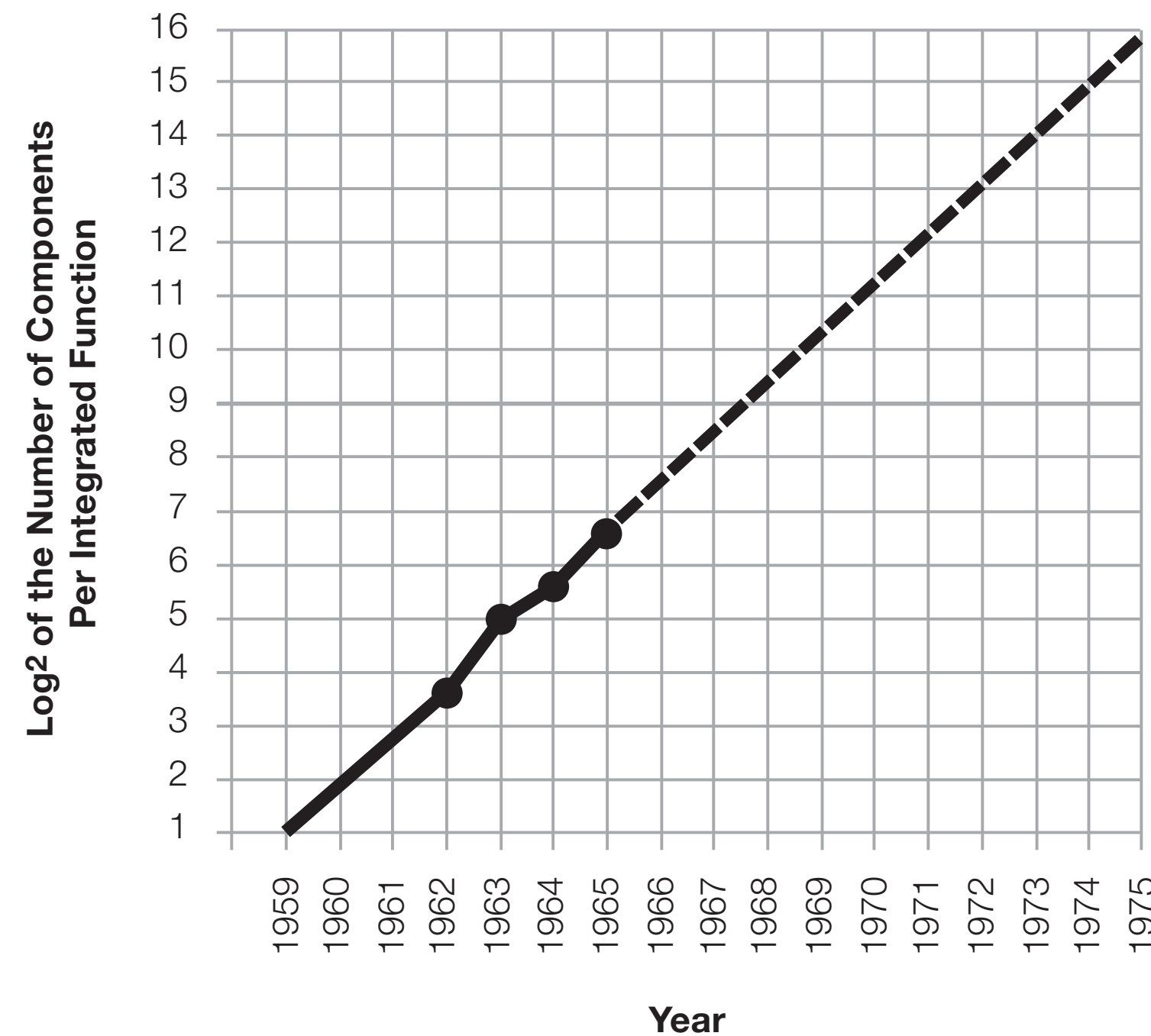


Challenges and Limitations

- What changes in the environment are affecting systems programs?
 - The end of Moore's law
 - Increasing concurrency – imposed due to hardware changes
 - Increasing need for security – the Internet
 - Increasing mobility and connectivity

The End of Moore's Law (1/2): Physical Limits

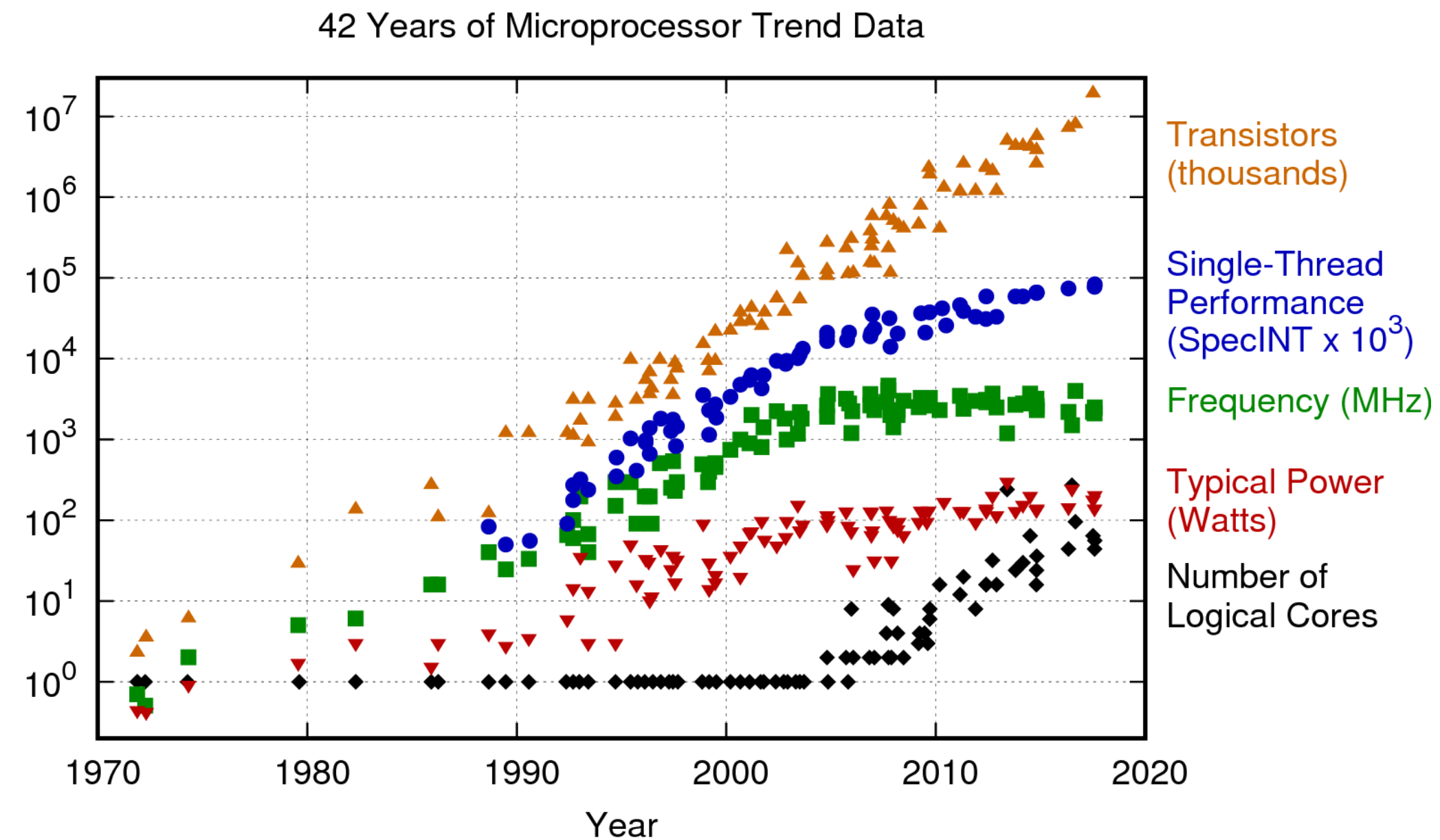


Source: Gordon Moore, "Cramming more components onto integrated circuits", Electronics, Vol. 38, Num. 5, April 1965.



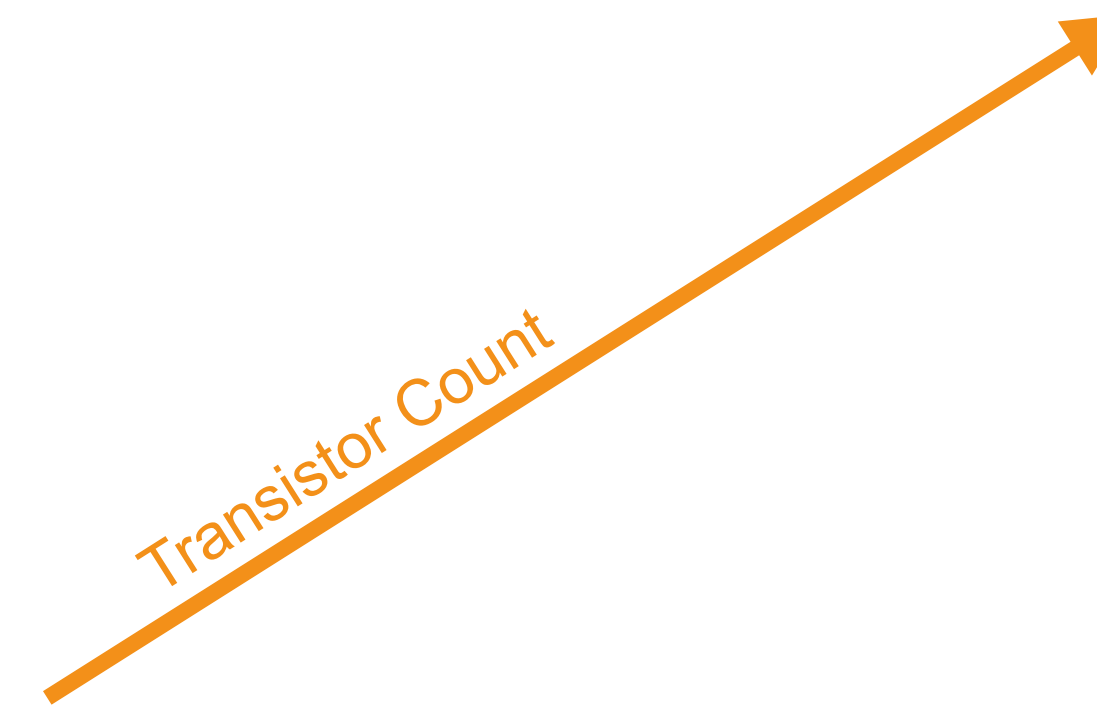
- Moore's law: advances in manufacturing double transistor count every two years

The End of Moore's Law (1/2): Physical Limits



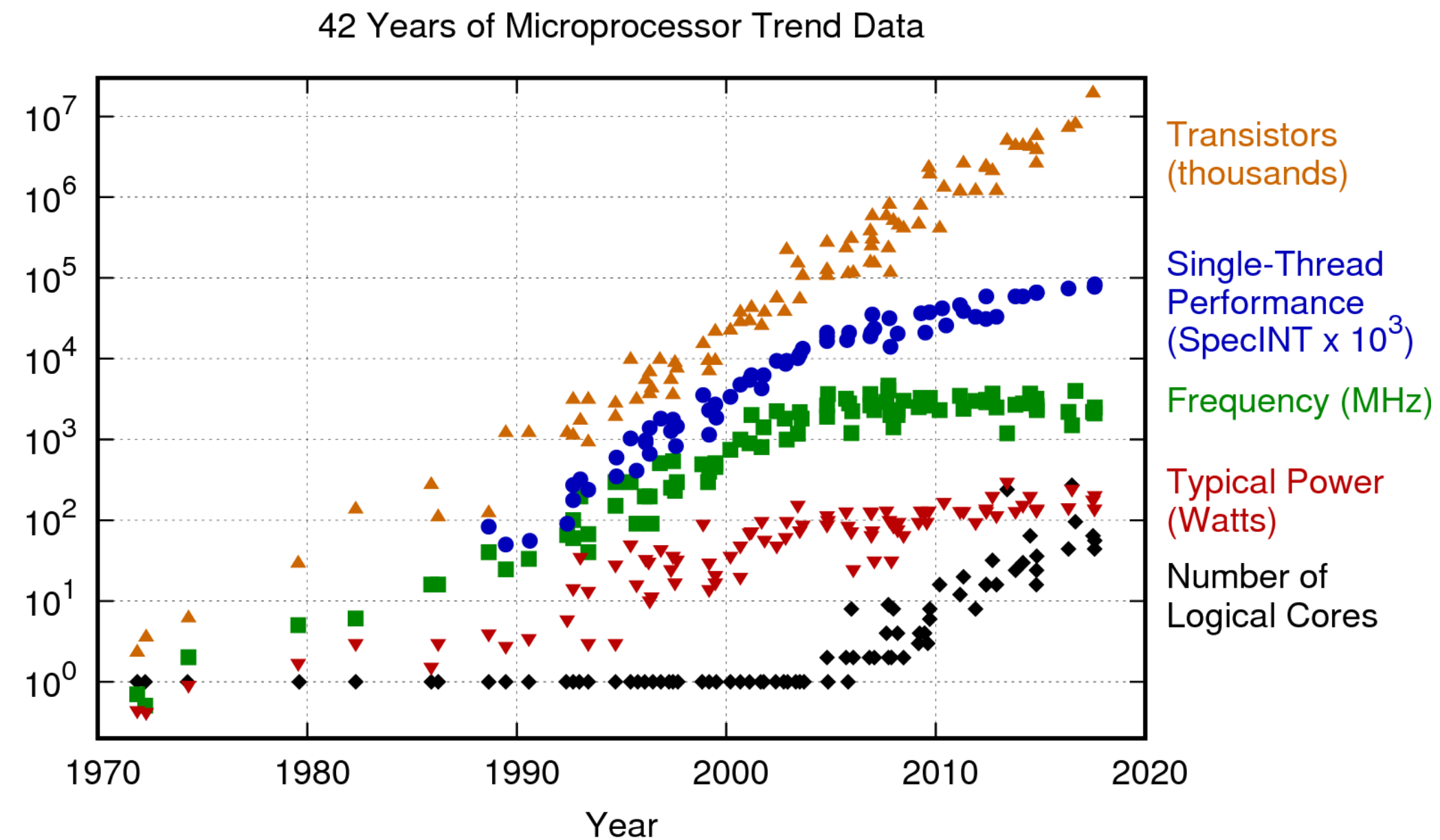
Original data up to the year 2010 collected and plotted by M. Horowitz, F. Labonte, O. Shacham, K. Olukotun, L. Hammond, and C. Batten
New plot and data collected for 2010-2017 by K. Rupp

Source: <https://www.karlrupp.net/2018/02/42-years-of-microprocessor-trend-data/>



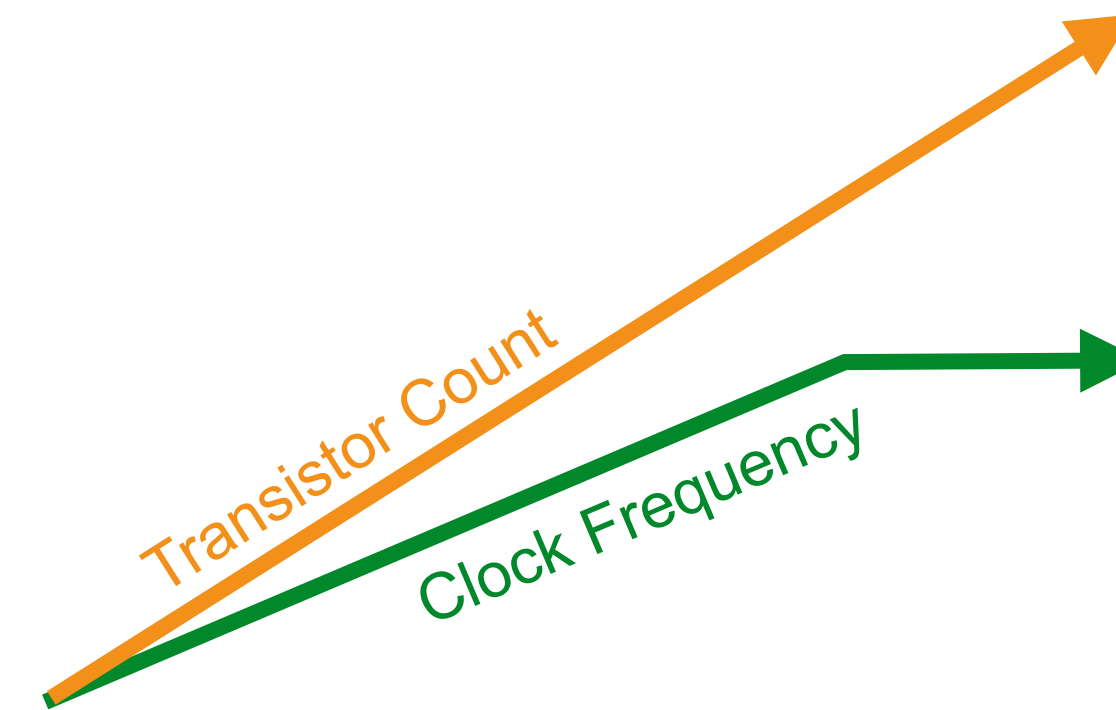
- Moore's law: advances in manufacturing double transistor count every two years
- But, rapidly approaching physical limits:
 - 10nm process → features ~40 atoms across
 - Transistors *will* stop shrinking soon

The End of Moore's Law (2/2): Dennard Scaling



Original data up to the year 2010 collected and plotted by M. Horowitz, F. Labonte, O. Shacham, K. Olukotun, L. Hammond, and C. Batten
New plot and data collected for 2010-2017 by K. Rupp

Source: <https://www.karlrupp.net/2018/02/42-years-of-microprocessor-trend-data/>

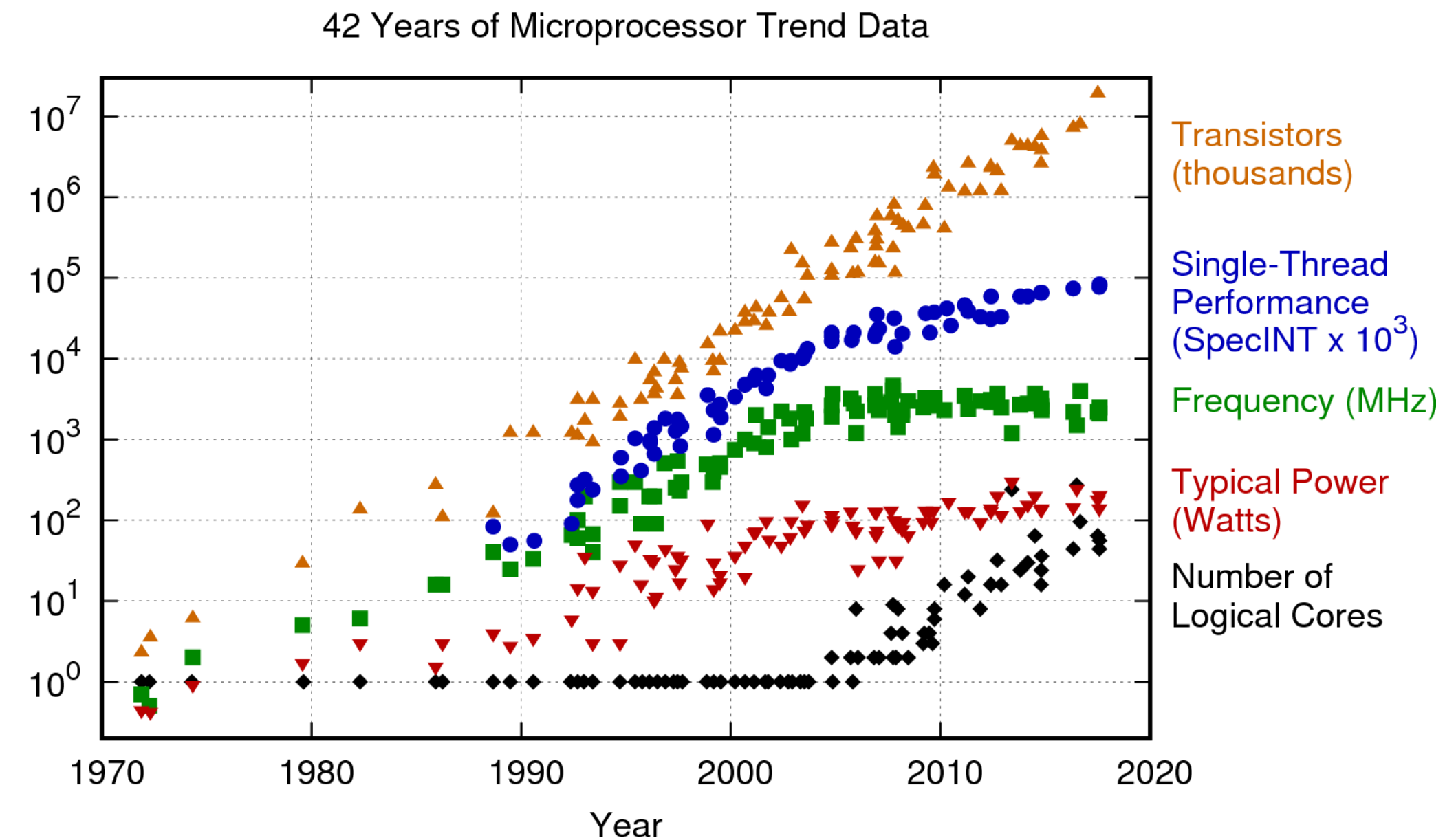


$$\text{Power consumption} \propto C \cdot F \cdot V^2 + L$$

- C = capacitance (transistor size)
- F = frequency (clock rate)
- V = voltage
- L = leakage

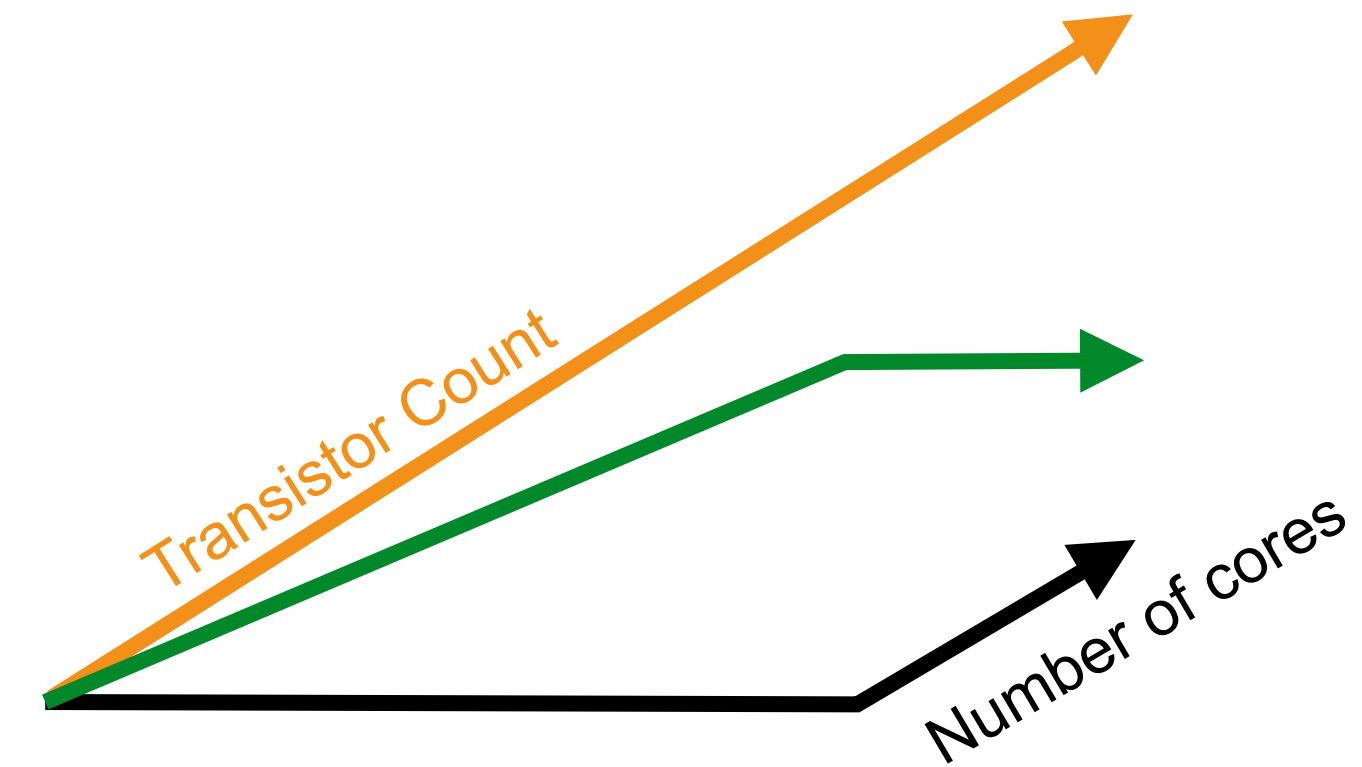
- Dennard scaling: smaller transistors reduce capacitance and voltage: frequency increase without increasing power consumption
- Scaling relation breaks down eventually, due to leakage, and clock frequency increase stalls

Increasing Concurrency



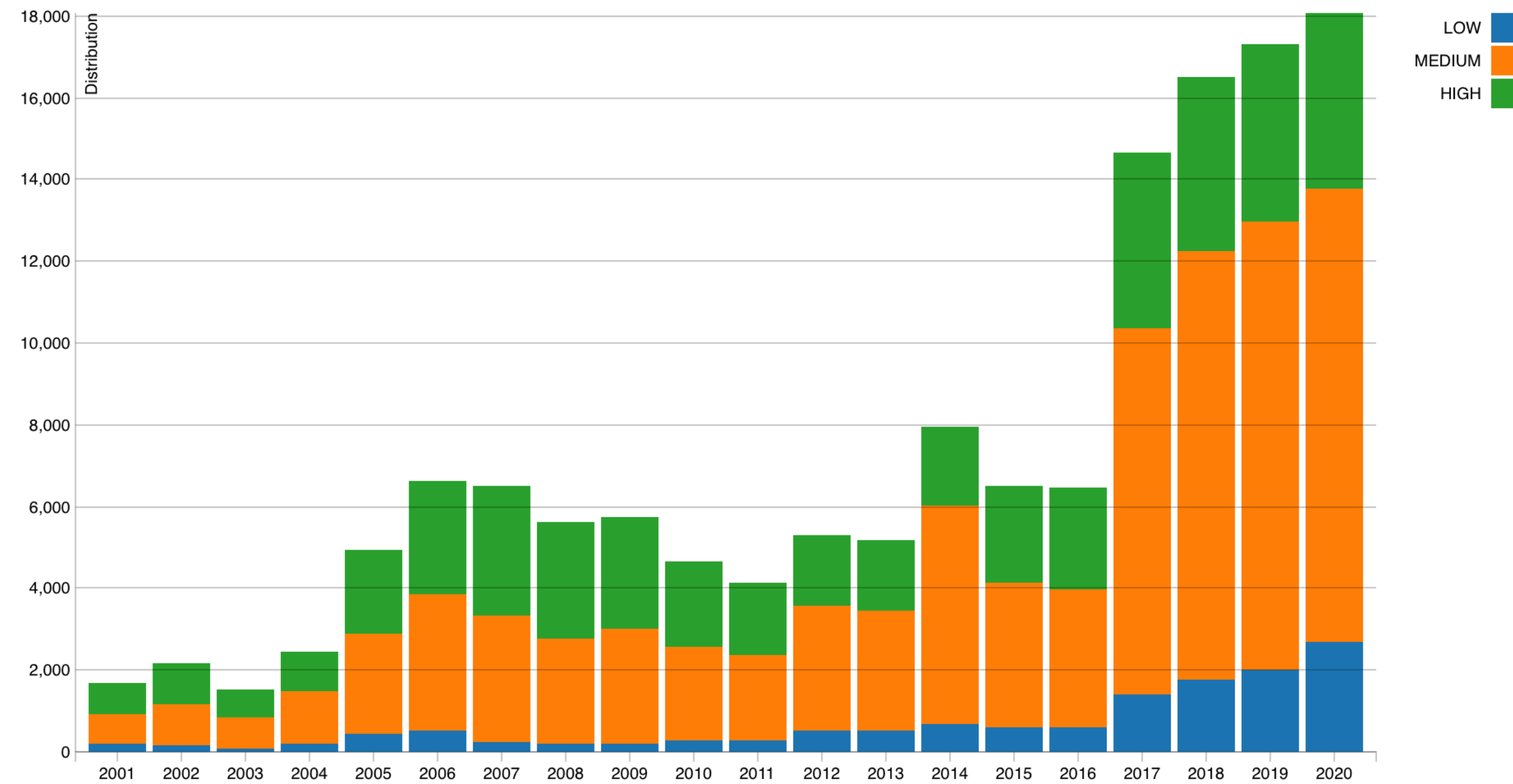
Original data up to the year 2010 collected and plotted by M. Horowitz, F. Labonte, O. Shacham, K. Olukotun, L. Hammond, and C. Batten
New plot and data collected for 2010-2017 by K. Rupp

Source: <https://www.karlrupp.net/2018/02/42-years-of-microprocessor-trend-data/>



- Breakdown of Dennard scaling limits clock frequency, but Moore's law gives more transistors → used to increase number of cores
- Concurrency related problems become more severe:
 - Performance with correctness, avoiding race conditions and deadlocks

Increasing Need for Security



Source: <https://nvd.nist.gov/general/visualizations/vulnerability-visualizations/cvss-severity-distribution-over-time>

Number of security vulnerabilities reported per year – US National Vulnerability Database

- Weaponisation of the Internet
- The combination of C and Unix has not proven easy to secure
- **Most** vulnerabilities due to weak typing and lack of memory safety

Increasing Mobility and Connectivity

- Computing increasingly implies mobile devices
 - Always on – but constrained by limitations of battery power
 - Always connected – by increasingly heterogenous networks
- Do we have the APIs, tools, and programming models to make effective use of such devices?

Systems Programming

- What is systems programming?
- The state of the art
- **Challenges and limitations**
- Next steps in systems programming