，指向圆心的力：

$$F_c = \frac{mv^2}{r} = m\omega^2 r = m \cdot a_c$$

其中：

- v — 线速度 (Linear velocity) [m/s]
- r — 圆周半径 (Radius) [m]
- ω — 角速度 (Angular velocity) [rad/s]
- $a_c = v^2/r = \omega^2 r$ — 向心加速度

Mnemonic / 记忆口诀:「向心力是拉绳的手」— 没有向心力，物体会沿切线飞出。

[**EN**]: Centripetal force keeps an object moving in a circle. Without it, the object would fly off tangentially (Newton's 1st Law).

Blackboard Challenge: Centripetal Acceleration / 向心加速度

[CN] 场景:「人转身时手臂长 $r = 0.6m$，角速度 $\omega = 3$ rad/s。求手腕处的向心加速度。」
Solution / 解答:

$$a_c = \omega^2 r = (3)^2 \times 0.6 = 9 \times 0.6 = \boxed{5.4 \text{ m/s}^2} \tag{44}$$

比较: $a_c = 5.4 \text{ m/s}^2 \approx 0.55g$
这个加速度会被手腕上的加速度计检测到！

[**EN**]: Centripetal acceleration $= \omega^2 r$. This contributes to accelerometer reading during rotation.

Thesis Connection

Thesis Bridge: Gyroscope + Rotation / 陀螺仪与旋转 [CN]: 这在跌倒检测中很重要...
Script: "During a fall, the body rotates. My MPU6050 measures:

- **Accelerometer**: Linear acceleration + Centripetal acceleration + Gravity
- **Gyroscope**: Angular velocity ω in rad/s

Problem: Accelerometer reading is contaminated by rotation:

$$\mathbf{a}_{measured} = \mathbf{a}_{linear} + \boldsymbol{\omega} \times (\boldsymbol{\omega} \times \mathbf{r}) + \mathbf{g}$$

Solution: Use gyroscope to calculate and subtract centripetal component:

$$a_{centripetal} = \omega^2 r$$

For typical human fall: $\omega \approx 2 - 5$ rad/s, $r \approx 0.5m \Rightarrow a_c \approx 2 - 12 \text{ m/s}^2$
This is significant and must be accounted for!"

Impulse-Momentum Theorem / 动量定理

$$\mathbf{J} = \int \mathbf{F}\, dt = \Delta \mathbf{p} = m\mathbf{v}_f - m\mathbf{v}_i$$

对于恒力：

$$\mathbf{F} \cdot \Delta t = m\Delta \mathbf{v}$$

Mnemonic / 记忆口诀:「力乘时间改变动量」— 越大的力作用越久，动量改变越大。

[**EN**]: Impulse equals change in momentum. Key for understanding collisions and impacts.

Blackboard Challenge: Fall Impact Force / 跌倒撞击力

[CN] 场景:「一个 70kg 的人从 1m 高度跌倒，撞击地面时间 0.1s。估算平均撞击力。」
Solution / 解答:
Step 1: 计算落地速度（能量守恒）

$$v = \sqrt{2gh} = \sqrt{2 \times 10 \times 1} = \sqrt{20} \approx 4.47 \text{ m/s}$$

Step 2: 计算动量变化

$$\Delta p = mv - 0 = 70 \times 4.47 = 313 \text{ kg} \cdot \text{m/s}$$

Step 3: 计算平均撞击力

$$F_{avg} = \frac{\Delta p}{\Delta t} = \frac{313}{0.1} = \boxed{3130 \text{ N}}$$

加速度: $a = F/m = 3130/70 = 44.7 \text{ m/s}^2 \approx \boxed{4.5g}$

[**EN**]: Impact force depends on stopping time. Shorter Δt = higher force. This is why padding helps!

Thesis Connection

Thesis Bridge: Fall Detection Threshold / 跌倒检测阈值 [CN]: 这是我论文算法的核心参数...
Script: "Based on physics calculation:

- Typical fall impact: 3-6g
- Sitting down hard: 1-2g
- Normal walking: < 1g variation

My detection thresholds:

1. **Free-fall phase**: $|a| < 0.4g$ for > 200ms
2. **Impact phase**: $|a| > 2.5g$ peak
3. **Rest phase**: $|a| \approx 1g$ and lying orientation

Why 2.5g not 4g?

- Elderly falls are often slower, less violent
- Want sensitivity (catch more falls) over specificity
- False alarms handled by additional checks (orientation, time)

"

Blackboard Challenge: MEMS Accelerometer Design / MEMS 加速度计设计

[CN] 场景:「MEMS 加速度计的 proof mass 为 10μg，弹簧常数 k 设计为测量 ±16g 范围。求 k 值和最大位移。」
Solution / 解答:
Step 1: 单位转换

- $m = 10\mu g = 10 \times 10^{-9} kg = 10^{-8} kg$
- $a_{max} = 16g = 16 \times 9.8 = 156.8\ \mathrm{m/s^2}$

Step 2: 计算最大力

$$F_{max} = m \cdot a_{max} = 10^{-8} \times 156.8 = 1.57 \times 10^{-6}\ \mathrm{N} = 1.57\mu N$$

Step 3: 设计位移（典型 MEMS 位移约 1μm 满量程）

$$x_{max} = 1\mu m = 10^{-6} m$$

Step 4: 计算弹簧常数

$$k = \frac{F_{max}}{x_{max}} = \frac{1.57 \times 10^{-6}}{10^{-6}} = \boxed{1.57\ \mathrm{N/m}}$$

Step 5: 验证谐振频率

$$f_0 = \frac{1}{2\pi}\sqrt{\frac{k}{m}} = \frac{1}{2\pi}\sqrt{\frac{1.57}{10^{-8}}} = \frac{1}{2\pi} \times 12530 \approx \boxed{2\ \mathrm{kHz}}$$

[**EN**]: MEMS design uses F=ma and Hooke's Law. Resonant frequency should be » signal bandwidth (human motion < 20Hz).

Thesis Connection

Thesis Bridge: Why MEMS Works for Fall Detection / MEMS 适用于跌倒检测 [**CN**]: 这解释了我的传感器选择...
Script: "The MPU6050 MEMS accelerometer is ideal because:

1. **Bandwidth**: 2kHz resonance » 20Hz human motion (no aliasing)
2. **Range**: ±16g covers worst-case fall impact
3. **Resolution**: 16-bit ADC = 0.5mg per LSB (sensitive enough)
4. **Power**: <1mW (battery-powered wearable)
5. **Cost**: <$5 (mass deployment feasible)

Physics insight:

$$\text{Signal BW} \ll f_0 \Rightarrow \text{Flat frequency response (no resonance effects)}$$

If human motion were at 1kHz (it's not!), I would need a different sensor."

核心公式 / Key Formula

Key Formulas Summary / 关键公式总结

1. **Newton's 2nd Law**: $F = ma$
2. **SHM Angular Frequency**: $\omega = \sqrt{k/m}$
3. **SHM Period**: $T = 2\pi\sqrt{m/k}$
4. **Kinetic Energy**: $KE = \frac{1}{2}mv^2$
5. **Gravitational PE**: $PE = mgh$
6. **Elastic PE**: $PE = \frac{1}{2}kx^2$
7. **Free Fall Velocity**: $v = \sqrt{2gh}$
8. **SHM Total Energy**: $E = \frac{1}{2}kA^2$

[EN]: Master these eight formulas. They cover force, motion, and energy — the three pillars of mechanics.

15 振动与波 / Oscillations & Waves (BE5B02PH1)

简谐振动 / Simple Harmonic Motion (SHM)

[CN] 定义: 物体受到的回复力与位移成正比且方向相反的运动 $(F = -kx)$。

- 方程: $x(t) = A\cos(\omega t + \phi)$.
- 周期 **(Period)**: $T = 2\pi/\omega$.
- 频率 **(Frequency)**: $f = 1/T$.

[EN] **Definition**: Motion where the restoring force is directly proportional to the displacement and acts in the direction opposite to that of displacement $(F = -kx)$.

- **Equation**: $x(t) = A\cos(\omega t + \phi)$.
- **Angular Frequency**: $\omega = \sqrt{k/m}$.

核心公式 / Key Formula

单摆 / Simple Pendulum:

$$T = 2\pi\sqrt{\frac{L}{g}}, \quad \omega = \sqrt{\frac{g}{L}} \tag{45}$$

(仅适用于小角度 $\theta \ll 1$ rad)
弹簧振子 / Spring Mass System:

$$T = 2\pi\sqrt{\frac{m}{k}}, \quad \omega = \sqrt{\frac{k}{m}} \tag{46}$$

阻尼与驱动 / Damped & Driven Oscillations

[CN] 定义:

- 阻尼 (**Damping**): 由于摩擦力导致能量耗散，振幅随时间指数衰减 ($A(t) = A_0 e^{-\beta t}$)。
- 驱动 (**Driven**): 受到周期性外力作用。当驱动频率接近固有频率时发生共振 (**Resonance**)。

[EN] **Definition**:

- **Damped**: Amplitude decreases over time due to energy loss (friction/drag).
- **Driven**: External periodic force is applied. **Resonance** occurs when driving frequency matches natural frequency ($\omega \approx \omega_0$), causing maximum amplitude.

机械波 / Mechanical Waves

[CN] 定义: 振动在介质中的传播。

- 横波 (**Transverse**): 质点振动垂直于传播方向 (如弦波、光波)。
- 纵波 (**Longitudinal**): 质点振动平行于传播方向 (如声波)。

[EN] **Definition**: Propagation of disturbances through a medium.

- **Transverse**: Particle oscillation is perpendicular to wave propagation (e.g., Light, String).
- **Longitudinal**: Particle oscillation is parallel to wave propagation (e.g., Sound).

核心公式 / Key Formula

波函数 / **Wave Equation**:

$$y(x,t) = A\cos(kx - \omega t) \tag{47}$$

$k = 2\pi/\lambda$ (波数 / Wave Number)
波速 / **Wave Speed**:

$$v = \lambda f = \frac{\omega}{k} \tag{48}$$

论文关联 / Project Application

[CN]:

- **MEMS 谐振器**: MPU6050 内部使用微小的振动质量块 (Vibrating Mass) 和电容检测。它们工作在谐振状态。Coriolis 力会改变振动模式。
- 信号滤波: 我们的" 移动平均滤波器" 本质上是一个低通滤波器，用于去除高频振动 (噪音)，只保留低频运动分量。

[EN]:

- **MEMS Resonator**: Inside MPU6050, vibrating masses operate at resonance. Coriolis forces shift this vibration, detected capacitively.
- **Filtering**: The moving average filter acts as a Low-Pass Filter, attenuating high-frequency oscillations (noise) while passing low-frequency motion.

考试陷阱 / Exam Pitfalls

- **Period vs Frequency**: $T = 1/f$. Don't mix them up.
- **Resonance**: 共振只发生在驱动频率 $\omega_d = \omega_0$ 时，此时能量传输最大，若无阻尼可能导致破坏。
- **Sound in Vacuum**: 声波是机械波，不能在真空中传播！ (Light can).

16 电场与磁场 / Electric & Magnetic Fields (BE5B02PH2)

静电场 / Electrostatics

[CN] 定义: 电荷周围存在的场，对其他电荷产生力。

- 库仑定律 (**Coulomb's Law**): 点电荷间的力 $F = k\frac{q_1 q_2}{r^2}$.
- 电场强度 (**E-Field**): 单位电荷受到的力 $\vec{E} = \vec{F}/q$.
- 电势 (**Potential**): 单位电荷的电势能 $V = E_p/q$.

[EN] **Definition**: Field around charges exerting force on other charges.

- **Coulomb's Law**: Force between point charges.
- **Electric Field** ($\vec{E}$): Force per unit charge ($\vec{E} = \vec{F}/q$). Vector.
- **Electric Potential** (V): Potential energy per unit charge. Scalar.

核心公式 / Key Formula

高斯定律 / Gauss's Law:

$$\oint \vec{E} \cdot d\vec{A} = \frac{Q_{enc}}{\epsilon_0} \tag{49}$$

电通量等于包围的净电荷除以介电常数。

电容 / Capacitance:

$$C = \frac{Q}{V} = \epsilon_0 \frac{A}{d} \quad \text{(平行板)} \tag{50}$$

静磁场 / Magnetostatics

[CN] 定义: 由运动电荷 (电流) 产生的场。

- 洛伦兹力 (**Lorentz Force**): 运动电荷在磁场中受到的力 $\vec{F} = q(\vec{v} \times \vec{B})$.
- 安培定律 (**Ampere's Law**): 电流产生磁场 $\oint \vec{B} \cdot d\vec{l} = \mu_0 I$.

[EN] **Definition**: Field produced by moving charges (currents).

- **Lorentz Force**: Force on a moving charge ($\vec{F} = q(\vec{v} \times \vec{B})$). Always perpendicular to velocity (does no work!).
- **Ampere's Law**: Current generates magnetic field.

电磁感应 / EM Induction

[CN] 定义: 磁通量变化产生感应电动势。

- 法拉第定律 (**Faraday's Law**): 感应电动势等于磁通量变化率的负值。
- 楞次定律 (**Lenz's Law**): 感应电流的方向总是阻碍磁通量的变化 (那个负号)。

[EN] **Definition**: Changing magnetic flux induces EMF.

- **Faraday's Law**: $\mathcal{E} = -\frac{d\Phi_B}{dt}$.
- **Lenz's Law**: The induced current flows in a direction that opposes the change in magnetic flux (Conservation of Energy).

论文关联 / Project Application

[CN]:

- **PCB 设计 (EMC)**: 快速变化的电流 (如 SPI/I2C 时钟) 会产生磁场辐射 (安培定律)。这是电磁干扰 (EMI) 的来源。
- 去耦电容: 为高频电流提供回路，减小环路面积，从而减小辐射 (EMI reduction)。
- 无线通信: ESP32 的 Wi-Fi 天线发射电磁波 (EM Waves)，即变化的电场产生磁场，变化的磁场产生电场。

[EN]:

- **PCB EMC**: High-speed currents (clock lines) generate Magnetic Fields (Ampere's Law), causing Electromagnetic Interference (EMI).
- **Decoupling**: Reduces loop area for high-frequency currents, minimizing radiated emissions.
- **Antenna**: ESP32 Wi-Fi works by radiating EM waves (Maxwell's Equations).

考试陷阱 / Exam Pitfalls

- **Magnetic Work**: 磁力 $\vec{F} \perp \vec{v}$，所以恒定磁场不对电荷做功！ (Work $= 0$).
- **Field Liens**: 电场线起于正止于负；磁场线是闭合曲线 (无磁单极子)。

17 Thermodynamics / 热力学 (PH2)

[CAUTION] PRIORITY: FOCUS MODE / 优先级：专注模式

[CN] 热力学优先级为 **CAUTION**。**Focus**: Hit Heat Capacity + First Law! [**EN**] Thermo priority is **CAUTION**. **Focus**: Heat Capacity + First Law!
Thesis Link: ESP32 Self-heating (Joule heating). ESP32 发热问题。

热力学定律 / Laws of Thermodynamics

[CN] 定义:

- 第零定律: 如果 A 和 B 平衡，B 和 C 平衡，则 A 和 C 平衡 (温度定义)。
- 第一定律: 能量守恒。内能的变化等于吸收的热量加上外界对系统做的功 ($\Delta U = Q + W$)。
- 第二定律: 孤立系统的熵 (Entropy) 永不减少。热量不能自发从低温流向高温。

[EN] **Definition**:

- **0th Law**: Defines Temperature (Thermal Equilibrium).
- **1st Law**: Conservation of Energy. $\Delta U = Q + W$.
- **2nd Law**: Entropy of an isolated system never decreases. Heat cannot spontaneously flow from cold to hot.

核心公式 / Key Formula

理想气体状态方程 / Ideal Gas Law:

$$pV = nRT = NkT \tag{51}$$

p: 压强 (pressure), V: 体积 (volume), T: 绝对温度 (absolute temperature, Kelvin).
热传递 / Heat Transfer:

- [**CN**] 传导 (Conduction): 接触传递 (Fourier's Law) / [**EN**] Contact transfer
- [**CN**] 对流 (Convection): 流体流动传递 / [**EN**] Fluid motion transfer
- [**CN**] 辐射 (Radiation): 电磁波传递 (Stefan-Boltzmann Law) / [**EN**] EM wave transfer

论文关联 / Project Application

[**CN**]:

- [**CN**] ESP32 发热: 芯片工作时消耗电能转换为热能 (焦耳热 $P = IV$)
  [**EN**] ESP32 Self-Heating: Chip converts electrical energy to heat (Joule heating $P = IV$)
- [**CN**] 散热设计: PCB 的铜箔层充当散热片 (Heatsink)，通过热传导将热量散发
  [**EN**] Heat Dissipation: PCB copper layers act as heatsinks via **conduction**
- [**CN**] BMP180 传感器: 测量环境温度，用于补偿 MEMS 偏移漂移
  [**EN**] BMP180 Sensor: Measures ambient temperature for compensating MEMS bias drift

[**EN**] **Full Mirror**:

- **Self-Heating**: ESP32 converts electrical energy into heat ($P_{loss} \approx IV$)
- **Heat Dissipation**: PCB copper layers act as heatsinks, dissipating heat via **Conduction**
- **Temperature Sensing**: BMP180 measures temperature, critical for compensating MEMS bias drift (temperature-dependent)

考试陷阱 / Exam Pitfalls

- [**CN**] Kelvin Scale: 热力学公式永远使用开尔文 ($T_K = T_C + 273.15$)
  [**EN**] Kelvin Scale: Thermodynamics formulas ALWAYS use Kelvin!
- [**CN**] Adiabatic vs Isothermal: 绝热过程 ($Q = 0$) 不等于等温过程 ($T = \text{const}$)
  [**EN**] Adiabatic ($Q = 0$) $\neq$ Isothermal ($T = \text{const}$)
- [**CN**] Entropy meaning: 熵是系统无序度 (Disorder) 的度量
  [**EN**] Entropy: measure of system's disorder

18 波动与光学 / Waves & Optics (BE5B02PH2)

波的特性 / Wave Properties

[CN] 定义:

- 干涉 (**Interference**): 波的叠加。同相增强 (Constructive)，反相抵消 (Destructive)。
- 衍射 (**Diffraction**): 波绕过障碍物的现象。孔越小，衍射越明显。
- 偏振 (**Polarization**): 横波振动方向的限制 (仅适用于横波，如光)。

[EN] **Definition**:

- **Interference**: Superposition of waves. Constructive (in-phase) or Destructive (out-of-phase).
- **Diffraction**: Bending of waves around obstacles. Significant when $\lambda \approx$ aperture size.
- **Polarization**: Orientation of oscillation (Transverse waves only).

核心公式 / Key Formula

电磁波谱 / **EM Spectrum**: Radio → Microwave → IR → Visible → UV → X-Ray → Gamma.
光速的关系:

$$c = \lambda f \approx 3 \times 10^8\,\mathrm{m/s} \tag{52}$$

论文关联 / Project Application

[CN]:

- **Wi-Fi 通信**: ESP32 使用 2.4 GHz 载波。波长计算: $\lambda = \frac{c}{f} = \frac{3\cdot 10^8}{2.4\cdot 10^9} \approx 0.125\,\mathrm{m} = 12.5\,\mathrm{cm}$。
- 天线设计: 最优天线长度通常是 $\lambda/4$ (约 3.1 cm)。这也是为什么 ESP32 模块上的 PCB 天线是这个尺寸。
- 多径干扰: 室内环境中，Wi-Fi 信号反射形成多径效应 (Multipath)，产生干扰。

[EN]:

- **Wi-Fi Carrier**: 2.4 GHz ISM band.
- **Wavelength**: $\lambda \approx 12.5$ cm. Optimum antenna length is typically $\lambda/4$ (≈ 3.1 cm), explaining the size of the PCB trace antenna.
- **Multipath**: Reflection causes signal interference (Fading) in indoor environments.

考试陷阱 / Exam Pitfalls

- **Medium Requirement**: 电磁波不需要介质 (可以在真空中传播)。声波需要介质。
- **Index of Refraction**: $n = c/v$. 光在介质中速度减慢。

Part IV

电子与计算机核心 / EECS Core

19 Circuit Analysis / 电路分析 (ZEO)

[CAUTION] PRIORITY: FOCUS MODE / 优先级：专注模式

[CN] 电路优先级为 **CAUTION**。练习：KVL/KCL 计算！**[EN]** Circuits priority is **CAUTION**. Practice KVL/KCL calculations.
Bridge to Thesis: Sensor interface circuits! 传感器接口电路！
Thesis Link: 分压器设计 → ADC 输入范围匹配 (0-3.3V for ESP32)

Core Survival Strategy | **核心生存策略** [CN] 电路理论是电子工程的基础，但考试时间有限。本章聚焦最高频考点：
[EN] Circuit theory is EE foundation. Focus on highest-frequency exam topics:

1. **[CN]** 欧姆定律 (Ohm's Law) — 必考计算 / **[EN]** Ohm's Law — must-know calculation
2. **[CN]** KVL/KCL — 电路分析核心 / **[EN]** KVL/KCL — circuit analysis core
3. **[CN]** 分压器 (Voltage Divider) — 传感器接口必备 / **[EN]** Voltage Divider — sensor interface essential
4. **[CN]** 戴维南等效 (Thevenin) — 简化复杂电路 / **[EN]** Thevenin — simplify complex circuits
5. **[CN]** 功率计算 (Power) — 电源设计基础 / **[EN]** Power — power supply design basis

[EN] **Full Mirror**: Circuit theory survival checklist: Ohm's Law (V=IR), Kirchhoff's Laws (KVL/KCL), Voltage Divider, Thevenin Equivalent, and Power calculations.

19.1 Ohm's Law | 欧姆定律

核心公式 / Key Formula

Ohm's Law | **欧姆定律公式**

$$V = I \cdot R \quad \Leftrightarrow \quad I = \frac{V}{R} \quad \Leftrightarrow \quad R = \frac{V}{I} \tag{53}$$

- V — 电压 (Voltage), 单位：伏特 (V)
- I — 电流 (Current), 单位：安培 (A)
- R — 电阻 (Resistance), 单位：欧姆 (Ω)

Ohm's Law: The voltage across a resistor equals current times resistance.

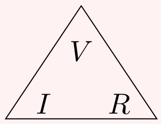
Blackboard Challenge 1: Ohm's Law | 欧姆定律计算

[CN] **Problem / 题目:** ESP32 的 GPIO 输出 3.3V，驱动一个 LED（正向压降 2V），需要 10mA 电流。求限流电阻值。
[EN] **Problem:** ESP32 GPIO outputs 3.3V, driving an LED (forward drop 2V), needs 10mA. Find the limiting resistor.
Step-by-step Solution / 分步解答:

1. [CN] 确定电阻两端电压 / [EN] Find voltage across resistor:
   $V_R = V_{GPIO} - V_{LED} = 3.3V - 2V = 1.3V$
2. [CN] 应用欧姆定律 / [EN] Apply Ohm's Law:
   $R = \frac{V_R}{I} = \frac{1.3V}{10mA} = \frac{1.3V}{0.01A}$
3. [CN] 计算结果 / [EN] Calculate result:
   $R = 130\Omega$

Answer / 答案: $\boxed{R = 130\Omega}$
[CN] 实际选用标准值 150Ω / [EN] Use standard value 150Ω in practice

Mnemonic: VIR Triangle | 记忆口诀口诀：“伏安欧，上下分”



遮住要求的量，剩下的就是公式：遮 V 得 IR，遮 I 得 V/R，遮 R 得 V/I

Cover what you want to find: Cover V → IR, Cover I → V/R, Cover R → V/I

19.2 Kirchhoff's Laws | 基尔霍夫定律

核心公式 / Key Formula

KVL: Kirchhoff's Voltage Law | 基尔霍夫电压定律

$$\sum_{k=1}^{n} V_k = 0 \quad \text{(沿闭合回路)} \tag{54}$$

物理意义：沿任意闭合回路，电压升等于电压降（能量守恒）

KVL: The algebraic sum of voltages around any closed loop equals zero.

核心公式 / Key Formula

KCL: Kirchhoff's Current Law | 基尔霍夫电流定律

$$\sum_{k=1}^{n} I_{in} = \sum_{k=1}^{m} I_{out} \quad \text{(在任意节点)} \tag{55}$$

物理意义：流入节点的电流等于流出节点的电流（电荷守恒）

KCL: The sum of currents entering a node equals the sum of currents leaving.

Blackboard Challenge 2: KVL Application | KVL 应用

[CN] Problem / 题目：串联电路中，$V_s = 12V$，$R_1 = 2k\Omega$，$R_2 = 4k\Omega$。求各电阻上的电压。
[EN] Problem: Series circuit with $V_s = 12V$, $R_1 = 2k\Omega$, $R_2 = 4k\Omega$. Find voltage across each resistor.
Step-by-step Solution / 分步解答:

1. **[CN]** 求总电阻 / **[EN]** Find total resistance:
   $R_{total} = R_1 + R_2 = 2k + 4k = 6k\Omega$
2. **[CN]** 求电流 / **[EN]** Find current:
   $I = \frac{V_s}{R_{total}} = \frac{12V}{6k\Omega} = 2mA$
3. **[CN]** 求 V_{R1} / **[EN]** Find V_{R1}:
   $V_{R1} = I \cdot R_1 = 2mA \times 2k\Omega = 4V$
4. **[CN]** 求 V_{R2} / **[EN]** Find V_{R2}:
   $V_{R2} = I \cdot R_2 = 2mA \times 4k\Omega = 8V$
5. **[CN]** 验证 KVL / **[EN]** Verify KVL:
   $V_s - V_{R1} - V_{R2} = 12 - 4 - 8 = 0$ ✓

Answer / 答案: $\boxed{V_{R1} = 4V, \quad V_{R2} = 8V}$

Mnemonic: KVL/KCL | **记忆口诀口诀：“电压绕圈零，电流进出平”**

- KVL: 电压绕圈 (Loop) 加起来等于零
- KCL: 电流进出节点 (Node) 要平衡

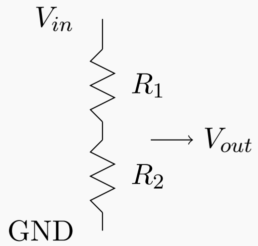
KVL: Voltages around Loop = 0; KCL: Currents at Node balance out.

19.3 Voltage Divider | 分压器

核心公式 / Key Formula

Voltage Divider Formula | **分压公式**

$$V_{out} = V_{in} \cdot \frac{R_2}{R_1 + R_2} \tag{56}$$



The output voltage is proportional to the ratio of R_2 to total resistance.

Blackboard Challenge 3: Voltage Divider | 分压器计算

Problem: 设计分压电路将 5V 传感器信号降至 ESP32 可接受的 3.3V。
Step-by-step Solution:

1. 分压比: $\frac{V_{out}}{V_{in}} = \frac{3.3V}{5V} = 0.66$
2. 设 $R_1 = 10k\Omega$，求 R_2:
3. $\frac{R_2}{R_1+R_2} = 0.66$
4. $R_2 = 0.66(R_1 + R_2)$
5. $R_2 = 0.66R_1 + 0.66R_2$
6. $0.34R_2 = 0.66R_1$
7. $R_2 = \frac{0.66}{0.34} \times 10k = 19.4k\Omega$

Answer: $\boxed{R_1 = 10k\Omega, \quad R_2 = 20k\Omega}$ (使用标准值)

Mnemonic: Voltage Divider | 记忆口诀口诀：“下分上总，电压按比分”
分压器输出 = 输入电压 × (下面电阻 / 总电阻)
注意：负载会影响分压比！ 带负载时 R_2 要与负载并联计算。

Output = Input × (Bottom R / Total R). Load affects the ratio!

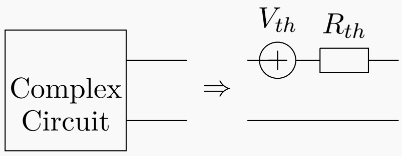
19.4 Thevenin Equivalent | 戴维南等效电路

核心公式 / Key Formula

Thevenin Theorem | 戴维南定理任何线性二端网络可等效为:

$$V_{th} = \text{开路电压 (Open-circuit voltage)} \tag{57}$$

$$R_{th} = \text{从端口看入的等效电阻 (Equivalent resistance)} \tag{58}$$



Thevenin: Any linear circuit = Voltage source V_{th} + Series resistance R_{th}

Blackboard Challenge 4: Thevenin Equivalent | 戴维南等效

Problem: 求下图电路的戴维南等效电路（从 AB 端口看）。$V_s = 10V$, $R_1 = 2\Omega$, $R_2 = 3\Omega$

Step-by-step Solution:

1. 求 V_{th}（开路电压）：
   - AB 开路时，R_2 无电流
   - $V_{th} = V_s \cdot \frac{R_2}{R_1+R_2} = 10 \cdot \frac{3}{5} = 6V$
2. 求 R_{th}（等效电阻）：
   - 将电压源短路（理想电压源内阻为 0）
   - $R_{th} = R_1 \parallel R_2 = \frac{R_1 \cdot R_2}{R_1+R_2} = \frac{2\times 3}{5} = 1.2\Omega$

Answer: $\boxed{V_{th} = 6V, \quad R_{th} = 1.2\Omega}$

Mnemonic: Thevenin Steps | 记忆口诀口诀:“开路求压，短源求阻”

1. 开路求压: 断开负载，计算开路电压 V_{th}
2. 短源求阻: 电压源短路，电流源开路，计算等效电阻 R_{th}

Open for V_{th}, Short sources for R_{th}

19.5 Transformer | 变压器

核心公式 / Key Formula

Transformer Equations | **变压器公式匝数比 (Turns Ratio):**

$$\frac{V_1}{V_2} = \frac{N_1}{N_2} = n \quad \text{(电压比等于匝数比)} \tag{59}$$

$$\frac{I_1}{I_2} = \frac{N_2}{N_1} = \frac{1}{n} \quad \text{(电流比等于匝数比的倒数)} \tag{60}$$

功率关系 (理想变压器):

$$P_1 = P_2 \quad \Rightarrow \quad V_1 I_1 = V_2 I_2 \tag{61}$$

阻抗变换:

$$Z_1 = n^2 \cdot Z_2 \quad \text{(阻抗按匝数比平方变换)} \tag{62}$$

Ideal transformer: Voltage ratio = Turns ratio; Current ratio = Inverse turns ratio.

Blackboard Challenge 5: Transformer | 变压器计算

Problem: 变压器初级 220V，次级需要 12V 供 ESP32 电源模块。匝数比和次级电流（初级 0.1A）?
Step-by-step Solution:

1. 匝数比: $n = \frac{N_1}{N_2} = \frac{V_1}{V_2} = \frac{220V}{12V} = 18.33$
2. 电流关系: $I_2 = I_1 \cdot n = 0.1A \times 18.33 = 1.833A$
3. 验证功率: $P_1 = 220 \times 0.1 = 22W$, $P_2 = 12 \times 1.833 = 22W$ ✓

Answer: $\boxed{n \approx 18:1, \quad I_2 \approx 1.83A}$

19.6 AC Power | 交流功率

核心公式 / Key Formula

AC Power Triangle | **交流功率三角形**

$$S = V \cdot I = \sqrt{P^2 + Q^2} \quad \text{(视在功率 Apparent Power, VA)} \tag{63}$$

$$P = V \cdot I \cdot \cos\phi \quad \text{(有功功率 Active Power, W)} \tag{64}$$

$$Q = V \cdot I \cdot \sin\phi \quad \text{(无功功率 Reactive Power, VAR)} \tag{65}$$

$$\text{Power Factor: } PF = \cos\phi = \frac{P}{S} \tag{66}$$

Power triangle: $S^2 = P^2 + Q^2$, Power Factor = $\cos\phi$ = P/S

Blackboard Challenge 6: Power Factor | 功率因数计算

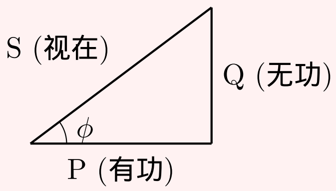
Problem: 电机额定 220V，电流 5A，功率因数 0.8（滞后）。求 P、Q、S。

Step-by-step Solution:

1. 视在功率: $S = V \cdot I = 220 \times 5 = 1100VA$
2. 有功功率: $P = S \cdot \cos\phi = 1100 \times 0.8 = 880W$
3. 无功功率: $Q = S \cdot \sin\phi = 1100 \times 0.6 = 660VAR$
4. 验证: $\sqrt{880^2 + 660^2} = \sqrt{774400 + 435600} = 1100VA$ ✓

Answer: $\boxed{S = 1100VA, \quad P = 880W, \quad Q = 660VAR}$

Mnemonic: Power Triangle | 记忆口诀口诀:“视在为斜，有功为底，无功为高”



功率因数低的危害: 电流大但做功少，浪费电网容量

Power triangle: S (hypotenuse), P (adjacent), Q (opposite), angle ϕ

19.7 Thesis Application: ESP32 Power Supply | 论文应用

Thesis Connection

ESP32 IoT Sensor Power Design | ESP32 物联网传感器电源设计论文关联：智能家居传感器节点的电源系统设计
实际应用：

1. 电源模块选择：
   - ESP32 工作电压：3.0–3.6V（典型 3.3V）
   - 峰值电流：WiFi 发射时可达 500mA
   - 选用 AMS1117-3.3 LDO 或 MP1584 DC-DC
2. 分压器应用：
   - 电池电压监测：锂电池 4.2V → ADC 可测范围
   - $V_{out} = 4.2V \times \frac{100k}{100k+100k} = 2.1V$
3. 功耗计算：
   - Deep Sleep: 10μA
   - Active: 80mA
   - WiFi TX: 380mA
   - 平均功耗决定电池寿命

Thesis Link: Power supply design for IoT sensor nodes using voltage dividers for battery monitoring and proper regulator selection for ESP32's varying current demands.

19.8 USB Cable Voltage Drop | USB 线缆压降 (Thesis Critical!)

Blackboard Challenge 7: USB Cable Voltage Drop | USB 线缆压降

[CN] 场景:「你的 ESP32 通过 2 米 USB 线供电，WiFi 发射时电流 500mA。USB 线电阻 0.5Ω（往返）。求到达 ESP32 的电压。」
Problem: 5V USB 电源经过有电阻的线缆，电压会下降
Step-by-step Solution:

1. 计算线缆压降：$V_{drop} = I \times R_{cable} = 0.5A \times 0.5\Omega = 0.25V$
2. 到达 ESP32 的电压：$V_{ESP32} = V_{USB} - V_{drop} = 5V - 0.25V = 4.75V$
3. 经过 LDO 后：$V_{out} = 3.3V$（LDO 只要输入>4V 就能稳定输出 3.3V）

危险情况:

- 如果线缆更长 (5m) 或更细 (AWG28)，R_{cable} 可能达到 2Ω
- 压降：$0.5A \times 2\Omega = 1V$，到达电压只有 4V
- 接近 LDO 的 dropout voltage 极限！

Answer: $\boxed{V_{ESP32} = 4.75V}$ (OK)，但长/细线缆可能导致电压过低

Thesis Connection

Thesis Bridge: Real-World Power Issues | 实际电源问题 [CN]: 这是我在开发中遇到的真实问题...
Script: "During my thesis development, I experienced random ESP32 resets. Investigation revealed:

- **Root cause**: Cheap USB cable with high resistance
- **Symptom**: WiFi TX (500mA) caused voltage sag below 3.0V
- **Solution**:
  1. Replaced with quality cable (AWG24, shorter)
  2. Added 470μF bulk capacitor near ESP32
  3. Capacitor provides charge during current spikes

The capacitor calculation:

$$V_{sag} = \frac{I \cdot \Delta t}{C} = \frac{0.5A \times 0.001s}{470\mu F} = 1.06V$$

With proper capacitor, voltage sag is limited even during WiFi bursts."

19.9 Battery Life Calculation | 电池寿命计算

Blackboard Challenge 8: Battery Life | 电池续航计算

[CN] 场景:「ESP32 用 2000mAh 锂电池供电，每 5 分钟测量一次并上传数据。求电池寿命。」
功耗模式:

- Deep Sleep: $I_{sleep} = 10\mu A$, $t_{sleep} = 299s$
- Active + WiFi: $I_{active} = 150mA$ (average), $t_{active} = 1s$

Step-by-step Solution:

1. 每周期消耗电量:

$$\begin{aligned} Q_{cycle} &= I_{sleep} \times t_{sleep} + I_{active} \times t_{active} && (67) \\ &= 10\mu A \times 299s + 150mA \times 1s && (68) \\ &= 2.99mAs + 150mAs = 152.99mAs && (69) \end{aligned}$$

2. 每周期时间: $T_{cycle} = 300s = 5min$
3. 平均电流:

$$I_{avg} = \frac{Q_{cycle}}{T_{cycle}} = \frac{152.99mAs}{300s} = 0.51mA$$

4. 电池寿命:

$$t_{life} = \frac{C_{battery}}{I_{avg}} = \frac{2000mAh}{0.51mA} = 3922h \approx \boxed{163 \text{ days}}$$

Answer: 约 163 天，实际会因自放电和效率损失约减少 20%

Thesis Connection

Thesis Bridge: Power Optimization | 功耗优化 [CN]: 这是我论文中的功耗优化策略...
Script: "To maximize battery life in my IoT sensor:

1. **Deep Sleep**: ESP32 consumes only 10μA (vs 80mA active)
2. **Batch Uploads**: Collect multiple readings, send once
3. **WiFi Fast Connect**: Store last AP credentials, skip scan
4. **Duty Cycling**: 5-minute interval is good balance

Power budget breakdown:

State	Current	Time/Cycle
Deep Sleep	10μA	299s (99.67%)
Wake + Measure	80mA	0.5s
WiFi Connect	120mA	0.3s
WiFi TX	200mA	0.2s
Average	**0.51mA**	

The key insight: 99.67% of time in deep sleep dominates the power budget."

19.10 Capacitor Sizing | 电容选型

Blackboard Challenge 9: Decoupling Capacitor | 去耦电容

[CN] 场景:「ESP32 电源需要平滑。选择合适的去耦电容组合。」
Design Approach / 设计方法:
1. Bulk Capacitor (储能):

- 目的: 提供瞬态电流
- 公式: $C = \frac{I \cdot \Delta t}{\Delta V}$
- 例: $C = \frac{0.5A \times 0.001s}{0.1V} = 5000\mu F$
- 实际选用: $470\mu F$ 电解 + $10\mu F$ 陶瓷

2. High-Frequency Decoupling (高频去耦):

- 目的: 抑制高频噪声
- 选择: $100nF$ 陶瓷电容（靠近芯片引脚）
- 自谐振频率: $f_r = \frac{1}{2\pi\sqrt{LC}}$

Complete Power Rail:

$$5\text{V} \rightarrow 470\mu F \rightarrow \text{LDO} \rightarrow 10\mu F \rightarrow 100nF \rightarrow \text{ESP32}$$

[**EN**]: Use multi-stage decoupling: bulk caps for energy storage, ceramic caps for high-frequency filtering.

19.11 Quick Reference | 速查表

核心公式 / Key Formula

Survival Formula Sheet | 生存公式速查

概念	公式	口诀
Ohm's Law	$V = IR$	伏安欧，上下分
KVL	$\sum V = 0$	电压绕圈零
KCL	$\sum I_{in} = \sum I_{out}$	电流进出平
Voltage Divider	$V_{out} = V_{in} \cdot \frac{R_2}{R_1+R_2}$	下分上总
Parallel R	$R_p = \frac{R_1 R_2}{R_1+R_2}$	积除和
Power	$P = VI = I^2R = \frac{V^2}{R}$	功率三公式
Transformer	$\frac{V_1}{V_2} = \frac{N_1}{N_2}$	压比等匝比
Power Factor	$PF = \cos\phi = \frac{P}{S}$	有功除视在

Keep this formula sheet handy for the exam. Master these 8 formulas for survival!

20 Semiconductors / 半导体 (ELP)

[GOOD] PRIORITY: CONFIDENT MODE / 优先级：自信模式

[CN] ELP 是你的强项。**You're comfortable with semiconductors!** [EN] You're comfortable with semiconductors! TCS34725 in your thesis = PN junction application!
Strategy: Attack questions about PN junctions! 主动攻击 PN 结相关问题！

PN 结 / PN Junction

[CN] 定义：PN 结是现代电子学的基石，由 P 型半导体 (空穴为主) 和 N 型半导体 (电子为主) 结合而成。

- 耗尽层 (**Depletion Region**)：接触面上载流子扩散复合，形成无自由载流子的区域和内建电场。
- 正向偏置 (**Forward Bias**)：外接电压对抗内建电场 ($V > V_{th} \approx 0.7V$)，导通电流。
- 反向偏置 (**Reverse Bias**)：外接电压增强内建电场，电流截止。

[EN] **Definition**: A PN junction is formed by joining P-type and N-type semiconductors.

- **Depletion Region**: A region devoid of free carriers at the interface, creating a built-in electric field.
- **Forward Bias**: Voltage applied against the built-in potential allowing current flow ($V > 0.7V$).
- **Reverse Bias**: Voltage applied supporting the built-in potential, blocking current flow.

核心公式 / Key Formula

肖克利方程 / Shockley Equation:

$$I = I_S \left(e^{\frac{V}{nV_T}} - 1 \right) \tag{70}$$

$V_T \approx 26mV$ (热电压 / Thermal Voltage).

晶体管 / Transistors

[CN] 定义:

- **BJT** (双极性结型晶体管): 电流控制电流设备 ($I_C = \beta I_B$)。输入阻抗低，线性性能好。
- **MOSFET** (场效应管): 电压控制电流设备 ($I_D \propto V_{GS}$)。输入阻抗极高 (栅极绝缘)。ESP32 使用 CMOS (互补 MOS) 工艺。

[EN] **Definition**:

- **BJT**: Current-controlled device. Low input impedance. Good for analog amplification.
- **MOSFET**: Voltage-controlled device. Very high input impedance (Gate Oxide). Used in digital logic (CMOS).

核心公式 / Key Formula

MOSFET 工作区 / Regions of Operation:

1. 截止 (**Cutoff**): $V_{GS} < V_{th}$ (Switch OFF)
2. 线性 (**Linear/Ohmic**): $V_{DS} < V_{GS} - V_{th}$ (Voltage controlled Resistor)
3. 饱和 (**Saturation**): $V_{DS} > V_{GS} - V_{th}$ (Constant Current / Amplifier)

论文关联 / Project Application

[CN]: 你的项目使用了多种半导体器件:

- 光电二极管 (**Photodiode**): TCS34725 颜色传感器内部含有光电二极管阵列。光子撞击 PN 结产生电子-空穴对，产生光电流 (Photocurrent)。
- **LED**: KY-037 模块上的指示灯。正向偏置时，电子与空穴复合释放能量 ($E = h\nu$)。

[EN]: Your project utilizes various semiconductor devices:

- **Photodiode**: Inside the TCS34725. Photons striking the PN junction generate electron-hole pairs, creating a photocurrent proportional to light intensity.
- **Light Emitting Diode (LED)**: On the KY-037 module. Recombination of electrons and holes releases energy as light when forward-biased.

考试陷阱 / Exam Pitfalls

- **Saturation Region**: MOSFET 的”饱和区”对应于恒流源特性（用于放大），而 BJT 的”饱和区”对应于开关导通（开关应用）。这两个术语在 BJT 和 MOSFET 中是反义的！
- **Threshold Voltage**: V_{th} 是开启 MOSFET 的门槛电压，不要和 V_T (热电压, 26mV) 混淆。

21 模拟与数字电路 / Analog & Digital Electronics (BE5B34MIE)

运算放大器 / Operational Amplifier

[CN] 定义: 运放 (Op-Amp) 是具有极高增益的电压放大器。理想特性:

- 输入阻抗无穷大 ($R_{in} = \infty$)：不从信号源吸取电流。
- 输出阻抗为零 ($R_{out} = 0$)：理想电压源。
- 开环增益无穷大 ($A_{OL} = \infty$)。

虚短与虚断: 在负反馈下，$V_+ = V_-$ 以及 $I_+ = I_- = 0$。

[EN] **Definition**: An Op-Amp is a high-gain differential voltage amplifier. **Ideal Properties**: Infinite R_{in}, Zero R_{out}, Infinite Gain. **Golden Rules**:

- **Virtual Short**: $V_+ = V_-$ (with negative feedback).
- **Virtual Open**: No current enters input terminals ($I = 0$).

核心公式 / Key Formula

常见配置 / **Common Configurations**:

- 反相放大器 (**Inverting**): $V_{out} = -\frac{R_f}{R_{in}} V_{in}$
- 同相放大器 (**Non-Inverting**): $V_{out} = (1 + \frac{R_f}{R_g}) V_{in}$
- 电压跟随器 (**Buffer**): $V_{out} = V_{in}$ ($R_f = 0, R_g = \infty$)

比较器 / Comparator

[CN] 定义: 比较器利用运放的开环高增益特性，将模拟信号与参考电压进行比较，输出数字电平 (高/低)。没有负反馈。

[EN] **Definition**: A comparator uses an Op-Amp in open-loop mode to compare an analog signal V_{in} against a reference V_{ref}, outputting a digital logic level (High/Low).

模数转换器 / AD Converter (ADC)

[CN] 定义：将连续的模拟电压信号转换为离散的数字值。关键指标：

- 分辨率 (**Resolution**)：比特数 (e.g., 12-bit → 0-4095)。
- 采样率 (**Sampling Rate**)：每秒采样次数 (Samples per second)。
- 混叠 (**Aliasing**)：如果采样率 $< 2f_{max}$，高频信号会伪装成低频噪音。

[EN] **Definition**: Converts continuous analog signals into discrete digital values. **Key Specs**:

- **Resolution**: Number of bits (e.g. 12-bit). $LSB = V_{ref}/2^N$.
- **Sampling Rate**: How often the signal is measured.
- **Nyquist Theorem**: Sampling rate must be $> 2 \times f_{max}$ to avoid Aliasing.

论文关联 / Project Application

[CN]: **KY-037 声音传感器 包含了完整的模拟电路链条：**

1. 换能器：驻极体麦克风将声波转换为微弱电压信号 (mV 级)。
2. 放大器：下方芯片 (LM393) 作为一个运算放大器，放大这个信号到 `Analog Out`。
3. 比较器：另一个运放通道作为比较器，当音量超过电位器设定阈值时，驱动 `Digital Out` 变高 (并点亮 LED2)。
4. **ADC**: ESP32 的 12-bit SAR ADC 读取模拟输出 ($0 - 3.3V \rightarrow 0 - 4095$)。

[EN]: The **KY-037 Sound Module** demonstrates the analog signal chain:

1. **Transducer**: Electret mic converts sound to weak voltage.
2. **Amplifier**: LM393 amplifies the signal for `Analog Out`.
3. **Comparator**: Another Op-Amp compares signal vs potentiometer voltage, triggering `Digital Out`.
4. **ADC**: ESP32's 12-bit SAR ADC digitizes the analog signal.

考试陷阱 / Exam Pitfalls

- **Op-Amp Real vs Ideal**: 实际运放输出电压受电源轨 (V_{CC}/GND) 限制 (Rail-to-Rail)。
- **ADC Range**: ESP32 的 ADC 是非线性的，且在 0V 和 3.3V 附近有盲区。
- **Comparator Hysteresis**: 实际比较器通常加入正反馈产生迟滞 (Hysteresis/Schmitt Trigger)，以防止在阈值附近由于噪声引起的频繁跳变。

22 Microcontrollers / 微控制器 (MIK)

[STAR] PRIORITY: SHOW OFF MODE / 优先级：展示模式

[CN] 这是你的主场！ **Thesis = Embedded System**. Show them you are an expert. **[EN]** This is your home turf. **Thesis = Embedded System**. Show them you are an expert. **Key Weapon**: Interrupts, DMA, Timers (ESP32 specific). **Power Move**: 任何中断/ADC/通信问题 → "In my thesis, I implemented this on ESP32..."

Chapter Overview | 章节概览微控制器是嵌入式系统的核心，本章作为最强科目，将深入覆盖所有考点：

1. Timer/Counter — PWM 生成与频率测量
2. GPIO — 通用输入输出配置
3. ADC — 模数转换与传感器接口
4. PWM — 脉宽调制与电机控制
5. Interrupts — 中断处理机制
6. UART — 串口通信协议
7. 综合应用 — ESP32 IoT 传感器系统

Microcontrollers are the heart of embedded systems. This chapter covers all exam topics comprehensively as your strongest subject.

22.1 Timer/Counter | 定时器/计数器

核心公式 / Key Formula

Timer Fundamentals | **定时器基础公式定时器溢出时间 (Timer Overflow Period):**

$$T_{overflow} = \frac{2^n \times \text{Prescaler}}{f_{clk}} \tag{71}$$

PWM 频率计算 (PWM Frequency):

$$f_{PWM} = \frac{f_{clk}}{\text{Prescaler} \times (TOP + 1)} \tag{72}$$

输入捕获频率测量 (Input Capture):

$$f_{signal} = \frac{f_{clk}}{\text{Prescaler} \times \Delta_{capture}} \tag{73}$$

- n — **定时器位数** (8-bit: 256, 16-bit: 65536)
- f_{clk} — **系统时钟频率**
- TOP — **定时器最大计数值（可配置）**
- Prescaler — **预分频值** (1, 8, 64, 256, 1024...)

Timer period depends on bit-width, prescaler, and clock frequency.

Blackboard Challenge 1: PWM Frequency | PWM 频率计算

Problem: ESP32 时钟 80MHz，使用 LEDC 模块，13-bit 分辨率，要产生 50Hz 的舵机控制信号。求分频值。

Step-by-step Solution:

1. 已知参数: $f_{clk} = 80MHz$, $f_{PWM} = 50Hz$, 分辨率 $=$ 13-bit
2. 13-bit 分辨率意味着: $TOP = 2^{13} - 1 = 8191$
3. 应用公式: $f_{PWM} = \frac{f_{clk}}{\text{Prescaler}\times(TOP+1)}$
4. 变换求 Prescaler:

$$
\begin{aligned}
\text{Prescaler} &= \frac{f_{clk}}{f_{PWM} \times (TOP+1)} \qquad (74)\\
&= \frac{80 \times 10^6}{50 \times 8192} \qquad (75)\\
&= \frac{80000000}{409600} \qquad (76)\\
&= 195.3125 \qquad (77)
\end{aligned}
$$

5. 实际选择: Prescaler $=$ 195 或 196（取整）
6. 验证: $f_{PWM} = \frac{80MHz}{195\times 8192} = 50.08Hz$ ✓

Answer: $\boxed{\text{Prescaler} \approx 195}$

ESP32 LEDC 配置代码要点:

```
ledc_timer_config_t timer = {
    .duty_resolution = LEDC_TIMER_13_BIT,
    .freq_hz = 50,  // 自⊠⊠算分⊠
    .speed_mode = LEDC_HIGH_SPEED_MODE
};
```

Blackboard Challenge 2: Timer Overflow | 定时器溢出

Problem: AVR ATmega328P (Arduino Uno), $f_{clk} = 16MHz$, Timer1 (16-bit), Prescaler $=$ 1024。求溢出周期和最大可测时间。

Step-by-step Solution:

1. 16-bit 定时器最大计数: $2^{16} = 65536$
2. 每个计数的时间: $T_{tick} = \frac{\text{Prescaler}}{f_{clk}} = \frac{1024}{16MHz} = 64\mu s$
3. 溢出周期: $T_{overflow} = 65536 \times 64\mu s = 4.194s$
4. 定时器频率: $f_{timer} = \frac{1}{64\mu s} = 15.625kHz$

Answer: $\boxed{T_{overflow} = 4.194s}$ (约 4.2 秒溢出一次)

应用：可测量最长约 4 秒的脉冲宽度或周期

Mnemonic: Timer Prescaler | 记忆口诀口诀:“预分频大，周期长；位数高，范围广”

- 预分频器 (Prescaler): 像变速箱，档位越高 (值越大)，转得越慢
- 定时器位数: 像油箱容量，越大能跑越久
- 时钟频率: 像发动机转速，越快计数越快

快速估算技巧:

- 8-bit + 1024 分频 @ 16MHz ≈ 16ms 溢出
- 16-bit + 1024 分频 @ 16MHz ≈ 4s 溢出

Higher prescaler = longer period; More bits = wider range

22.2 GPIO Configuration | GPIO 配置

核心公式 / Key Formula

GPIO Modes | GPIO 模式基本配置模式:

Mode	中文	应用场景
Input	输入模式	读取按键、传感器数字信号
Output	输出模式	驱动 LED、继电器
Input Pull-up	上拉输入	按键 (低电平有效)
Input Pull-down	下拉输入	按键 (高电平有效)
Open-drain	开漏输出	I2C 总线、电平转换
Analog	模拟模式	ADC 输入、DAC 输出
Alternate Function	复用功能	UART/SPI/I2C/PWM

GPIO can be configured as input, output, or alternate functions with optional pull resistors.

Blackboard Challenge 3: Pull-up Resistor | 上拉电阻计算

Problem: 按键接 GPIO，使用内部上拉。ESP32 内部上拉约 45kΩ，按键按下时 GPIO 接地。求按下和释放时的电压，以及功耗。

Step-by-step Solution:

1. 按键释放时 **(Open):**
   - 无电流流过，GPIO 通过上拉接 3.3V
   - $V_{GPIO} = 3.3V$ (逻辑高)
   - 功耗: $P = 0W$
2. 按键按下时 **(Closed):**
   - GPIO 直接接地
   - $V_{GPIO} = 0V$ (逻辑低)
   - 电流: $I = \frac{3.3V}{45k\Omega} = 73.3\mu A$
   - 功耗: $P = 3.3V \times 73.3\mu A = 242\mu W$

Answer: $\boxed{V_{released} = 3.3V, \quad V_{pressed} = 0V, \quad P_{pressed} = 242\mu W}$

设计考虑: 低功耗应用应使用外部上拉 (100kΩ+) 减少电流

GPIO Register Architecture | GPIO 寄存器架构**典型 GPIO 寄存器组 (以 STM32 为例):**

- `GPIOx_MODER` — 模式寄存器 (Input/Output/AF/Analog)
- `GPIOx_OTYPER` — 输出类型 (Push-pull/Open-drain)
- `GPIOx_OSPEEDR` — 输出速度 (Low/Medium/High/Very High)
- `GPIOx_PUPDR` — 上拉/下拉配置
- `GPIOx_IDR` — 输入数据寄存器 (只读)
- `GPIOx_ODR` — 输出数据寄存器
- `GPIOx_BSRR` — 位设置/复位寄存器 (原子操作)

ESP32 GPIO Matrix 特点:

- 任意 GPIO 可映射到任意外设功能 (通过 GPIO Matrix)
- 支持 RTC 域 GPIO (Deep Sleep 时仍可工作)
- 部分 GPIO 仅支持输入 (GPIO34-39)

GPIO registers control mode, speed, pull resistors, and data. ESP32 has flexible GPIO matrix for peripheral mapping.

Mnemonic: GPIO Modes | 记忆口诀口诀："上拉高，下拉低；开漏要外拉，推挽可直驱"

- 上拉输入：默认高电平，按键按下变低（低电平有效）
- 下拉输入：默认低电平，按键按下变高（高电平有效）
- 开漏输出：只能拉低，拉高需外部上拉（用于 I2C、电平转换）
- 推挽输出：可主动拉高拉低，驱动能力强

ESP32 GPIO 陷阱:

- GPIO6-11: 连接 Flash，勿使用！
- GPIO34-39: 仅输入，无上拉
- GPIO0/2/15: Boot 模式引脚，使用需小心

Pull-up = default HIGH; Pull-down = default LOW; Open-drain needs external pull-up.

22.3 ADC | 模数转换器

核心公式 / Key Formula

ADC Fundamentals | ADC 基础公式分辨率与量化步长 **(Resolution and LSB):**

$$\mathrm{LSB} = \frac{V_{ref}}{2^n} \quad \text{(最小可分辨电压)} \tag{78}$$

数字值与电压转换 (Digital to Voltage):

$$V_{analog} = \frac{\mathrm{ADC\_Value} \times V_{ref}}{2^n} \tag{79}$$

电压转数字值 (Voltage to Digital):

$$\mathrm{ADC\_Value} = \frac{V_{analog} \times 2^n}{V_{ref}} \tag{80}$$

采样率与奈奎斯特 (Sampling Rate):

$$f_s \geq 2 \times f_{max} \quad \text{(奈奎斯特定理)} \tag{81}$$

- n — ADC 位数 (ESP32: 12-bit, STM32: 12-bit)
- V_{ref} — 参考电压 (ESP32: 1.1V 内部或 3.3V 衰减后)
- LSB — Least Significant Bit (最低有效位)

ADC resolution determines the smallest voltage step. Higher bits = finer resolution.

Blackboard Challenge 4: ADC Resolution | ADC 分辨率计算

Problem: ESP32 ADC 12-bit，参考电压 3.3V（11dB 衰减）。求：(a) 分辨率，(b)1.65V 对应的 ADC 值，(c)ADC 值 2048 对应的电压。

Step-by-step Solution:

1. **(a) 分辨率/LSB:**
$$\text{LSB} = \frac{3.3V}{2^{12}} = \frac{3.3V}{4096} = 0.806mV \tag{82}$$

2. **(b) 1.65V 对应的 ADC 值:**
$$\text{ADC} = \frac{1.65V \times 4096}{3.3V} = \frac{6758.4}{3.3} = 2048 \tag{83}$$

3. **(c) ADC 值 2048 对应的电压:**
$$V = \frac{2048 \times 3.3V}{4096} = 1.65V \tag{84}$$

4. **验证:** 2048 是 4096 的一半，对应 V_{ref} 的一半 ✓

Answer: $\boxed{\text{(a) LSB} = 0.806mV, \quad \text{(b) ADC} = 2048, \quad \text{(c) V} = 1.65V}$

Blackboard Challenge 5: Temperature Sensor | 温度传感器 ADC

Problem: NTC 热敏电阻与 10kΩ 电阻分压，接 ESP32 ADC。NTC 在 25C 时 10kΩ，温度升高阻值降低。ADC 读数 3000 时，求 NTC 阻值和估算温度。

Step-by-step Solution:

1. **电路分析:** $V_{out} = 3.3V \times \frac{R_{fixed}}{R_{NTC}+R_{fixed}}$

2. **从 ADC 值求电压:**
$$V_{out} = \frac{3000 \times 3.3V}{4096} = 2.417V \tag{85}$$

3. **从电压求 NTC 阻值:**
$$2.417 = 3.3 \times \frac{10k}{R_{NTC} + 10k} \tag{86}$$
$$R_{NTC} + 10k = \frac{3.3 \times 10k}{2.417} = 13.65k \tag{87}$$
$$R_{NTC} = 3.65k\Omega \tag{88}$$

4. **温度估算 (Steinhart-Hart 简化):**
   - NTC 阻值降低，说明温度升高
   - 10kΩ @ 25C → 3.65kΩ 约对应 50-60C

Answer: $\boxed{R_{NTC} = 3.65k\Omega}$ (温度约 50-60C)

Mnemonic: ADC | 记忆口诀口诀:“位数定精度，参考定范围；采样要翻倍，混叠会捣乱”

- **位数定精度**: 12-bit = 4096 级 = 0.024%精度
- **参考定范围**: V_{ref} 决定可测最大电压
- **采样要翻倍**: $f_s \geq 2f_{max}$ (奈奎斯特)
- **混叠会捣乱**: 采样率不够会产生假信号

ESP32 ADC 注意事项:

- ADC2 在 WiFi 使用时不可用！
- 非线性需要校准（esp_adc_cal）
- **衰减设置**: 0dB(1.1V), 2.5dB(1.5V), 6dB(2.2V), 11dB(3.3V)

Bits = precision; V_{ref} = range; Sample rate must be $\geq 2\times$ max frequency.

22.4 PWM | 脉宽调制

核心公式 / Key Formula

PWM Fundamentals | PWM 基础公式占空比 **(Duty Cycle):**

$$D = \frac{T_{on}}{T_{period}} \times 100\% = \frac{T_{on}}{T_{on} + T_{off}} \times 100\% \tag{89}$$

平均电压 (Average Voltage):

$$V_{avg} = D \times V_{max} = \frac{T_{on}}{T_{period}} \times V_{max} \tag{90}$$

PWM 分辨率与占空比精度:

$$\text{Duty Step} = \frac{100\%}{2^n} \quad \text{(n-bit 分辨率)} \tag{91}$$

舵机控制 (Servo):

$$\text{Pulse Width: } 1ms \text{ (0 deg)} \leftrightarrow 1.5ms \text{ (90 deg)} \leftrightarrow 2ms \text{ (180 deg)} \tag{92}$$

PWM duty cycle controls average voltage. Higher resolution = finer control.

Blackboard Challenge 6: Servo Control | 舵机控制计算

Problem: 使用 ESP32 LEDC 控制舵机，PWM 频率 50Hz，13-bit 分辨率。求 0 deg、90 deg、180 deg 对应的占空比和寄存器值。

Step-by-step Solution:

1. **PWM 周期:** $T = \frac{1}{50Hz} = 20ms$
2. **占空比计算:**
   - 0 deg (1ms): $D = \frac{1ms}{20ms} = 5\%$
   - 90 deg (1.5ms): $D = \frac{1.5ms}{20ms} = 7.5\%$
   - 180 deg (2ms): $D = \frac{2ms}{20ms} = 10\%$
3. **寄存器值计算 (13-bit = 8192):**
   - 0 deg: $\text{Value} = 0.05 \times 8192 = 409.6 \approx 410$
   - 90 deg: $\text{Value} = 0.075 \times 8192 = 614.4 \approx 614$
   - 180 deg: $\text{Value} = 0.10 \times 8192 = 819.2 \approx 819$

Answer: $\boxed{0^\circ \to 410, \quad 90^\circ \to 614, \quad 180^\circ \to 819}$

角度到寄存器值的线性公式: $\text{Value} = 410 + \frac{\theta}{180} \times (819 - 410) = 410 + 2.27\theta$

Blackboard Challenge 7: LED Dimming | LED 调光

Problem: ESP32 控制 LED，要求 256 级亮度调节（8-bit 感知），但 LEDC 用 13-bit。设计映射关系实现感知线性亮度。

Step-by-step Solution:

1. 问题: 人眼对亮度感知是对数关系，线性 PWM 会感觉不均匀
2. 解决方案 — **Gamma 校正:**

$$\text{PWM}_{output} = \left(\frac{\text{Level}}{255}\right)^{\gamma} \times 8191 \tag{93}$$

3. 常用 $\gamma = 2.2$:
   - Level 0: $(\frac{0}{255})^{2.2} \times 8191 = 0$
   - Level 128: $(\frac{128}{255})^{2.2} \times 8191 = 1853$
   - Level 255: $(\frac{255}{255})^{2.2} \times 8191 = 8191$
4. 查表法实现: 预计算 256 个值存入数组

Answer: $\boxed{\text{PWM} = \left(\frac{\text{Level}}{255}\right)^{2.2} \times 8191}$

使用 Gamma 校正实现感知线性的亮度调节。

Mnemonic: PWM | 记忆口诀口诀：“高时间比总时间，平均电压占比算”

- 占空比 = 高电平时间 / 总周期
- 平均电压 = 占空比 × 峰值电压
- 频率越高，滤波后越平滑

舵机口诀：“一毫零度，二毫满转，中间 1.5”

- 1ms 脉宽 → 0 deg
- 1.5ms 脉宽 → 90 deg
- 2ms 脉宽 → 180 deg

Duty = ON time / Period; Servo: 1ms=0 deg, 1.5ms=90 deg, 2ms=180 deg

22.5 Interrupts | 中断

核心公式 / Key Formula

Interrupt vs Polling | 中断与轮询对比

特性	**Polling (轮询)**	**Interrupt (中断)**
CPU 占用	持续检查，占用高	事件触发，占用低
响应时间	取决于轮询间隔	几乎立即（μs 级）
实时性	差	好
功耗	高（CPU 一直运行）	低（可休眠等待）
编程复杂度	简单	需处理并发
适用场景	简单任务、非实时	按键、通信、定时

Polling: CPU continuously checks; Interrupt: Event-driven, efficient for real-time.

Interrupt Handling | **中断处理流程中断响应过程:**

1. **中断请求 (IRQ):** 外设产生中断信号
2. **中断响应:** CPU 完成当前指令，保存上下文 (PC, SR, 寄存器)
3. **中断向量:** 查表获取 ISR 入口地址
4. **执行 ISR:** 运行中断服务程序
5. **中断返回:** 恢复上下文，继续主程序

中断延迟 (Interrupt Latency):

$$T_{latency} = T_{sync} + T_{save} + T_{vector} + T_{ISR\_entry} \tag{94}$$

ESP32 中断优先级: 1-7 级（7 最高），支持嵌套中断
ISR 编写原则:

- 尽量短小，只做标记
- 避免使用阻塞函数（delay, printf）
- 使用 volatile 声明共享变量
- ESP32: 使用 IRAM_ATTR 放入 IRAM

ISR should be short, non-blocking, and use volatile for shared variables.

Blackboard Challenge 8: Interrupt Latency | 中断延迟分析

Problem: ESP32 @ 240MHz，按键触发 GPIO 中断。假设上下文保存需要 20 个时钟周期，向量查找 10 周期，ISR 入口 10 周期。求最小中断延迟。
Step-by-step Solution:

1. **时钟周期时间:**
$$T_{cycle} = \frac{1}{240MHz} = 4.17ns \tag{95}$$
2. **总周期数:** $20 + 10 + 10 = 40$ cycles
3. **中断延迟:**
$$T_{latency} = 40 \times 4.17ns = 166.8ns \tag{96}$$
4. **实际考虑:**
   - 流水线清空: +20 cycles
   - Cache Miss: +100 cycles (if ISR not in IRAM)
   - 实际延迟: 约 200-500ns

Answer: $\boxed{T_{latency,min} \approx 167ns}$ (理想情况)
实际约 0.5-2μs，取决于 Cache 状态和 ISR 位置。

Mnemonic: Interrupt | **记忆口诀口诀：“轮询费 CPU，中断省功耗；ISR 要短快，volatile 不能少”**
中断处理五字诀：“请响向执返”

1. 请 — 中断请求
2. 响 — CPU 响应
3. 向 — 查向量表
4. 执 — 执行 ISR
5. 返 — 中断返回

ISR 三不要：

- 不要 delay
- 不要 printf
- 不要太长

Polling wastes CPU; Interrupts save power; ISR must be short with volatile variables.

22.6 UART | 串口通信

核心公式 / Key Formula

UART Fundamentals | UART **基础波特率计算 (Baud Rate):**

$$\text{Baud Rate} = \frac{f_{clk}}{\text{Divisor} \times 16} \tag{97}$$

位时间 (Bit Time):

$$T_{bit} = \frac{1}{\text{Baud Rate}} \tag{98}$$

帧格式 (Frame Format):

Start	Data (5-9 bits)	P	Stop
1 bit	8 bits	0/1	1-2

常见配置：8N1 = 8 **数据位** + **无校验** + 1 **停止位**
有效数据率：

$$\text{Effective Rate} = \frac{\text{Data bits}}{\text{Total bits}} \times \text{Baud Rate} \tag{99}$$

UART frame: Start bit + Data + Parity (optional) + Stop bit(s)

Blackboard Challenge 9: UART Baud Rate | 波特率计算

Problem: ESP32 时钟 80MHz，配置 UART 波特率 115200。求分频值和实际波特率误差。
Step-by-step Solution:

1. **理论分频值:**

$$\text{Divisor} = \frac{f_{clk}}{\text{Baud Rate} \times 16} = \frac{80MHz}{115200 \times 16} = 43.403 \tag{100}$$

2. **实际分频值:** 取整为 43

3. **实际波特率:**

$$\text{Actual Baud} = \frac{80MHz}{43 \times 16} = 116279 \text{ bps} \tag{101}$$

4. **误差计算:**

$$\text{Error} = \frac{116279 - 115200}{115200} \times 100\% = 0.94\% \tag{102}$$

5. **可接受范围:** UART 允许 $\pm 2\%$误差，0.94% ✓

Answer: $\boxed{\text{Divisor} = 43, \quad \text{Error} = 0.94\%}$

Blackboard Challenge 10: Data Transfer Time | 数据传输时间

Problem: UART 配置 115200 bps, 8N1 格式。传输 1000 字节需要多长时间？
Step-by-step Solution:

1. **每帧总位数 (8N1):**
   - 1 Start bit + 8 Data bits + 0 Parity + 1 Stop bit = 10 bits

2. **每字节传输时间:**

$$T_{byte} = \frac{10 \text{ bits}}{115200 \text{ bps}} = 86.8\mu s \tag{103}$$

3. **1000 字节总时间:**

$$T_{total} = 1000 \times 86.8\mu s = 86.8ms \tag{104}$$

4. **有效数据率:**

$$\text{Effective} = \frac{8}{10} \times 115200 = 92160 \text{ bps} = 11.52 \text{ KB/s} \tag{105}$$

Answer: $\boxed{T = 86.8ms, \quad \text{Effective Rate} = 11.52 \text{ KB/s}}$

Mnemonic: UART | 记忆口诀口诀:“起始低，停止高；数据中间跑，校验可选要”

- **Start bit:** 总是 LOW (下降沿触发同步)
- **Stop bit:** 总是 HIGH (确保下一帧能检测 Start)
- **Data:** LSB first (低位先发)

8N1 口诀: “8 位数据无校验，1 个停止够简单”
常见波特率: 9600, 19200, 38400, 57600, 115200, 921600
波特率误差口诀: “误差 2%内都 OK”

Start=LOW, Stop=HIGH, Data in between, 8N1 is most common.

22.7 Thesis Application: ESP32 IoT Sensor System | 论文应用

Thesis Connection

ESP32 Smart Home Sensor Integration | ESP32 智能家居传感器集成论文关联：基于 ESP32 的智能家居环境监测系统
系统架构：

1. 传感器接口 **(GPIO + ADC)**:
   - 温湿度: DHT22 (单线协议, GPIO)
   - 光照: BH1750 (I2C, GPIO16/17)
   - 空气质量: MQ-135 (ADC 通道)
   - PIR 运动检测: GPIO 中断
2. 数据采集配置:

```
// ADC 配置 (空气□量□感器)
adc1_config_width(ADC_WIDTH_BIT_12);
adc1_config_channel_atten(ADC1_CHANNEL_0, ADC_ATTEN_DB_11);

// GPIO 中断配置 (PIR)
gpio_config_t io_conf = {
    .pin_bit_mask = (1ULL << PIR_PIN),
    .mode = GPIO_MODE_INPUT,
    .pull_up_en = GPIO_PULLUP_DISABLE,
    .pull_down_en = GPIO_PULLDOWN_ENABLE,
    .intr_type = GPIO_INTR_POSEDGE
};
gpio_install_isr_service(0);
gpio_isr_handler_add(PIR_PIN, pir_isr, NULL);
```

3. **PWM** 应用:
   - LED 状态指示灯 (呼吸灯效果)
   - 风扇调速 (基于温度 PID 控制)
   - 舵机控制 (通风窗开关)
4. 通信协议:
   - UART: 调试输出和传感器模块通信
   - WiFi/MQTT: 云端数据上传
   - BLE: 本地手机配置

功耗优化策略:

- Deep Sleep 模式: 10μA @ 等待
- 定时器唤醒: 每 5 分钟采集一次
- GPIO 唤醒: PIR 触发立即响应
- 平均功耗: <1mA (电池寿命 >1 年)

Thesis Link: Complete IoT sensor node using ESP32 with multiple sensor interfaces (ADC, GPIO, I2C), interrupt-driven motion detection, PWM-controlled actuators, and UART/WiFi communication for smart home applications.

22.8 Quick Reference | 速查表

核心公式 / Key Formula

Comprehensive Formula Sheet | 综合公式速查

Topic	**Formula**	**Mnemonic**
Timer Overflow	$T = \frac{2^n \times Pre}{f_{clk}}$	位数 × 分频/时钟
PWM Frequency	$f_{PWM} = \frac{f_{clk}}{Pre \times (TOP+1)}$	时钟/分频 × 顶值
ADC Value	$V = \frac{ADC \times V_{ref}}{2^n}$	值 × 参考/满量程
ADC Resolution	$LSB = \frac{V_{ref}}{2^n}$	参考/分辨率
PWM Duty	$D = \frac{T_{on}}{T_{period}}$	高/总
PWM Average V	$V_{avg} = D \times V_{max}$	占空比 × 峰值
Servo Pulse	$1ms \leftrightarrow 2ms$	1 毫零度 2 毫满
UART Baud	$Baud = \frac{f_{clk}}{Div \times 16}$	时钟/分频 ×16
UART 8N1	10 bits/byte	1 起 8 数 1 停
Nyquist	$f_s \geq 2f_{max}$	采样翻倍

Master these formulas for comprehensive microcontroller understanding!

ESP32 Quick Reference | ESP32 速查

Feature	**Specification**
CPU	Dual-core Xtensa LX6 @ 240MHz
GPIO	34 pins (6 input-only: 34-39)
ADC	2x 12-bit SAR ADC, 18 channels
DAC	2x 8-bit DAC (GPIO25, GPIO26)
PWM	LEDC: 16 channels, up to 20-bit
UART	3x UART
SPI	4x SPI (2 usable)
I2C	2x I2C
Timer	4x 64-bit general purpose
Flash GPIO	6-11 (DO NOT USE)
Boot Pins	0, 2, 15 (use with care)

ESP32 key specifications for IoT development.

23 算法与复杂性 / Algorithms & Complexity (BE5B33ALG)

算法复杂性 / Computational Complexity

[CN] 定义: 大 O 符号 ($O(\cdot)$) 描述了算法在最坏情况下的运行时间或空间需求随输入规模 N 增长的趋势。

- $O(1)$: 常数时间 (如数组索引)。
- $O(\log N)$: 对数时间 (如二分查找)。
- $O(N)$: 线性时间 (如遍历链表)。
- $O(N^2)$: 平方时间 (如冒泡排序)。

[EN] **Definition**: Big-O notation describes the worst-case growth rate of an algorithm's time or space requirements relative to input size N.

- $O(1)$: Constant Time (e.g., Array Access).
- $O(\log N)$: Logarithmic (e.g., Binary Search).
- $O(N)$: Linear (e.g., Iterating a list).
- $O(N \log N)$: Linearithmic (e.g., QuickSort/MergeSort).

排序算法 / Sorting Algorithms

[CN] 定义:

- 快速排序 (**QuickSort**): 分治法。平均 $O(N \log N)$，但不稳定。
- 归并排序 (**MergeSort**): 分治法。保证 $O(N \log N)$，稳定，但需要额外空间。
- 堆排序 (**HeapSort**): 利用二叉堆。$O(N \log N)$，原地排序。

[EN] **Definition**:

- **QuickSort**: Divide and Conquer. Avg $O(N \log N)$. Unstable.
- **MergeSort**: Stable, $O(N \log N)$, requires $O(N)$ extra space.
- **HeapSort**: Uses Binary Heap structure. In-place $O(N \log N)$.

论文关联 / Project Algorithms

[CN]: 你的固件中实施了特定的实时算法:

- **移动平均滤波 (Moving Average)**: 公式: $y[n] = y[n-1] + \frac{x[n]-x[n-N]}{N}$ (递归实现)。复杂度: $O(1)$ (如果递归) 或 $O(N)$ (如果每次由头求和)。用于平滑传感器噪音。
- **跌倒检测 (Fall Detection)**: 逻辑: `if (acc > 2.4G && gyro > 240 deg/s)`. 复杂度: $O(1)$。这是实时系统的关键,保证了在资源受限的 ESP32 上极低的延迟。

[EN]: Your firmware implements real-time algorithms:

- **Moving Average Filter**: Used to smooth sensor noise. Complexity: $O(1)$ (Recursive implementation) or $O(N)$ (Naive sum).
- **Fall Detection**: Logic: Threshold comparison. Complexity: $O(1)$ (Constant time). Critical for low latency on the ESP32.

核心公式 / Key Formula

图搜索算法 / **Graph Search**:

- **BFS** (广度优先): 使用队列 (Queue)。寻找无权图最短路径。
- **DFS** (深度优先): 使用栈 (Stack) 或递归。用于回溯法。
- **Dijkstra**: 使用优先队列 (Priority Queue)。寻找加权图最短路径。

考试陷阱 / Exam Pitfalls

- **Binary Search Requirements**: 二分查找要求数据必须是有序的 (Sorted)。
- **Stack vs Queue**: Stack is LIFO (Last In First Out); Queue is FIFO (First In First Out).
- **Recursion Risk**: 递归虽然代码简洁,但深度过大时会导致栈溢出 (Stack Overflow),在嵌入式中需谨慎。

Part V
专业方向 / Specialization

24 Electromagnetic Theory / 电磁场理论 (OUT OF SCOPE)

[SKIP] NOT IN YOUR EXAM SCOPE / 不在你的考试范围

[CN] 你没有修过 BE5B17EMT。此专业题不会出现在你的考试中。跳过此章节!
[EN] You **did NOT take** BE5B17EMT. This topic will NOT appear in your exam. **SKIP this chapter!**
Your Specialization: Power Engineering (EN1/EN2) → 去看 Topic 22

(Content below is for reference only / 以下内容仅供参考)

麦克斯韦方程组 / Maxwell's Equations

[CN] 定义: 经典电磁学的核心，包含四个方程:

1. 高斯电场定律: 电荷产生散开的电场 ($\nabla \cdot E = \rho/\epsilon_0$).
2. 高斯磁场定律: 无磁单极子 ($\nabla \cdot B = 0$).
3. 法拉第定律: 变化的磁场产生电场 ($\nabla \times E = -\partial B/\partial t$).
4. 安培定律: 电流和变化的电场产生磁场 ($\nabla \times B = \mu_0 J + \mu_0\epsilon_0 \partial E/\partial t$).

[EN] **Definition**: The core of classical electromagnetism:

1. **Gauss's Law**: Electric charges produce diverging E-fields.
2. **Gauss's Law for Magnetism**: No magnetic monopoles.
3. **Faraday's Law**: Changing B-field induces E-field.
4. **Ampere's Law**: Currents and changing E-fields produce B-fields.

核心公式 / Key Formula

传输线 / **Transmission Lines**: 特性阻抗 (Characteristic Impedance):

$$Z_0 = \sqrt{\frac{L}{C}} \approx 50\Omega \tag{106}$$

为了防止反射 (Reflection)，负载阻抗必须匹配 $Z_L = Z_0$。

论文关联 / Project Application

[CN]:

- 阻抗匹配: ESP32 的天线输出被设计为 50Ω。PCB 走线宽度必须精确计算以保持此阻抗，防止信号向源端反射。
- 去耦: 在电源线上放置电容是为了提供高频信号的低阻抗返回路径，减小辐射回路面积。

[EN]:

- **Impedance Matching**: ESP32 antenna output requires 50Ω. PCB traces are dimensioned to match this to prevent signal reflection (S_{11}).
- **Decoupling**: Capacitors provide a low-impedance return path for high-frequency currents, reducing the loop area and EMI.

25 逻辑系统 / Logic Systems (BE5B01LGS)

布尔代数 / Boolean Algebra

[CN] 定义: 数字逻辑的数学基础。

- 基本运算: AND ($A \cdot B$), OR ($A + B$), NOT ($\bar{A}$).
- 德摩根定律: $\overline{A \cdot B} = \bar{A} + \bar{B}$, $\overline{A + B} = \bar{A} \cdot \bar{B}$.

[EN] **Definition**: Mathematical foundation of digital logic.

- **Ops**: AND (Conjunction), OR (Disjunction), NOT (Negation).
- **De Morgan's Laws**: NAND equals OR of negations; NOR equals AND of negations.

时序逻辑 / Sequential Logic

[CN] 定义: 输出取决于当前输入以及过去输入的电路（有记忆）。

- 触发器 (**Flip-Flop**): 基本存储单元 (如 D-FF)。在时钟边沿改变状态。
- 寄存器 (**Register**): 并联的 D-FF，用于存储多位数据。

[EN] **Definition**: Circuits where output depends on current inputs **and** history (Memory).

- **Flip-Flop**: Basic storage element (e.g., D Flip-Flop). State changes on clock edge.
- **Register**: Parallel D-FFs storing multi-bit data.

论文关联 / Project Application

[CN]:

- **GPIO 模式**: ESP32 的 GPIO 输入寄存器读取引脚电压。配置为 `INPUT_PULLUP` 实际上是在内部连接了一个上拉电阻，形成逻辑 1。
- **I2C 硬件**: ESP32 内部的 I2C 控制器是由大量状态机 (FSM) 和移位寄存器 (Shift Register) 组成的复杂时序逻辑电路。

[EN]:

- **GPIO**: Configured via registers. `INPUT_PULLUP` connects an internal resistor, defaulting logic High.
- **I2C Controller**: Implemented in silicon using Finite State Machines (FSMs) and Shift Registers to serialize data.

26 Signals & Systems / 信号与系统 (OUT OF SCOPE)

[SKIP] NOT IN YOUR EXAM SCOPE / 不在你的考试范围

[CN] 你没有修过 BE5B31TES。此专业题不会出现在你的考试中。跳过此章节！
[EN] You **did NOT take** BE5B31TES. This topic will NOT appear in your exam. **SKIP this chapter!**
Your Specialization: Power Engineering (EN1/EN2) → 去看 Topic 22

(Content below is for reference only / 以下内容仅供参考)

傅里叶变换 / Fourier Transform

[CN] 定义: 将信号从时域 (Time Domain) 转换到频域 (Frequency Domain)。任何周期信号都可以分解为正弦波的叠加。

[EN] **Definition**: Transforms a signal from Time Domain to Frequency Domain. States that any periodic function can be expressed as a sum of sines and cosines.

核心公式 / Key Formula

采样定理 / **Nyquist-Shannon Theorem**:

$$f_s \geq 2f_{max} \tag{107}$$

采样率必须至少是信号最高频率的两倍，否则会发生混叠 (Aliasing)。

论文关联 / Project Application

[CN]:

- 采样率选择: 你的 MPU6050 采样率为 10Hz。这意味着只能准确捕捉 5Hz 以下的运动（人体正常运动通常 $<$ 2Hz）。
- 滤波: 你的移动平均滤波器实际上是一个低通滤波器 (Low Pass Filter)，切断了高频噪声。

[EN]:

- **Sampling**: MPU6050 @ 10Hz. Nyquist limit is 5Hz, sufficient for human motion ($<$ 2Hz).
- **Filtering**: The Moving Average Filter acts as an FIR Low Pass Filter, attenuating high-frequency noise.

27 电机学 / Electrical Machines (BE5B14ESP)

变压器 / Transformer

[CN] 定义: 基于电磁感应，只转换交流电压/电流，不改变频率。$V_1/V_2 = N_1/N_2$。

[EN] **Definition**: Static device transferring AC energy via induction. Steps up/down voltage ($V_p/V_s = N_p/N_s$) without changing frequency.

电动机 / Electric Motors

[CN] 定义:

- 直流电机 (**DC Motor**): 使用换向器 (Brushed) 或电子换向 (BLDC)。速度 $\propto$ 电压。
- 感应电机 (**Induction Motor**): 异步。转子速度总是落后于旋转磁场 (Slip)。
- 同步电机 (**Synchronous Motor**): 转子速度锁定于电源频率。

[EN] **Definition**:

- **DC Motor**: Speed $\propto$ Voltage. Brushed or Brushless (BLDC).
- **Induction (Asynchronous)**: Rotor "slips" behind the rotating magnetic field.
- **Synchronous**: Rotor rotates in lock-step with supply frequency.

论文关联 / Project Application

[CN]: 虽然你的项目主要是传感器节点，但智能家居通常控制电机负载：

- 继电器控制: 你的 ESP32 可以驱动继电器来开启/关闭大功率交流电机（如风扇、水泵）。
- 感性负载: 电机是感性负载，关闭时会产生反电动势 (Back EMF)。需要反向二极管 (Flyback Diode) 保护电路。

[EN]: Smart homes often control motors:

- **Relays**: ESP32 drives relays to switch AC motors (fans, pumps).
- **Inductive Load**: Motors generate Back EMF when switched off. A Flyback Diode is required to protect the control circuitry.

28 材料科学 / Materials (BE5B13MAT)

材料分类 / Classification

[CN] 定义: 根据导电性能分类 (能带理论):

- 导体 (**Conductor**): 电子自由移动 (如铜 Cu)。价带与导带重叠。
- 半导体 (**Semiconductor**): 导电性介于导体和绝缘体之间 (如硅 Si)。带隙较小 ($E_g \approx 1.1$eV)。
- 绝缘体 (**Insulator**): 电子被束缚 (如玻璃)。带隙很大。

[EN] **Definition**: Based on energy bands:

- **Conductor**: Free electron movement (Copper). Overlapping bands.
- **Semiconductor**: Intermediate conductivity (Silicon). Small Bandgap.
- **Dielectric (Insulator)**: No free charges (Glass, FR4). Large Bandgap.

论文关联 / Project Application

[CN]:

- **PCB 基板 (FR4)**: 玻璃纤维环氧树脂。它是绝缘体 (介电材料)，其介电常数 ($\epsilon_r \approx 4.4$) 影响阻抗匹配。
- 导线 **(Copper)**: PCB 走线是铜箔，具有非零电阻。大电流走线需要足够的宽度以减少发热。
- 半导体: ESP32 芯片本身是基于硅工艺 (CMOS) 制造的。

[EN]:

- **FR4**: The PCB substrate. It is a dielectric with $\epsilon_r \approx 4.4$, affecting trace impedance.
- **Copper**: Traces have resistance. High-current power traces must be wide to minimize voltage drop and heating.
- **Silicon**: The base material for the ESP32 SoC (CMOS process).

29 Power Engineering / 电力工程 (EN1/EN2)

[SPECIALIZATION] YOUR SPECIALIZATION / 你的专业方向

[CN] EN1/EN2 是你的专业选修题来源。考试会从这里出 1 道专业题！
[EN] EN1/EN2 is your **Specialization Topic Source**. 1 exam question WILL come from here!
Focus: 发电厂类型 | 输配电网络 | 变压器原理 | 功率因数校正

电力 / Electric Power

[CN] 定义:

- 有功功率 **(Active Power, P)**: 实际做功的功率。单位：瓦特 (W)。
- 无功功率 **(Reactive Power, Q)**: 在电感/电容中振荡但未消耗的功率。单位：VAR。
- 视在功率 **(Apparent Power, S)**: 总功率。$S = \sqrt{P^2 + Q^2}$。单位：VA。

[EN] **Definition**:

- **Active Power (P)**: Real useful power (Watts).
- **Reactive Power (Q)**: Oscillating power stored in L/C fields (VAR).
- **Apparent Power (S)**: Vector sum magnitude (VA).

核心公式 / Key Formula

功率因数 / **Power Factor**:

$$\mathrm{PF} = \frac{P}{S} = \cos\phi \tag{108}$$

理想情况下 PF = 1。

论文关联 / Project Application

[CN]:

- 电池供电: 我们的设计使用 Li-Po 电池 (3.7V - 4.2V)。
- **电源管理 (LDO)**: AMS1117-3.3 线性稳压器将电池电压降至 3.3V 供 ESP32 使用。效率较低 ($\eta = V_{out}/V_{in}$)，多余能量变为热量。
- 功耗: ESP32 Wi-Fi 发送时峰值电流可达 240mA。必须确保 LDO 和走线能通过此电流。

[EN]:

- **Battery**: Li-Po cell nominal 3.7V.
- **LDO Regulator**: Steps down voltage to 3.3V. Linear regulators dissipate excess voltage as heat (Low efficiency).
- **Peak Current**: Wi-Fi transmission spikes up to 240mA. Power traces must handle this.

30 AI & Cybernetics / 人工智能 (KUI/RPZ)

[WARN] PRIORITY: SURVIVAL MODE / 优先级：求生模式

[CN] KUI 优先级为 **CRITICAL**。只背: 状态空间搜索 (BFS/DFS/A*) + 启发式！ **[EN]** KUI priority is **CRITICAL**. **ONLY memorize**: State Space Search (BFS/DFS/A*) + Heuristics! **Thesis Link**: 跳倒检测中的阈值判断 vs AI 分类器 → "Heuristic-based rule in my thesis could be upgraded to ML classifier"

[MUST KNOW] State Space Search / 状态空间搜索

[CN] 核心概念:

- 状态空间: 所有可能状态的集合 (Initial State → Goal State)
- **BFS** (广度优先): 层层搜索，完备性 (Complete)，内存消耗大 $O(b^d)$
- **DFS** (深度优先): 先往深走，不完备，内存 $O(bd)$ 但可能陷入无限循环
- **A*** 算法: $f(n) = g(n) + h(n)$，$h(n)$ 是启发式函数

[EN] **Key Concepts**:

- **State Space**: Set of all possible states (Initial → Goal)
- **BFS**: Level-by-level, **Complete**, Memory $O(b^d)$
- **DFS**: Go deep first, **NOT complete**, Memory $O(bd)$
- **A***: $f(n) = g(n) + h(n)$, where $h(n)$ is heuristic (admissible = never overestimates)

分类与学习 / Machine Learning

[CN] 定义：从数据中学习模式的算法。

- 监督学习 (**Supervised**)：训练数据有标签 (如：这组数据是”跌倒”，那组是”走路”)。
- 无监督学习 (**Unsupervised**)：数据无标签，寻找内在结构 (如聚类)。
- 神经网络 (**Neural Network**)：模拟人脑神经元的层级结构。

[EN] **Definition**: Learning patterns from data.

- **Supervised**: Data is labeled (Input → Output mapping). Classification/Regression.
- **Unsupervised**: No labels (Clustering).
- **Neural Networks**: Layers of artificial neurons (Perceptrons) with weights and activation functions.

论文关联 / Project Application

[CN]:

- **TinyML**: 在微控制器 (MCU) 上运行机器学习。
- 跌倒检测：目前使用的是基于阈值的规则 (Heuristic)。
- 未来改进：可以收集加速度数据训练一个 SVM (支持向量机) 或简单的神经网络分类器，部署在 ESP32 上以区分”跌倒”和”跳跃”，减少误报。

[EN]:

- **TinyML**: Running ML inference on Edge devices (ESP32).
- **Current**: Heuristic Threshold-based detection.
- **Future Work**: Train a Classifier (SVM or Neural Net) on acceleration data to distinguish Fall vs Jump, improving Specificity.

31 Computer Architecture / 计算机体系结构 (OUT OF SCOPE)

[SKIP] NOT IN YOUR EXAM SCOPE / 不在你的考试范围

[CN] 你没有修过 BE5B35APO。此专业题不会出现在你的考试中。跳过此章节！
[EN] You **did NOT take** BE5B35APO. This topic will NOT appear in your exam. **SKIP this chapter**!
Note: MIK (Topic 15) already covers microcontroller architecture. Focus there instead.

(Content below is for reference only / 以下内容仅供参考)

流水线与缓存 / Pipeline & Cache

[CN] 定义:

- **流水线 (Pipelining)**: 将指令执行分解为多个阶段 (取指, 译码, 执行...) 并行处理，提高吞吐量。
- **缓存 (Cache)**: 位于 CPU 和内存之间的小容量高速存储，利用局部性原理 (Locality) 减少内存访问延迟。L1, L2, L3。

[EN] **Definition**:

- **Pipelining**: Splitting instruction processing into stages (Fetch, Decode, Execute, Writeback) to increase throughput (Instructions Per Cycle).
- **Cache**: Fast, small memory hiding DRAM latency. Relies on Spatial and Temporal Locality.

指令集架构 / ISA

[CN] 定义:

- **CISC (复杂指令集)**: 指令复杂，长度可变 (x86)。
- **RISC (精简指令集)**: 指令简单，长度固定，利用流水线 (ARM, RISC-V, Xtensa)。

[EN] **Definition**:

- **CISC**: Complex instructions, variable length (Intel x86).
- **RISC**: Reduced instructions, fixed length, optimized for pipelining (ARM, ESP32).

论文关联 / Project Application

[CN]:

- **ESP32 架构**: 基于 Tensilica Xtensa LX7 核心，是一个典型的 **RISC** 架构。
- 双核: 它有两个核心 (PRO_CPU, APP_CPU)。FreeRTOS 调度器可以在两个核心上运行任务。
- **DMA**: 直接内存访问控制器允许外设 (如 SPI, I2C) 在不占用 CPU 的情况下传输数据，这对于高频传感器采样至关重要。

[EN]:

- **Xtensa LX7**: A RISC architecture powering the ESP32-S3.
- **Dual Core**: Symmetric Multiprocessing (SMP). Contains PRO_CPU and APP_CPU.
- **DMA**: Direct Memory Access allowing peripherals to transfer data to RAM without CPU intervention, critical for efficient sensor sampling.

32 Control Systems / 控制系统 (OUT OF SCOPE)

[SKIP] NOT IN YOUR EXAM SCOPE / 不在你的考试范围

[CN] 你没有修过 BE5B35ARI。此专业题不会出现在你的考试中。跳过此章节！
[EN] You **did NOT take** BE5B35ARI. This topic will NOT appear in your exam. **SKIP this chapter**!
Your Specialization: Power Engineering (EN1/EN2) → 去看 Topic 22

(Content below is for reference only / 以下内容仅供参考)

控制结构 / Control Structures

[CN] 定义:

- 开环控制 (**Open-Loop**): 控制动作独立于系统输出。无法纠正干扰带来的误差。(例如：普通烤面包机)。
- 闭环控制 (**Closed-Loop**): 使用反馈 (Feedback) 将输出与期望值比较，根据误差调整控制动作。(例如：空调恒温)。

[EN] **Definition**:

- **Open-Loop**: Control action is independent of the process output. Cannot compensate for disturbances (e.g., toaster).
- **Closed-Loop**: Uses Feedback to compare output with reference. Adjusts control action based on error (e.g., thermostat).

核心公式 / Key Formula

闭环传递函数 / **Closed-Loop Transfer Function**:

$$T(s) = \frac{Y(s)}{R(s)} = \frac{G(s)}{1 + G(s)H(s)} \tag{109}$$

$G(s)$: Plant (对象), $H(s)$: Sensor (传感器), $R(s)$: Reference (参考).

PID 控制器 / PID Controller

[CN] 定义: 工业中最常用的反馈控制器。包含三个项:

- 比例 (P): 当前误差。响应快，但这也是主要的控制力。
- 积分 (I): 过去误差的累积。用于消除稳态误差 (Steady-state error)。
- 微分 (D): 误差变化率。预测未来趋势，增加阻尼，减少超调 (Overshoot)。

[EN] **Definition**: The most common industrial controller.

- **Proportional (P)**: Reacts to current error. Main drive.
- **Integral (I)**: Reacts to accumulated past errors. Eliminates steady-state error.
- **Derivative (D)**: Reacts to rate of change. Predicts future error, adds damping, reduces overshoot.

核心公式 / Key Formula

PID 公式 / PID Formula:

$$u(t) = K_p e(t) + K_i \int e(t)dt + K_d \frac{de(t)}{dt} \tag{110}$$

调参口诀: P 决定响应速度，I 消除静差但导致振荡，D 抑制振荡。

稳定性 / Stability

[CN] 定义: 一个系统被称为 BIBO (Bounded-Input Bounded-Output) 稳定，如果任何有界输入都产生有界输出。在频域中，线性系统稳定的充要条件是: 所有闭环极点 **(Poles)** 都位于复平面的左半部分 **(LHP)**。

[EN] **Definition**: A system is BIBO Stable if every bounded input produces a bounded output. In the frequency domain, a linear system is stable if and only if **all closed-loop poles are located in the Left Half Plane (LHP)**.

论文关联 / Project Application

[CN]: 虽然你的毕业设计主要关注数据采集，但 Home Assistant 也可以由控制理论解释:

- **Bang-Bang** 控制: 比如当温度 > 25 度时开启风扇，< 24 度时关闭。这是一种带有迟滞 (Hysteresis) 的非线性控制。
- 反馈回路: 传感器 (SHT30) $\rightarrow$ 服务器 (HA) $\rightarrow$ 智能开关 (Relay) $\rightarrow$ 房间温度 $\rightarrow$ 传感器。

[EN]: Home Assistant automations can be viewed as control loops:

- **Bang-Bang Control**: Turning a fan ON if Temp > 25, OFF if < 24. This is non-linear control with Hysteresis.
- **Feedback Loop**: Sensor (SHT30) $\rightarrow$ Controller (HA) $\rightarrow$ Actuator (Relay) $\rightarrow$ Plant (Room Temp) $\rightarrow$ Sensor.

考试陷阱 / Exam Pitfalls

- **Right Half Plane (RHP)**: 只要有一个极点在右半平面，系统就不稳定！ (Unstable).
- **Integral Windup**: 积分饱和。如果执行器达到极限，积分项会持续累积导致系统失控。解决方法是“积分分离”或“抗饱和”。
- **Phase Margin**: 相位裕度越小，系统越接近振荡。通常设计目标是 $45° - 60°$。