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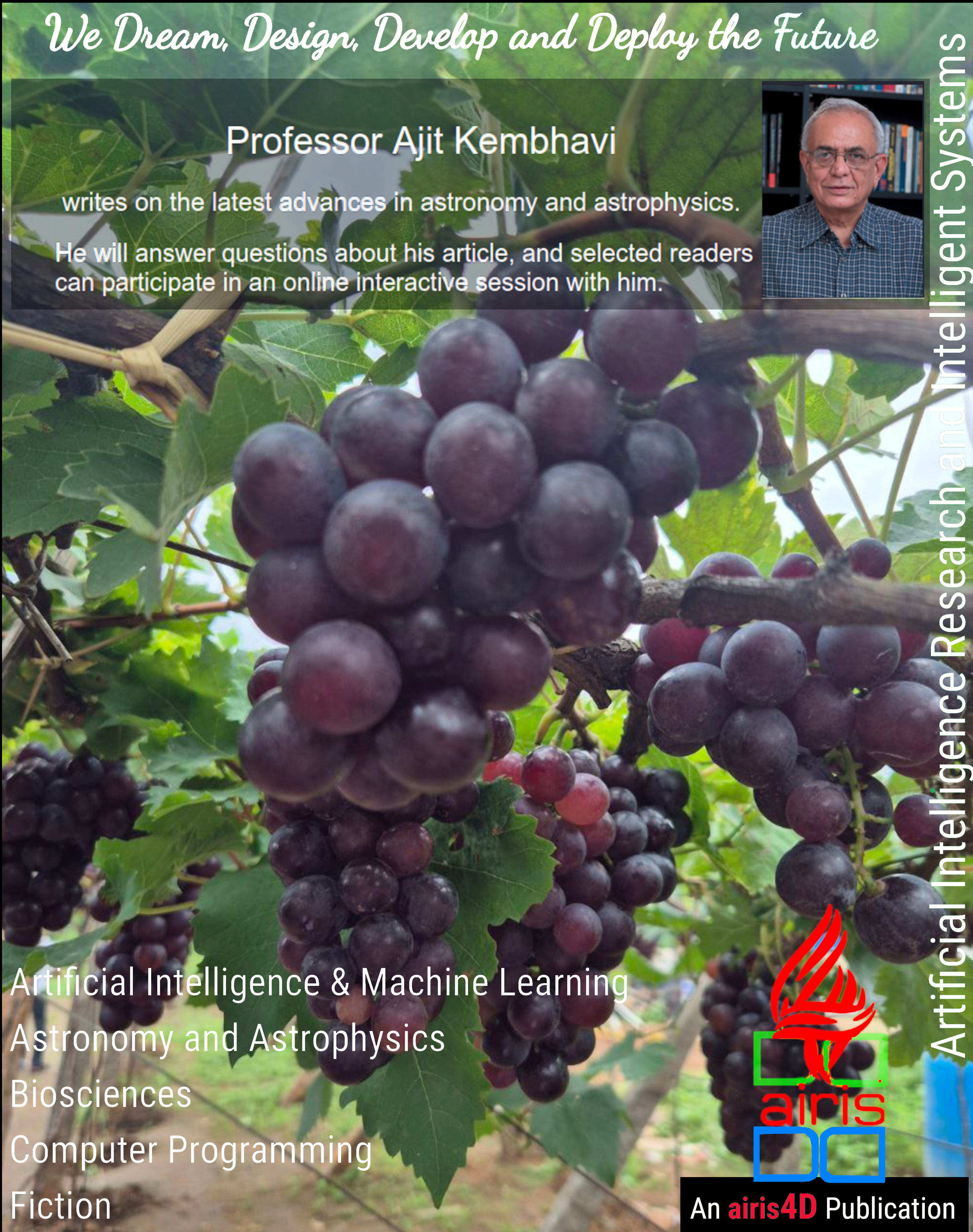

## Professor Ajit Kembhavi

writes on the latest advances in astronomy and astrophysics.

He will answer questions about his article, and selected readers can participate in an online interactive session with him.

Artificial Intelligence Research and Intelligent Systems

Artificial Intelligence & Machine Learning
Astronomy and Astrophysics
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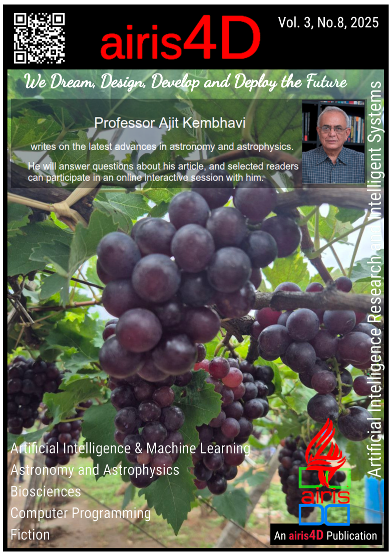


## Cover page

Image Name: *Vitis vinifera* :Vitis vinifera , the common grape vine, is a woody, deciduous, climbing plant native to the Mediterranean, Central Europe, and southwestern Asia, and is widely cultivated on every continent except Antarctica. With a diversity of between 5,000 and 10,000 varieties as of 2012, only a small number are commercially significant for wine and table grape production. Its grapes can be eaten fresh, dried into raisins, sultanas, or currants, or processed into juice, wine, and vinegar. Grape leaves are also used in many cuisines. Varieties of Vitis vinifera form the foundation of the global wine industry, with all familiar wine types produced from this species Photo: Geetha Paul




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# Editorial

*by Fr Dr Abraham Mulamoottil*

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This edition starts with the article by Arun Aniyan. **Need for AI Regulations: A Layperson's Guide**. He emphasises the urgent need for comprehensive regulations to govern the rapidly evolving field of Artificial Intelligence (AI). While AI holds immense promise—transforming healthcare, education, transportation, and climate solutions—it also poses significant risks if left unchecked. Key concerns include algorithmic bias, privacy invasion, lack of accountability, job displacement, misinformation, and the ethical dilemmas surrounding autonomous weapons. The article argues that just as rules exist for cars and medicine, AI requires similar guardrails to ensure safety, fairness, and accountability. Rather than stifling innovation, thoughtful regulation can guide ethical development, foster public trust, and ensure AI serves the collective good.

The article **Ambiguity, Redundancy, and Predictability: An Entropic View of Human Language** by Jinsu Ann Mathew explores how the concepts of entropy from information theory help explain three key features of natural language—ambiguity, redundancy, and predictability. Though these features may seem contradictory, they work together to make human communication both expressive and reliable. Ambiguity introduces uncertainty and flexibility, increasing entropy but enriching meaning; redundancy reduces entropy by reinforcing information, improving clarity and robustness; and predictability allows efficient processing by lowering uncertainty in communication. Rather than flaws, these characteristics are strategic tools that language uses to balance clarity and creativity. The article argues that the power of human language lies not in minimising entropy, but in managing it intelligently to achieve a dynamic balance between expressiveness and comprehensibility.

Ajit Kembhavi's article **Black Hole Stories-20: The LIGO Gravitational Wave Detectors** provides an in-depth yet accessible explanation of how LIGO (Laser Interferometer Gravitational-Wave Observatory) detects gravitational waves using advanced Michelson interferometry. Gravitational waves slightly alter the distances between mirrors in the interferometer, causing detectable changes in the interference patterns of laser beams. LIGO's detectors—featuring 4 km-long arms, high-powered stabilised lasers, ultra-reflective mirrors, and extreme vacuum systems—are engineered to measure minuscule mirror displacements as small as one-thousandth the diameter of a proton. The article describes how noise from seismic activity, thermal effects, and air molecules is minimised using sophisticated technology, allowing LIGO to achieve the sensitivity necessary to detect distant cosmic events. The current version, Advanced LIGO (aLIGO), is most effective in the 100–300 Hz frequency range and has already made groundbreaking detections, paving the way for future discoveries and upcoming facilities like LIGO-India.

The article **Is Every Crash a Firework? Observing Starbursts in Interacting Galaxies** by Robin Thomas explores how interactions between galaxies affect star formation, using ultraviolet (UV) and radio (HI) observations of three nearby galaxy pairs. While such encounters can trigger dramatic bursts of star formation, the study finds that the outcomes vary widely depending on factors like encounter geometry, gas content, and especially the mass ratio between galaxies. Near-equal-mass encounters tend to produce stronger star formation enhancements, whereas more unequal pairs show only modest effects. Interestingly, galaxy separation alone does not correlate well with star formation activity. The research also identifies candidates for tidal dwarf galaxies—new galactic entities forming from stripped material, highlighting that interactions can both disrupt and create galaxies. These findings support a nuanced view of galaxy evolution, advocating for future studies combining simulations with molecular gas and spectral data to better understand how cosmic collisions shape the universe.

Sindhu G's article **Understanding the Johnson Magnitude** offers a comprehensive overview of the Johnson photometric system, a foundational method in observational astronomy for measuring stellar brightness. Developed in the 1950s by Harold Johnson and William Morgan, the system introduced standardised broadband filters—U (ultraviolet), B (blue), and V (visual), later expanded to R (red) and I (infrared)—which remain central to astrophysical research. The system revolutionised photometry by enabling accurate, reproducible brightness measurements and colour indices like (B–V), which help determine stellar temperatures, classify stars, correct for interstellar extinction, and estimate distances. Despite newer systems like SDSS and CCD-adapted filters, the Johnson system endures due to its historical continuity, simplicity, and widespread calibration legacy. It remains a cornerstone in both research and education, linking past and present astronomical observations.

The article **Protein Folding and Its Vital Role in Biology** by Geetha Paul explains how proteins—essential molecules responsible for nearly all cellular functions—must fold into precise three-dimensional shapes to function properly. This folding process begins as a linear chain of amino acids is assembled during translation and proceeds through stages, forming secondary structures (e.g., alpha helices, beta sheets), tertiary structures, and sometimes quaternary structures. Molecular chaperones facilitate proper protein folding and prevent errors under stress. Misfolded proteins can aggregate, leading to serious diseases like Alzheimer's, Parkinson's, and cystic fibrosis by disrupting cellular function and triggering toxicity, inflammation, and impaired clearance systems. The article emphasises that understanding protein folding and misfolding is crucial for advancing treatments in neurodegenerative and other protein-related diseases.

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# Part I

# Artificial Intelligence and Machine Learning

# Need for AI Regulations: A Layperson's Guide

*by Arun Aniyan*

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## 1.1 Introduction

Artificial Intelligence (AI) is rapidly transforming our world. From the helpful suggestions on our smartphones to the complex algorithms driving self-driving cars, AI is no longer a futuristic concept but an integral part of our daily lives. While AI offers immense potential for progress and innovation, its rapid advancement also brings significant challenges and risks. Just as we have rules and laws for new technologies like cars or medicine, we need a clear set of guidelines and regulations for AI. This article will explain, in simple terms, why AI regulations are not just a good idea but an absolute necessity for our collective future.

## 1.2 What Exactly is AI Regulation?

Before we dive into why we need them, let's understand what AI regulations are. Think of regulations as a rulebook. For cars, we have traffic laws, seatbelt regulations, and manufacturing standards to ensure safety. For medicine, there are strict rules about testing, approval, and prescription to protect public health. AI regulations aim to do the same for AI.

- **Set Standards**: Define what is considered acceptable and safe AI behaviour.
- **Establish Responsibilities**: Determine who is accountable when AI makes a mistake or causes harm.
- **Protect Rights**: Safeguard individual privacy, prevent discrimination, and ensure fairness.
- **Foster Trust**: Build public confidence in AI technologies by ensuring they are developed and used responsibly.
- **Guide Innovation**: Provide a clear framework for developers and companies, encouraging ethical and beneficial AI development while preventing harmful applications.

The burgeoning field of artificial intelligence presents both immense opportunities and significant challenges. Therefore, the discussion around AI regulations is not an attempt to hinder technological advancement or stifle the groundbreaking work being done by innovators. On the contrary, the core objective of developing comprehensive AI regulations is to establish a framework that ensures the benefits of AI are widely distributed across society, promoting inclusivity and equitable access to these benefits. Simultaneously, it's crucial to proactively mitigate potential negative consequences, preventing the inadvertent creation of new societal, ethical, or economic problems that could arise from the unchecked development and deployment of AI systems. This thoughtful and balanced approach is crucial for harnessing the full potential of AI responsibly and sustainably.

## 1.3 The Promise of AI: Why We're Excited

To understand the need for regulation, it's important to appreciate the incredible promise of AI. AI can:

- **Revolutionise Healthcare**: Assist in diagnosing diseases earlier, developing personalised treatments, and even speeding up drug discovery. Imagine AI helping doctors identify subtle signs of illness that human eyes might miss.
- **Transform Transportation**: Lead to safer and more efficient self-driving vehicles, reducing accidents and traffic congestion.
- **Boost Economic Growth**: Automate repetitive tasks, increase productivity, and create new industries and job opportunities.
- **Address Global Challenges**: Help us tackle climate change, optimise energy consumption, and manage natural resources more effectively.
- **Enhance Education**: Provide personalised learning experiences for students, adapting to their individual needs and pace.

With such vast potential, it's easy to be optimistic. The future may hold advancements in healthcare, education, and environmental sustainability, ultimately leading to a more prosperous and equitable world. Imagine AI-driven diagnostics that identify diseases at their earliest stages, personalised learning platforms that adapt to each student's unique needs, or intelligent systems that optimise energy consumption and waste reduction. These are just a few glimpses of the positive transformations AI promises.

However, without proper guardrails, this promise can quickly turn into peril. The very power that allows AI to solve complex problems also presents significant risks if not managed responsibly. Unregulated AI could lead to widespread job displacement, algorithmic bias perpetuating societal inequalities, or even autonomous systems making critical decisions without human oversight. The potential for misuse, such as in surveillance or the spread of misinformation, is also a serious concern. Therefore, establishing robust ethical frameworks and regulatory measures is not merely an option, but an urgent necessity to ensure AI serves humanity's best interests.

## 1.4 The Perils of Unregulated AI: Why We Should Be Concerned

While the benefits are clear, the risks of unregulated AI are equally significant and, in some cases, truly alarming.

### 1.4.1 Bias and Discrimination: The "Garbage In, Garbage Out" Problem

AI systems learn from the data they are fed. If this data reflects existing human biases—whether conscious or unconscious—the AI will learn and perpetuate those biases. This is often referred to as "garbage in, garbage out."

Some examples are :

- **Hiring Algorithms**: If an AI hiring tool is trained on historical data where certain demographics were less likely to be hired for specific roles, it might unfairly screen out qualified candidates from those groups, even if they are equally or more capable.
- **Facial Recognition**: Studies have shown that some facial recognition systems are less accurate at identifying individuals with darker skin tones or women, leading to higher rates of misidentification and potential wrongful arrests. This is because the training data for these systems was predominantly composed of lighter-skinned individuals and men.
- **Loan Approvals**: An AI system used by banks to approve loans could deny loans to individuals from certain neighbourhoods or backgrounds if its training data links those demographics to higher default rates, even if the individual applicant is creditworthy.

Regulations can mandate fairness audits, require transparency in data collection, and impose penalties for discriminatory outcomes, forcing developers to actively identify and mitigate bias in their AI systems.

### 1.4.2 Privacy Invasion: The All-Seeing Eye

AI systems often require vast amounts of data to function effectively. This data can include personal information, online behaviours, location data, and even biometric details. Without strict privacy regulations, this data can be misused or exposed.

- **Targeted Advertising**: While often seen as harmless, extreme personalisation based on AI analysis of personal data can lead to manipulative advertising practices or even psychological targeting.
- **Surveillance**: Governments and corporations could use AI-powered surveillance systems to track citizens' movements, monitor their online activities, and analyse their behaviours without consent, leading to a chilling effect on civil liberties.
- **Data Breaches**: AI systems storing massive amounts of personal data become prime targets for cyberattacks. A breach could expose sensitive information, leading to identity theft, financial fraud, and other serious consequences.

Regulations like GDPR (General Data Protection Regulation) in Europe are pioneers in this area, giving individuals more control over their data. Future AI regulations need to expand on this, ensuring data minimisation (collecting only what's necessary), secure data storage, and strict rules around consent and data usage.

### 1.4.3 Accountability and Liability: Who's to Blame?

When an AI system causes harm, who is responsible? Is it the developer who coded the algorithm, the company that deployed it, or the user who interacted with it? This question becomes incredibly complex as AI systems become more autonomous. The following examples illustrate the case.

- **Self-Driving Car Accidents**: If an autonomous vehicle causes an accident, is it the car manufacturer, the software developer, or the owner of the vehicle who is liable for damages or injuries?
- **AI in Healthcare**: If an AI diagnostic tool provides an incorrect diagnosis that leads to adverse patient outcomes, who is accountable? The hospital, the AI vendor, or the doctor who relied on the AI's output?
- **Automated Trading Systems**: A malfunction in an AI-powered financial trading system could cause significant market disruptions or financial losses. Pinpointing responsibility in such a complex chain of events is challenging.

Regulations can establish clear frameworks for accountability, defining legal responsibilities for AI developers, deployers, and users. This can involve requiring human oversight, independent audits, and robust testing before deployment.

### 1.4.4 Job Displacement and Economic Inequality: The Automation Dilemma

As AI and automation become more sophisticated, they will inevitably impact the job market. While new jobs will be created, many existing jobs may be automated, potentially leading to widespread job displacement and exacerbating economic inequality if not managed carefully.

- **Manufacturing and Logistics**: AI-powered robots and automated systems can perform tasks historically done by human workers in factories and warehouses.
- **Customer Service**: Chatbots and AI assistants are increasingly handling customer inquiries, reducing the need for human customer service representatives.
- **Data Entry and Clerical Work**: Many administrative tasks can be automated by AI.

While regulations can't stop technological progress, they can influence its trajectory. Governments can implement policies like retraining programs, universal basic income (UBI) experiments, or incentives for companies to invest in job creation alongside automation. Regulations could also require impact assessments before large-scale AI deployments to understand potential societal effects.

### 1.4.5 Algorithmic Manipulation and Misinformation: The Echo Chamber Effect

The pervasive influence of AI algorithms, particularly those employed by social media platforms, stems from their fundamental design: to maximise user engagement. This objective, while seemingly benign, often leads to the prioritisation of content that affirms a user's pre-existing beliefs. This phenomenon, commonly referred to as the creation of "echo chambers," has profound implications for individual perception and societal discourse.

Within these algorithmic echo chambers, users are consistently exposed to information that reinforces their current viewpoints, while dissenting or alternative perspectives are systematically filtered out. This selective exposure can lead to a distorted understanding of reality, as individuals become less aware of the complexities and nuances of various issues. The constant validation of existing beliefs can also foster an increased sense of certainty and an unwillingness to engage with opposing arguments.

A significant consequence of this algorithmic design is a heightened susceptibility to misinformation and manipulation. When users are primarily exposed to content that aligns with their biases, their critical thinking skills can be dulled. They may become less adept at discerning factual information from fabricated narratives, as the content they consume consistently validates their existing worldview. This vulnerability makes individuals more susceptible to propaganda, conspiracy theories, and other forms of deceptive content, which can be strategically disseminated within these echo chambers. The long-term effects include a polarisation of opinions, a breakdown in civil discourse, and a diminished capacity for collective problem-solving.

- **Political Polarisation**: AI algorithms can reinforce existing political views by showing users only content that aligns with their ideology, leading to increased polarisation and reduced civil discourse.
- **Spread of Fake News**: Malicious actors can use AI to generate highly convincing fake news articles, images, and videos (deepfakes), which can spread rapidly and influence public opinion, elections, and even incite violence.
- **Erosion of Critical Thinking**: Constant exposure to algorithmically curated content can diminish individuals' capacity for critical thinking and discernment between fact and fiction.

Regulations could require greater transparency from platforms about how their algorithms work, impose stricter rules on content moderation, and mandate fact-checking initiatives. They could also hold platforms accountable for the spread of harmful misinformation.

### 1.4.6 Autonomous Weapons Systems: The "Killer Robots" Dilemma

One of the most alarming and ethically fraught concerns surrounding artificial intelligence is the proliferation and development of fully autonomous weapons systems. These are sophisticated AI-powered weapons, often colloquially referred to as "killer robots," designed to independently select and engage targets without human intervention or oversight in the decision-making process. The very notion of machines making life-or-death decisions raises profound moral, legal, and ethical questions, striking at the core of human dignity and accountability.

The potential implications of killer robots are vast and terrifying. In a conflict scenario, the deployment of such systems could lead to an accelerated pace of warfare, reducing the time for human deliberation and potentially escalating conflicts beyond control. There are also concerns about the potential for unintended consequences, as the AI's programming might not fully account for the complexities of real-world situations, leading to civilian casualties or misidentification of targets. Furthermore, the absence of a human in the loop blurs the lines of accountability, making it difficult to assign responsibility when errors or atrocities occur. The potential for these weapons to fall into the wrong hands, or to be used in violation of international humanitarian law, adds another layer of grave concern to an already complex issue.

The following are the main concerns in this regard.

- **Loss of Human Control**: Handing over life-and-death decisions to machines raises profound ethical and moral questions
- **Escalation of Conflict**: Autonomous weapons could accelerate conflicts and reduce the threshold for war.
- **Accountability Gap**: If an autonomous weapon commits a war crime, who is responsible? The programmer, the manufacturer, or the commander who deployed it?

Many experts and organisations are calling for AI regulation to ensure its responsible development and deployment. This is driven by a number of concerns, including the potential for job displacement, ethical dilemmas surrounding autonomous decision-making, the spread of misinformation, and privacy violations. Proponents of regulation argue that clear guidelines can foster public trust, encourage innovation within safe boundaries, and prevent a "race to the bottom" where companies prioritise speed over safety. Additionally, regulation can address issues of accountability when AI systems cause harm and ensure equitable access to the benefits of AI technologies.

## 1.5 Conclusion

The incredible potential of Artificial Intelligence is undeniable, promising advancements that can enrich our lives and solve complex global challenges. However, as this guide has outlined, the path to fully realising these benefits is fraught with significant risks if left unregulated. From the insidious spread of bias and the erosion of privacy to the complex questions of accountability and the profound ethical dilemmas posed by autonomous weapons, the perils of unchecked AI are too great to ignore.

Just as societies have historically established rules and frameworks for other transformative technologies, a comprehensive and proactive approach to AI regulation is not merely advisable but essential. Such regulations are not intended to stifle innovation, but rather to guide it responsibly, ensuring that AI development remains ethical, transparent, and aligned with human values. By setting clear standards, defining accountability, protecting fundamental rights, and mitigating societal disruptions, well-crafted AI regulations can foster public trust and pave the way for a future where AI serves humanity's best interests, rather than undermining them. The time to act is now, to ensure that the transformative power of AI is harnessed for the collective good, securing a safer and more equitable future for all.

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**About the Author**

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# Ambiguity, Redundancy, and Predictability: An Entropic View of Human Language

*by Jinsu Ann Mathew*

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In the previous articles, we explored how entropy helps quantify uncertainty in language—from the fundamental definitions in information theory to specific measures like lexical entropy, n-gram entropy, and cross-entropy in language models. Building on that foundation, we now turn to three essential characteristics of natural language: ambiguity, redundancy, and predictability.

These features often seem contradictory. Ambiguity introduces multiple meanings, which could confuse a listener. Redundancy repeats information that might appear unnecessary. Predictability makes language easier to process but potentially less informative. Yet, together, these features form a delicate balance that allows human communication to be both expressive and reliable.

Viewed through the lens of entropy, we can better understand why language behaves this way. Ambiguity reflects areas of high entropy—where multiple interpretations are possible. Redundancy works in the opposite direction, lowering entropy to make messages more robust against noise or misunderstanding. Predictability, meanwhile, allows both humans and machines to process information efficiently by reducing uncertainty in upcoming words or phrases.

This article explores how entropy provides a useful framework for analyzing these three aspects of language. We'll see how ambiguity can be measured using lexical entropy, how redundancy contributes to communication reliability, and how predictability shapes both sentence processing and model performance. Rather than treating these features as limitations, we'll understand them as essential design elements of human language—and key considerations in computational models that aim to understand or generate text.

## 2.1 Ambiguity: When One Form Has Many Meanings

Ambiguity occurs when a word, phrase, or sentence can be interpreted in more than one way. It adds uncertainty to communication and is a key contributor to higher entropy in language. There are several forms:

### Lexical ambiguity

A single word has multiple meanings.

Example: “He swung the bat.” → The word “bat” could refer to an animal (a flying mammal) or a piece of sports equipment. Without more context, it's unclear which one is meant.

### Syntactic ambiguity

A sentence allows multiple grammatical interpretations.

Example: “Visiting relatives can be annoying.” → This can mean either (1) the act of visiting relatives is annoying, or (2) the relatives who are visiting are annoying.

### Semantic ambiguity

The overall meaning is unclear even if the grammar is correct.

Example: "He saw the man with the telescope." → It's unclear whether he used a telescope to see the man, or whether the man had the telescope.

In all these cases, ambiguity increases uncertainty—and therefore entropy—because multiple interpretations are possible. However, in real communication, context usually helps resolve the intended meaning. For example, in "The bat flew across the cave," the context makes it clear that "bat" refers to the animal.

In computational linguistics, this kind of uncertainty is often measured using lexical entropy. Words that are used evenly across multiple senses tend to have higher entropy, indicating greater ambiguity. Systems like search engines or translation tools must estimate the most likely meaning based on surrounding words.

## 2.2 Redundancy: Saying More to Ensure Understanding

Redundancy in language refers to the inclusion of extra information that may not be strictly necessary to convey the core message, but helps make communication more clear, reliable, and error-resistant. From an information theory perspective, redundancy works by reducing entropy—it makes language more predictable and easier to process, especially when there's a chance of miscommunication.

While redundancy might seem wasteful, it's actually a key feature of natural language. It helps listeners understand a message even when parts of it are unclear, misheard, or missing. This is particularly useful in noisy environments, fast speech, or casual conversation.

Consider this sentence:

"I saw it with my own eyes." → The phrase "with my own eyes" is technically unnecessary—"I saw it" already conveys the full meaning. But the repetition serves to emphasize the speaker's certainty and make the message more forceful and clear. If the sentence were spoken in a noisy room, the added redundancy also increases the chance that the core meaning is still understood.

Another example:

"The reason he left is because he was tired." → This sentence contains overlapping phrases: "the reason" and "because" both express causality. One could be removed without changing the basic meaning, but including both makes the structure more familiar and easier to follow.

Redundancy is a natural strategy for error correction in human communication. Just like in digital systems, where repeated signals can help correct transmission errors, redundant elements in language help listeners recover meaning when the input is incomplete or distorted.

In short, redundancy may reduce efficiency, but it improves clarity, emphasis, and robustness—qualities that are essential in real-world communication.

## 2.3 Predictability: Anticipating What Comes Next

Predictability in language refers to how easily a listener or reader can guess what word or phrase is likely to come next. It plays a central role in how we process and understand language in real time. When a sentence follows familiar patterns or uses common phrases, it becomes more predictable and easier to comprehend.

From an information theory perspective, predictability is closely related to low entropy. The more predictable a word is in its context, the lower its entropy. This means the listener needs less effort to understand it, since it causes less surprise.

For example:

"She drank a cup of..."

→ Most people would expect the next word to be something like "tea" or "coffee." These are high-probability continuations in everyday language, so they are highly predictable and carry less information. If the sentence ended with "vinegar" instead, it would be unexpected, and therefore more informative—but also more surprising.

Predictability is not just a linguistic curiosity—it's central to how our brains handle language. Studies in psycholinguistics show that people read predictable words faster, fixate on them for less time, and remember them differently. Our minds are constantly generating expectations based on what we've heard or read so far.

Language models work in a similar way. They calculate the probability of each possible next word and use that to generate fluent sentences. The more predictable a word is in its context, the higher its probability—and the lower its contribution to the model's calculated entropy.

In practice, predictability helps make communication efficient and smooth. Speakers can rely on shared knowledge and familiar structures, while listeners use context to fill in gaps. This makes language faster to process and easier to follow, especially in everyday conversation.

## 2.4 Striking the Balance: Why Language Needs All Three

Language is not designed to eliminate entropy—but to manage it intelligently. Ambiguity, redundancy, and predictability each affect the level of entropy in different ways, and the effectiveness of language lies in how it balances these forces rather than avoiding them entirely.

### Ambiguity increases entropy—on purpose

Ambiguity introduces uncertainty into a message, raising entropy. A word with multiple meanings or a sentence open to multiple interpretations can make communication less certain on the surface. But this isn't a flaw—it's a feature. Ambiguity makes language compact and flexible, allowing us to reuse words and structures in different contexts. It enables metaphor, humor, creativity, and even politeness.Without ambiguity, language would be rigid and unnecessarily long. But without limits, it would become unintelligible.

### Redundancy reduces entropy—strategically

Redundancy helps bring entropy down by repeating or reinforcing information. This makes messages more robust and recoverable, especially in noisy or uncertain environments. From a communication theory standpoint, redundancy serves as a buffer against loss: even if part of the signal is lost, the message can still be understood. Redundancy lowers entropy—but at the cost of efficiency. So language uses it selectively, where precision and clarity matter most.

### Predictability controls entropy—efficiently

Predictable patterns in language reduce entropy by making it easier to anticipate the next word or structure. This speeds up processing and lightens the cognitive load. Language relies on familiar phrases, grammar rules, and contextual cues so that not every word needs to be consciously analyzed. High predictability means low entropy—but too much predictability makes language dull or repetitive.

### The Real Power: Balancing Entropy, Not Erasing It

The genius of human language is in how it balances entropy, rather than trying to minimize or maximize it outright.

A poem may allow more ambiguity (higher entropy) for emotional or aesthetic depth.

A legal document may use redundancy (lower entropy) to avoid misinterpretation.

Everyday conversation often favors predictability to enable fast and fluent exchange.

Natural language operates in this sweet spot—not too chaotic, not too rigid. It allows just enough entropy to be expressive, but controls it through redundancy and predictability to remain clear and usable.

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**About the Author**

Jinsu Ann Mathew is a research scholar in Natural Language Processing and Chemical Informatics. Her interests include applying basic scientific research on computational linguistics, practical applications of human language technology, and interdisciplinary work in computational physics.

# Part II

# Astronomy and Astrophysics

# Black Hole Stories-20
# The LIGO Gravitational Wave Detectors

*by Ajit Kembhavi*

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In this story we will describe the LIGO gravitational wave detectors, which are based on the principle of the Michaelson interferometer.

## 1.1 A Simple Gravitational Wave Detector

We have seen in BHS-19 how the concept of a Michaelson interferometer provides a way to detect gravitational waves. We reproduce here, for convenience, the corresponding figure.

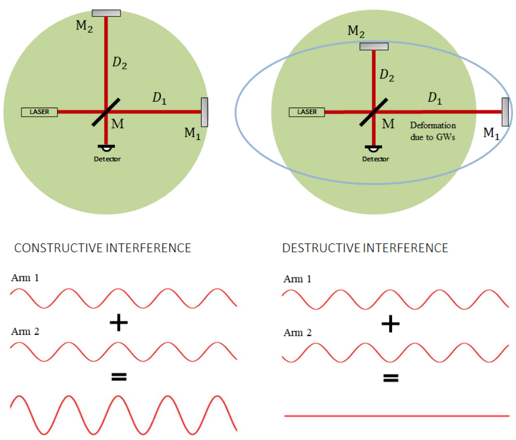



**Figure 1:** A schematic representation of a Michaelson interferometer for detecting gravitational waves.

Credit: Kaushal Sharma and Ajith Parameswaran.

The functioning of the interferometer has been described in BHS-19. To summarise, half of a laser beam reaching the semi-reflecting mirror M passes through to mirror M1, while the other half is reflected to mirror M2. The returning beams meet at the detector. The distances D1 and D2 are equal, so the beams, which start from a single source, reach the detector in phase and combine to produce a bright spot at the centre of the detector. Now suppose a gravitational wave passes through the circle of particles, so that it is stretched to form an ellipse as shown on the right of the figure. The mirror M1 is now farther from M than it was in the absence of the wave, while M2 has moved closer to M, so D2 is greater than D1. The distances travelled by the two beams are therefore different and for a certain difference in the path length, equal to an odd integral multiple of half the wavelength of the laser, the interference is destructive and a dark spot is seen. As the mirrors move back and forth the interference changes periodically, which can be detected by the changing intensity of the spot. The changing interference becomes a signature of the passage of a gravitational wave. The idea is schematically represented in the lower half of Fig. 1.

## 1.2 Laser Interferometric Detectors

These are based on the principle of the Michelson interferometer described above. To be able to detect the very weak gravitational waves reaching the Earth from distant cosmic events, the detectors have very long arm lengths. The present detectors of this type are (1) the detectors near Livingston, Louisiana and near Hanford, Washington State, which are both part of LIGO, the Laser Interferometric Gravitational Wave Observatory – each with 4 km long arms; (2) the VIRGO detector near Pisa with 3 km arms; (3) the GEO600 detector near Hanover with 600 m arms and (4) the KAGRA underground detector at Kamioka in Japan with 3 km long arms. The detectors undergo periodic upgrades in technology to make them more sensitive. The current version of the LIGO detector is known as Advanced-LIGO (aLIGO), and the following description pertains to this version of the detector.

Translating from laboratory scale interferometers to the LIGO scale with each arm being 4 km long is obviously rather difficult. The difficulty is greatly compounded by the accuracy that is required for the detection of gravitational waves. In the laboratory, an interferometer is used, for example, to measure the wavelength of light. This requires an accuracy of about $10^{-12}$ m in very precise measurements. But the displacement caused by a gravitational wave in the LIGO mirrors can be as small as $10^{-19}$ m, which is about $\frac{1}{8500}$ of the radius of a proton. This extremely small displacement has to be observed against a background of much larger displacements caused by various effects.

The required sensitivity is reached by adapting a series of technical innovations designed to eliminate or minimise spurious vibrations, which we can term as noise. Some of the measures are (1) using a powerful laser as the source of the light beams; (2) using extra mirrors to increase the intensity of light and the distance traversed by the beam through repeated reflections; (3) placing the entire interferometer in a high vacuum enclosure and (4) using very sophisticated suspensions for holding the mirrors. The details that we describe below are for aLIGO, but similar systems are used in the other detectors.

## 1.3 The Advanced LIGO Detector

Michaelson interferometers originally used conventional light at optical wavelengths, whereas gravitational wave detectors use lasers. The laser provides a very intense, steady and non-diverging beam of light at a precisely determined wavelength. The complex laser device used in the aLIGO detector produces a laser beam at a wavelength of 1064 nm, with output power of 200 Watts. It is one of the most steady and powerful lasers operating at the chosen wavelength, which is in the near-infrared part of the spectrum. The laser is stabilised to a level of one part in ten billion in intensity and one part in a billion in frequency. The power produced by the laser needs further great amplification to serve the needs of the detector, which is achieved by recycling the beam between mirrors designed for the purpose. The power finally achieved is about 750 kilo Watts.

The length of each arm of LIGO, from the beam splitter to the reflecting mirror at the end of the arm is 4 km. The longer this length, the higher is the sensitivity of the detector. A much longer length is effectively achieved by placing an additional mirror, called a signal recycling mirror, in each arm exactly 4 km from the mirror at the end of the arm. The 4 km long space is known as a Fabry-Perot cavity. The beam in each cavity is reflected back and forth about 300 times, effectively increasing the arm length to about 1200 km, and also increasing the light intensity in the arms, which helps in reducing noise.

The arrangement of the optics is such that when the arm lengths are equal, a dark spot is produced at the detector. As the arm lengths change, the interference changes, and the spot gets brighter. Conventionally, equal arm lengths would lead to constructive interference and a bright spot would be seen at the detector. But in the LIGO interferometer, a dark spot is chosen by adjusting the optics, because it is easier to judge the brightening of a dark spot, rather than the dimming of a bright spot. A schematic of the aLIGO interferometer is shown in Figure 2. The functions of the various mirrors are indicated in the figure. The arrangement in the real interferometer is far more complex, of course.

The mirrors in the LIGO interferometer are used to set the beam paths as described above, but they also have another crucial function: they act as free particles which respond to the passage of a gravitational wave. We have seen in BHS-19 how a circle of free particles oscillates between circular and elliptical forms as a gravitational wave passes through. In the gravitational wave interferometer, the two mirrors at the end of the beam paths (M1 and M2 in Figure 1, and marked as end mirrors in Figure 2) can be considered to be two

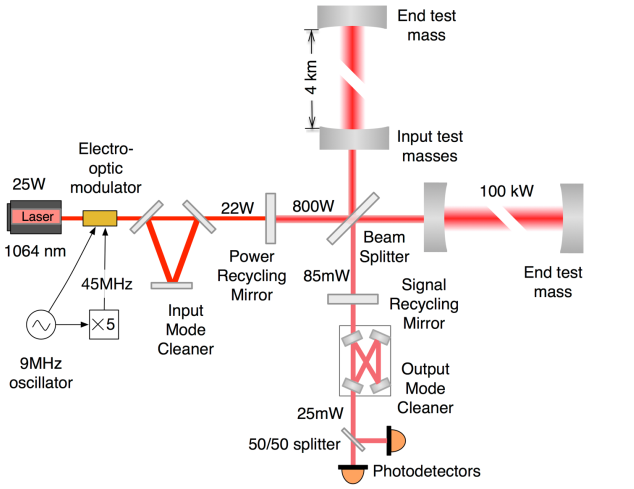



**Figure 2:** A schematic diagram of the Advanced LIGO interferometer.

Image Credit: D.V. Martynov et al. Phys.Rev.D 93, 112004, 2016.

free particles on a circle. The distance of these mirrors from the centre is equal, but becomes different as a gravitational wave passes through. For this to happen, the mirrors are to be free, in the sense that no net force, other than the gravitational force produced by the wave are acting on them. If such forces exist, they would dominate the extremely tiny effect produced. The mirrors are suspended from above, so that in the vertical direction the downwards gravitational force of the Earth is balanced by the upwards tension in the suspension. The mirrors can move freely in the horizontal direction and the effect of a gravitational wave would be to change the horizontal distances.

It is necessary to minimise the effects of any other forces which would result in the unwanted horizontal movement of the mirrors, which is considered to be noise, since it can conceal the tiny effect due to gravitational waves. That requires advanced mirror isolation technology, which has evolved over the years. In spite of the advanced technology used for noise reduction, there is residual noise which can cause small displacements in the mirror. There is seismic noise due to ground vibrations or seismic disturbance caused by human activities, winds, tidal motions in the ground caused by the Sun and the Moon similar to tides in the oceans, and ocean waves which can cause disturbance even when the coastline is far away. Disturbances can also be caused due to slight heating by the laser beams of the mirrors and their suspensions and mechanical loss of the reflective coatings of the mirrors. This affects the random motion of the particles in them, leading to thermal noise. The effect of these sources of noise on the sensitivity of the aLIGO detector has to be taken into account.

The mirrors which constitute the free particles have a diametre of 34 cm, thickness 20 cm and weigh 40 kg each, the large mass helping to hold them still. They are made of extremely pure and homogeneous fused silica. The mirrors have very precisely defined shapes which are accurate to better than $10^{-12}$ m, which is far greater precision than is required for mirrors used in large optical telescopes. The surfaces of the mirrors are so highly reflective that they absorb only about one out of 2.3 million photons which reach the mirrors. Any absorbed photons lead to heating of the mirror. Due to the very high intensity of the light, in spite of the small absorption, the heat produced is sufficient to produce a slight distortion of the mirror surface. To avoid that, a system is used, which monitors the shape of the surface and makes the necessary corrections.

The entire LIGO interferometer is operated in a high vacuum. The laser beams pass through two steel tubes each of which is 4 km long and the mirrors are enclosed by end stations. The whole evacuated assembly has a volume of about 10 million litres. The only bigger evacuated volume than LIGO is the Large Hadron Collider in CERN in Switzerland, which was used to discover the Higgs Boson. The vacuum is so good that the pressure of the residual gases in the volume is only a trillionth of the air pressure at sea level. The high vacuum is required for various reasons. The molecules of air are in incessant motion due to their heat energy. The molecules collide with the mirrors to produce tiny motions in them. If the pressure is not low enough, the jitter produced in the mirrors would produce noise at an unacceptable level. When light propagates through air, its direction of travel can be slightly altered depending on the density of the air. There are always small disturbances in air which can cause the beam to randomly deviate from its straight path, which changes slightly the length travelled by the beam, adversely affecting the interference pattern. The air can contain dust particles which scatter the beam

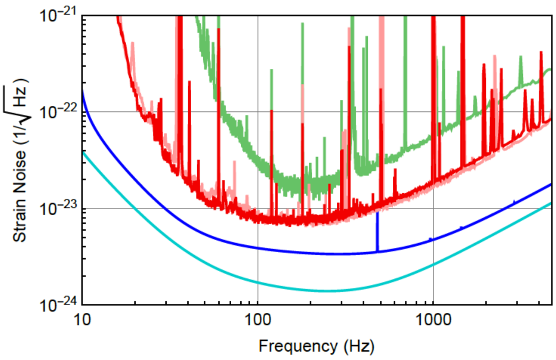



**Figure 3:** The sensitivity of the aLIGO detectors as function of frequency. See text for a description of the figure.

Image Credit; B. P. Abbott et al. Phys. Rev. Letters 116, 131103, 2016.

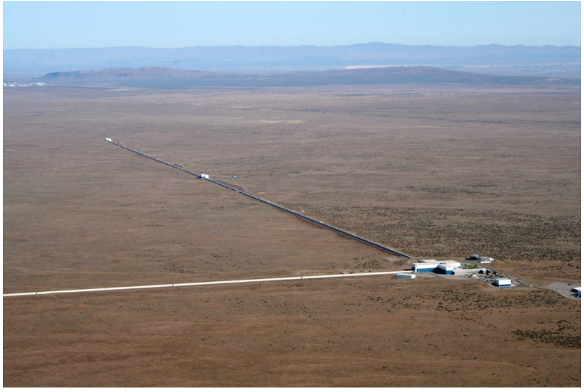


**Figure 4:** The LIGO observatory in Hanford, Washington State, USA. The two 4 km long arms are seen. The central part of the detector is in the buildings at the intersection of the two arms.

from its straight line path. These effects are all very small and would not matter at all in other situations. But because of the very small changes produced by gravitational waves the effects can become important in comparison. The very high vacuum is needed to reduce such effects to an acceptable level.

The sensitivity of the aLIGO detector to gravitational waves and to noise in the system as a function of the gravitational wave frequency is shown in Fig. 3. The frequency at which the measurement is made is shown on the horizontal axis, while a quantity known as the strain noise is shown on the vertical axis. This quantity is indicative of the ratio of the net displacement produced in the two arms to the total distance traversed by the beam in the multiple reflections discussed above. The curve in dark red shows the strain noise for the aLIGO detector at Hanford during the first observing run O1 in 2015 during which the first detection of a gravitational wave source was made by aLIGO. The detection will be described in the next story. The curve in light red is for the detector at Livingston. The near coincidence of the two curves shows that the sensitivity of the two detectors has nearly the same dependence on the frequency.

The green curve shows the sensitivity of an earlier version of the LIGO detector, while the blue and cyan curves are the planned sensitivities of future versions of the detector. A gravitational wave source can be detected by aLIGO only if the strain produced by the source is above the curves. How much confidence we can place in the detection depends upon how much above the curve the source is located. Therefore, the lower a curve is on the diagram, the better the detector would be for observing faint sources. Using this criterion, it is seen that the aLIGO detectors are most sensitive in the frequency range of 100-300 Hz. The strong lines at various points along the red and green curves are due to specific contributions to the noise from the suspensions, from AC power lines and due to signals injected for calibration purposes. The lines are accounted for in the analysis of the data.

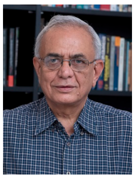
An aerial view of the LIGO facility at Hanford in Washington State and a close-up of its Northern arm are shown in Figure 4. The LIGO-India facility, to be completed over the next several years, will be similar in nature.

Further detail about the LIGO detectors and observatory, and LIGO-India, can be found in the book Gravitational Waves – A New Window to the Universe, by Ajit Kembhavi & Pushpa Khare, Springer 2020.

In the next few stories we will describe some of the gravitational wave sources detected by LIGO, all but one of which were black hole binaries which merged together to form a single black hole. The one exception was a neutron star binary which again merged to form a black hole.

I thank Dr. Joe Jacob for careful reading of the story and suggesting corrections.

**About the Author**

 Professor Ajit Kembhavi is an emeritus Professor at Inter University Centre for Astronomy and Astrophysics and is also the Principal Investigator of the Pune Knowledge Cluster. He was the former director of Inter University Centre for Astronomy and Astrophysics (IUCAA), Pune, and the International Astronomical Union vice president. In collaboration with IUCAA, he pioneered astronomy outreach activities from the late 80s to promote astronomy research in Indian universities.

# Is Every Crash a Firework? Observing Starbursts in Interacting Galaxies

*by Robin Thomas*

AIRIS4D, VOL.3, NO.8, 2025

www.airis4d.com

## 2.1 Introduction: Galaxies in Motion

Galaxies evolve within a constantly changing gravitational landscape. When two massive galaxies pass sufficiently close to one another, mutual tidal forces torque their stellar disks and, more importantly, redistribute their gaseous reservoirs. Such interactions can channel gas toward galactic centres, ignite nuclear starbursts, or expel material into tidal bridges and tails where it may cool and condense into off-disk star-forming regions. However, observational surveys and simulations increasingly demonstrate that the outcome is not uniform: while some encounters trigger dramatic, system-wide increases in star formation, others lead to only modest enhancements—or even temporary suppression—depending on encounter geometry, gas fraction, orbital parameters, and, critically, the mass ratio of the pair. Our study was designed to quantify this diversity by examining both the local (kiloparsec-scale) and global (galaxy-integrated) star-formation response in a small but well-characterised sample of nearby interacting systems.

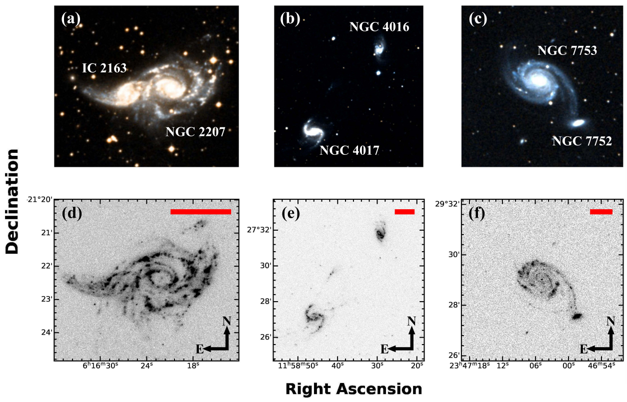



**Figure 1:** Colour composite images from the HiPS survey and corresponding UVIT image for the sample of galaxies are shown in the top and bottom panels, respectively. The galaxy pairs in our sample are labelled in panels (a), (b) and (c). The emission in FUV1 for NGC 2207/IC 2163 and NGC 4016/4107 and in FUV2 for NGC 7752/7753 are shown in panels (d), (e) and (f), respectively. The red bars in the bottom panels represent an extent of 20 kpc at the distance to the galaxy pairs. The foreground stars in the FOV were confirmed and removed using *Gaia* DR3 catalogue (Gaia Collaboration et al., 2021).

To explore how different dynamical configurations influence star formation, we targeted three nearby, nearly face-on interacting pairs: NGC 2207/IC 2163, NGC 4017/4016 (ARP 305), and NGC 7753/7752 (ARP 86). These systems span a range of interaction stages and morphologies—from near-grazing encounters with pronounced ocular features to bridge–satellite configurations—allowing us to isolate the role of geometry and timing. Their proximity permits high spatial resolution in the ultraviolet (UV), enabling us to resolve individual star-forming clumps and compare them directly with the underlying gas distribution traced by neutral hydrogen (HI). By studying different "snapshots" of the interaction sequence, we can extract trends that would be obscured in a heterogeneous, poorly resolved sample.

## 2.2 Observing in Two Languages: Ultraviolet and Radio

Young, massive stellar populations emit strongly in the far- and near-ultraviolet, making UV imaging an excellent proxy for recent ($\lesssim$100 Myr) star formation. We exploited AstroSat/UVIT's sub-arcsecond point spread function (~ 1.2 – 1.4") to isolate discrete star-forming knots across disks, bridges, and tidal debris. After standard CCDLAB reduction and photometric calibration using established zero-points, we derived star formation rates (SFRs) and surface densities ($\Sigma_{\rm SFR}$) for each knot. To map the fuel reservoir and dynamical response of the gas, we combined these UV maps with archival or newly reduced HI 21-cm data from the VLA and GMRT. Neutral hydrogen is both spatially extended and dynamically sensitive to tidal perturbations; thus, its column-density distribution provides a direct measure of where gas has been compressed or displaced. The juxtaposition of UV and HI maps therefore reveals not only where stars are forming, but also how efficiently the disturbed gas is being converted into stars.

## 2.3 Trends in the local star formation

### 2.3.1 NGC 2207/IC 2163: Triggered Star Formation and a New TDG Candidate

In NGC 2207/IC 2163, the UVIT data reveal a broad range of $\Sigma_{\rm SFR}$ values (roughly $10^{-3}$ - $10^{-2} \rm M_{\odot} yr^{-1} kpc^{-2}$) distributed both along the primary interaction interface and on the far side of the main disk, indicating that tidal perturbations propagate across the system rather than being confined to the direct overlap region. A particularly notable result is the **first detection** of ongoing star formation within the northwestern gas complex *N2207-NW1*. Its coincident HI column density and systemic velocity make it a **strong candidate for a tidal dwarf galaxy** (TDG), a self-gravitating system formed from tidally stripped, chemically enriched gas rather than from primordial collapse. This detection underscores the capacity of interactions not merely to rearrange existing stellar material, but to seed the formation of entirely new galactic entities in debris fields.

### 2.3.2 ARP 305 (NGC 4017/4016): Distributed, Moderate Enhancement

The ARP 305 system exhibits widespread but moderate star formation spread over spiral arms, tidal debris, and bridges. The spatial distribution suggests a significant prior pericentric passage that stirred the gas on large scales yet did not funnel it into a single dominant nuclear starburst. Instead, the interaction appears to have created numerous local pockets of compression suitable for star formation. This pattern is consistent with scenarios in which the strongest tidal torques have subsided, leaving behind a "fossil record" of triggered clumps that continue to form stars as long as sufficient gas remains locally unstable.

### 2.3.3 ARP 86 (NGC 7753/7752): A Gas-Rich Satellite and Another Debris-Born Candidate

In ARP 86, the smaller companion NGC 7752 is exceptionally gas-rich, with an HI-to-total mass fraction around 0.17, which is substantially higher than typical values reported for classical starbursts. UV imaging shows moderate to high $\Sigma_{\rm SFR}$ within the satellite, whereas the main galaxy and connecting bridge exhibit more modest levels. Embedded within an HI bridge of column density exceeding $10^{21} \rm cm^{-2}$ lies *2MASXJ23470758+2926531*, which also hosts detectable star formation. Its location and properties make it another compelling TDG candidate. Collectively, these findings illustrate how tidal bridges can serve as nurseries for new dwarf systems, provided that the displaced gas remains sufficiently dense and self-gravitating.

The identification of active star formation in debris-bound condensations such as *N2207-NW1* and *2MASXJ23470758+2926531* strengthens the evidence that interactions can spawn long-lived, self-gravitating tidal dwarf galaxies. TDGs inherit chemically enriched gas from their progenitors. Their prevalence has implications for the metallicity distribution in group environments and the census of dwarf populations

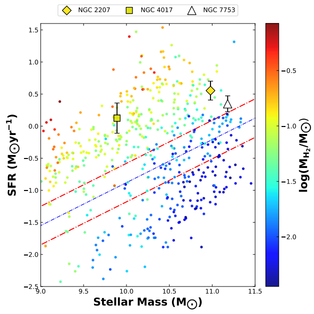



**Figure 2:** The SFMS of galaxies is presented. Circles represent the xCOLD GASS sample (Saintonge et al., 2017), color mapped to represent the molecular gas fraction in them. The main sequence obtained from Dave (2008) is represented by blue dotted lines, with the red dotted line representing 0.3 dex scatter. Our sample of main galaxies are also color mapped to represent the gas fraction. Due to the absence of relevant estimations of molecular gas mass in NGC 7753, its molecular gas fraction is not represented. We observe an enhancement in the global SFR in our sample of main galaxies.

in the nearby universe. By identifying ongoing star formation in these structures, our work adds to the growing recognition that galaxy interactions can both dismantle and create galaxies in the same event.

## 2.4 Global Context: Placement on the Star-Forming Main Sequence

To assess the global impact of these interactions, we located each primary galaxy on the star-forming main sequence (SFMS), the empirical SFR–$M_\odot$ relation for star-forming disks. Using literature stellar masses and SFRs from xCOLDGASS (Saintonge et al., 2017), we find that all three main galaxies lie above the canonical SFMS (e.g., Dave (2008)), indicating statistically significant but moderate enhancements in their integrated SFRs relative to isolated counterparts. Such moderate offsets are increasingly recognised as characteristic of many interacting systems, highlighting the need to move beyond a binary "starburst vs. quiescent" framework when interpreting galaxy-galaxy encounters.

To quantify the physical parameters that might govern the observed enhancement, we study the star formation enhancement as functions of stellar pair mass ratio and pair separations.

### 2.4.1 Pair mass ratio as a metric

By quantifying SFR enhancement as the ratio of each galaxy's SFR to that of a mass, morphology and distance matched control sample, we isolate the effect of interaction parameters. A clear inverse correlation emerges between enhancement and pair mass ratio: encounters between near-equal-mass galaxies maximise tidal torques and gas inflows, whereas highly unequal pairs often generate only weak responses in the more massive member. This empirical result corroborates hydrodynamic simulations (e.g., Cox et al., 2008; Hani et al., 2020), which predict that mass symmetry enhances dissipation and central gas accumulation. Consequently, mass ratio should be treated as a first-order predictor when estimating the star-forming impact of a given interaction.

### 2.4.2 Pair separation as a limiting parameter

In contrast, projected pair separation shows no statistically significant linear correlation with SFR enhancement (Pearson $r \approx 0.05$) across our systems and in the larger comparison sample. While there is an obvious physical limit—galaxies too widely separated cannot tidally influence one another—the absence of a tight trend within interacting pairs implies that separation alone cannot predict the magnitude of the response. Projection effects, differing orbital phases, encounter velocities, and time lags between gas compression and observable star formation all contribute to the scatter. Thus, separation should be interpreted as a contextual parameter, not a deterministic one.

## 2.5 Limitation of the study

Several caveats accompany our analysis. Projected separations may underestimate true three-dimensional distances, diluting any intrinsic trends with tidal strength. UV-based SFRs are sensitive to dust attenuation and recent star-formation histories. Even though the UV fluxes were accounted for extinction,

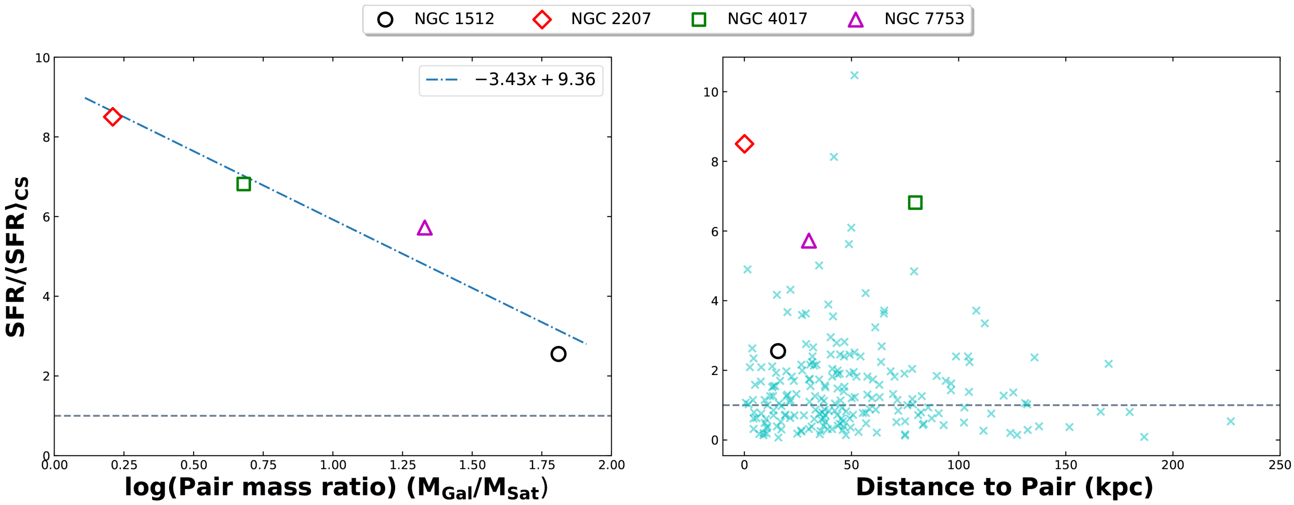



**Figure 3:** (Left) SFR enhancement studied as a function of the pair mass ratios. We find an inverse correlation between the SFR enhancement and mass ratios. (Right) SFR enhancement was studied as a function of the pair separation. Star formation enhancement for interacting galaxies from Knapen et al. (2015) are also plotted as a function of pair separation. We find an absence of correlation, with a Pearson coefficient of 0.05.

residual uncertainties can remain without full spectral energy distribution fitting. Finally, although our three systems are illustrative, they cannot capture the full diversity of interaction outcomes—hence the necessity of the larger statistical cross-check.

## 2.6 Future scope

A natural next step is to couple our observational constraints with tailored N-body/hydrodynamical simulations that recover each system's orbital history and gas inflow patterns. High-resolution CO mapping with ALMA or NOEMA would directly link dense molecular gas to the UV-bright knots, clarifying the efficiency of the $HI - H_2$ conversion into stars disturbed environments. Integral-field spectroscopy can disentangle photoionization from shock excitation in extraplanar regions and bridges, providing a more complete diagnostic of the physical processes at work. Finally, deeper, wider-field UV and radio observations will reveal fainter tidal structures and nascent TDGs, enabling a more complete census of interaction-induced substructure.

## 2.7 Conclusion

Galaxy–galaxy interactions influence the morphology, gas dynamics and star formation properties, all of which depend sensitively on the physical context of each encounter. In the three nearby pairs examined here, we find that tidal forces redistribute gas and ignite patchy, kiloparsec-scale bursts of star formation across disks, bridges, and debris, while the galaxies' integrated SFR rise only moderately above the star-forming main sequence.

Among the parameters we probed, the stellar mass ratio emerges as the most predictive lever: encounters between near-equal-mass partners yield stronger tidal torques, deeper gas inflows, and larger SFR enhancements than highly unequal pairs. By contrast, present-day projected separation shows no tight correlation with enhancement, underscoring that proximity alone is a blunt proxy once a system is already interacting. These empirical trends corroborate hydrodynamic simulations and argue for including mass symmetry, orbital geometry, and gas fraction as first-order inputs in models of interaction-triggered activity.

Taken together, these results advocate for a multi-scale, multi-phase approach to interaction studies. Future work that combines tailored simulations with molecular gas and integral-field spectroscopy will be essential to reconstruct the dynamical histories of such systems and to quantify, with greater physical fidelity, how often and how efficiently interactions reshape the star-forming lives of galaxies.

**Correspondence:** robinthomas546@gmail.com
**Reference:** Thomas et al. (2024), *MNRAS*, 534, 1902
**Data Sources:** AstroSat UVIT; VLA; uGMRT

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Dr Robin is currently a Project Scientist at the Indian Institute of Technology Kanpur. He completed his PhD in astrophysics at CHRIST University, Bangalore, with a focus on the evolution of galaxies. With a background in both observational and simulation-based astronomy, he brings a multidisciplinary approach to his research. He has been a core member of CosmicVarta, a science communication platform led by PhD scholars, since its inception. Through this initiative, he has actively contributed to making astronomy research accessible to the general public.

# Understanding the Johnson Magnitude System in Astronomy

*by Sindhu G*

airis4D, Vol.3, No.8, 2025

www.airis4d.com

## 3.1 Introduction

In the field of observational astronomy, the precise measurement of stellar brightness is fundamental to our understanding of the universe. From determining stellar distances and compositions to studying the evolution of galaxies, photometric measurements underpin nearly every branch of astrophysical research. Over the years, various magnitude systems have been developed to quantify the brightness of stars and other celestial objects. Among these, the Johnson-Morgan photometric system, more commonly referred to as the Johnson system, stands as one of the most influential and widely adopted standards.

Developed in the early 1950s by Harold Lester Johnson and William Wilson Morgan, the Johnson system was the first comprehensive photoelectric photometric system. It replaced older visual methods with more accurate and reproducible measurements across well-defined filter bands. The system standardized the use of color indices and helped lay the groundwork for modern multi-band photometric surveys. Even today, many modern photometric systems are calibrated using Johnson's original UBV filters or derived from them.

## 3.2 The Historical Background and Evolution

The concept of stellar magnitude dates back to antiquity, when Greek astronomer Hipparchus introduced a six-magnitude scale to classify the brightness of visible stars. This logarithmic idea was formalized in the 19th century when Norman Pogson defined a first magnitude star as 100 times brighter than a sixth magnitude star. However, this classification was based on visual observation and lacked instrumental precision.

With the advent of photoelectric photometry in the early 20th century, astronomers gained tools to measure brightness with unprecedented accuracy. It was in this context that Harold Johnson and William Morgan developed the UBV photometric system. In 1953, they published a landmark paper introducing a system based on three filters — U (ultraviolet), B (blue), and V (visual) — centered around specific wavelength bands. This was soon extended to include R (red) and I (infrared) filters.

The Johnson system offered a major advancement in standardizing observations between observatories, enabling large-scale comparison of stellar properties. For the first time, astronomers had a reproducible and calibrated method for measuring and comparing stellar magnitudes across different wavelength regions.

## 3.3 Structure of the Johnson Photometric System

The original Johnson system is characterized by a set of broadband filters with well-defined wavelength ranges. These filters are designed to correspond to different parts of the electromagnetic spectrum, capturing the continuum light of stars rather than individual spectral lines. The most commonly used filters include:

| Filter | Name | Central $\lambda$ (nm) | Bandwidth (nm) |
|---|---|---|---|
| U | Ultraviolet | ~360 | ~60 |
| B | Blue | ~440 | ~100 |
| V | Visual (Green) | ~550 | ~90 |
| R | Red | ~700 | ~150 |
| I | Infrared | ~900 | ~150 |

**Table 3.1:** Broadband filters in the Johnson photometric system.

The UBV system was the earliest and remains the most frequently cited. The color indices derived from this system, such as $(B - V)$ and $(U - B)$, provide valuable information about the temperature, reddening, and spectral classification of stars.

- **(B–V) Index:** A measure of the star's temperature; hotter stars are bluer and have lower $(B - V)$ values.
- **(U–B) Index:** Sensitive to both temperature and interstellar reddening.

These indices are differential magnitudes, calculated by subtracting the magnitudes measured in two filters:

$$(B - V) = m_B - m_V \tag{3.1}$$

where $m_B$ and $m_V$ are the magnitudes in the B and V bands, respectively.

## 3.4 Applications of Johnson Magnitudes in Astrophysics

### 3.4.1 Stellar Classification and Temperature Determination

The Johnson system plays a critical role in spectral classification of stars. The (B–V) color index is directly correlated with the effective temperature of a star. This relationship enables astronomers to classify stars along the Hertzsprung–Russell diagram, distinguishing between main-sequence stars, giants, and white dwarfs.

For example:

- O-type stars (very hot): $(B - V) \approx -0.3$
- Sun-like stars (G-type): $(B - V) \approx 0.65$
- Cool red stars (M-type): $(B - V) > 1.5$

### 3.4.2 Extinction and Reddening Studies

Starlight traveling through interstellar dust is absorbed and scattered, causing interstellar extinction and a phenomenon known as reddening. Since dust affects shorter wavelengths more strongly, blue light is absorbed more than red light, making stars appear redder than they are.

By comparing observed color indices with intrinsic (theoretical or known) indices, astronomers can estimate the amount of dust between the star and Earth. The color excess $E(B - V)$ is calculated as:

$$E(B - V) = (B - V)_{observed} - (B - V)_{\text{intrinsic}} \tag{3.2}$$

This value helps derive the visual extinction $A_V$, often using:

$$A_V = R_V \cdot E(B - V) \tag{3.3}$$

with $R_V \approx 3.1$ for the Milky Way.

### 3.4.3 Distance Measurements

Johnson magnitudes also support the determination of distances through the distance modulus:

$$m - M = 5 \log_{10}(d) - 5 + A_V \tag{3.4}$$

where:

- $m$ = apparent V magnitude
- $M$ = absolute V magnitude
- $d$ = distance in parsecs
- $A_V$ = extinction in the V band

Thus, photometry in the Johnson system allows astronomers to estimate distances to stars and stellar clusters, provided extinction and intrinsic luminosity are known.

### 3.4.4 Color–Magnitude Diagrams (CMDs)

Color–Magnitude Diagrams (CMDs) are essential tools in stellar population studies. Plotting the $V$ magnitude against the $(B - V)$ color, for example, reveals the distribution of stars by brightness and temperature. These diagrams are used to study:

- Open and globular clusters,
- Star formation history, and
- Stellar evolution stages.

Because of the Johnson system's widespread adoption, a vast library of CMDs exists throughout the literature for objects across the Galaxy and the Local Group.

## 3.5 Comparison with Other Photometric Systems

While the Johnson system was foundational, newer photometric systems have been developed to suit specific instruments and scientific objectives. Notable examples include:

- **Cousins System (RI)**: Modified the redder filters ($R$ and $I$) to better match CCD detector response.
- **Strömgren System**: Utilizes narrow-band filters for high-precision determination of stellar parameters such as temperature, gravity, and metallicity.
- **Sloan Digital Sky Survey (SDSS)**: Employs five filters ($u$, $g$, $r$, $i$, $z$) optimized for modern CCDs and large-area sky surveys.

Despite these advancements, the Johnson system remains highly relevant. Many space- and ground-based observations still rely on transformations between modern photometric systems and Johnson UBVRI magnitudes to maintain consistency and comparability with historical datasets.

## 3.6 Limitations and Calibration Challenges

Despite its strengths, the Johnson system has several limitations:

- **Filter Variability**: Different observatories may use slightly different filter transmission curves, introducing systematic errors in the measured magnitudes.
- **CCD Incompatibility**: Originally designed for photoelectric photometers, Johnson filters are not ideally matched to the spectral response of modern CCD detectors.
- **Atmospheric Dependence**: UV measurements, particularly in the $U$ band, are highly sensitive to atmospheric extinction and therefore require careful calibration.

To mitigate these issues, astronomers have developed transformation equations and networks of secondary standard stars to cross-calibrate data obtained from different instruments and photometric systems.

## 3.7 Legacy and Continuing Use

The Johnson photometric system's legacy is visible in almost every corner of stellar astrophysics. Its color indices are still quoted in the latest catalogues, from GAIA to 2MASS, and its filters remain a reference point for calibration.

Moreover, the system provides a historical link between older observations and modern surveys. Many photometric databases, such as Simbad, Vizier, and AAVSO, list Johnson magnitudes as baseline photometric data.

In education, the Johnson system is often the first photometric system taught to students because of its clarity, simplicity, and central role in stellar astrophysics.

## 3.8 Conclusion

The development of the Johnson magnitude system represented a transformative moment in astronomical measurement. By providing a standardized, repeatable method for quantifying stellar brightness across multiple wavelengths, Johnson and Morgan ushered in a new era of precision photometry. The system's influence continues to shape the way astronomers measure, classify, and understand stars and galaxies.

While newer systems have evolved to meet the demands of digital detectors and large-scale surveys, the Johnson UBVRI filters remain deeply embedded in the fabric of observational astronomy. For both historical continuity and practical application, the Johnson system continues to serve as a vital photometric standard — a testament to its enduring utility in unveiling the cosmos.

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# Part III

# Biosciences

# Protein Folding and its Vital Role in Biological Function

*by Geetha Paul*

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## 1.1 Introduction

Proteins are the molecular workhorses of all living cells, responsible for various biological tasks, from catalysing metabolic reactions to providing structural support and transmitting signals. Yet, the functionality of these remarkable molecules depends not merely on their chemical composition, but critically on how they fold into unique three-dimensional shapes. Protein folding is the intricate process by which a chain of amino acids, synthesised in a linear sequence according to the instructions encoded in DNA, adopts a specific conformation that allows it to perform its designated function. This process is essential for life: every movement, thought, and heartbeat relies on properly folding proteins within the body.

The significance of protein folding is underscored by its central role in cellular biology. The journey from gene to functional protein is more than a matter of assembling the correct amino acids; it enables these polymers to self-assemble into complex architectures, precisely tailored for tasks as diverse as carrying oxygen, repairing DNA, or defending against pathogens. This intricate folding occurs under the crowded and dynamic conditions typically found within cells. Despite the potential for error, most proteins consistently fold into their functional forms within seconds or minutes, a feat made possible by the delicate balance of chemical and physical forces acting along the polypeptide chain.

Disruptions in protein folding can have dramatic consequences. Even a single error in this process can transform a helpful protein into a harmful entity, leading to the formation of aggregates that are hallmarks of diseases like Alzheimer's, Parkinson's, and cystic fibrosis. Understanding how proteins fold, and what happens when folding goes awry, is one of the grand challenges of modern biology. Recent innovations in research, ranging from uncovering the fundamental principles that direct protein folding to advancing computational approaches for structure prediction, are having far-reaching impacts. These breakthroughs are transforming medicine, enabling the development of more precise drugs, and accelerating progress in biotechnology, establishing protein folding as both a cornerstone and a cutting-edge field in modern science.

## 1.2 Translation and Primary Structure Formation

Protein folding begins at the molecular level by synthesising a polypeptide chain, a process called translation. During this step, ribosomes read the genetic code carried by messenger RNA (mRNA) and link amino acids in a precise order, producing the linear primary structure of the protein. This sequence determines the intrinsic chemical properties of the future protein by dictating how amino acids with different side chains interact. Hydrophilic, hydrophobic, acidic, or basic will interact. Remarkably, the primary sequence alone encodes all the information required for the protein to adopt its native, functional structure. The growing protein chain may start folding into preliminary structures even before synthesis is complete, a process known as co-translational folding.

## 1.3 Folding to Secondary and Tertiary Structure: The Search for Native Conformation

As the newly synthesised chain is released from the ribosome, it undergoes rapid structural transitions. The first level is the formation of local secondary structures, alpha helices and beta sheets, stabilised by hydrogen bonding patterns within the backbone. These early structures form rapidly, providing a framework for further folding.

The polypeptide chain then experiences a process called hydrophobic collapse, where water-fearing (hydrophobic) residues tuck inside, away from the surrounding aqueous environment, leading to a compact "molten globule" state. This intermediate is more ordered than the unfolded chain but still flexible. Folding continues as further interactions occur between distant regions of the chain, such as hydrophobic contacts, salt bridges, disulfide bonds, and van der Waals forces, driving the conversion into the tertiary structure, which is the unique, three-dimensional form required for biological activity. Proteins reach their functional state usually by traversing an "energy landscape," avoiding misfolded intermediates or kinetic traps.

Some proteins, especially larger or more complex ones, require assistance to fold correctly. Molecular chaperones act as folding facilitators, preventing improper contact and aggregation, particularly under conditions prone to causing errors, such as heat shock or cellular stress. Chaperones do not determine the final structure but provide an environment in which correct folding can occur efficiently.

## 1.4 Quality Control, Quaternary Structure Assembly, and Functional Verification

Once the tertiary structure is achieved, some proteins interact with other polypeptide chains or subunits, assembling into quaternary structures. They are complexes that function as multimeric machines (e.g., haemoglobin, which consists of four subunits). Stability and correct assembly are ensured by the same types of non-covalent interactions that govern earlier folding stages.

Cellular machinery constantly monitors proteins for incorrect or incomplete folding. Misfolded proteins are recognised and tagged for degradation by quality-control systems such as the ubiquitin-proteasome pathway or autophagy. This process helps prevent the accumulation of potentially toxic protein aggregates, which are implicated in neurodegenerative and systemic amyloid diseases if allowed to persist.

Thus, the journey from a linear amino acid sequence to a finely tuned functional protein is a tightly regulated, multi-step process essential to cellular function and survival.

Protein aggregates are a hallmark of several neurodegenerative diseases, such as Alzheimer's, Parkinson's, and cystic fibrosis, and play a central role in their pathology. These aggregates typically consist of misfolded proteins that have adopted abnormal conformations rich in $b$-sheet structures. This conformation exposes hydrophobic regions normally buried inside the protein, promoting oligomerisation and fibril formation, which leads to insoluble deposits in cells or extracellular spaces.

In Alzheimer's disease, protein aggregates include extracellular amyloid plaques formed mainly from $b$-amyloid peptides and intracellular neurofibrillary tangles composed of hyperphosphorylated tau protein. Parkinson's disease is characterised by Lewy bodies, intracellular aggregates primarily of $a$-synuclein protein. Similarly, cystic fibrosis involves misfolding and aggregation of the CFTR protein, affecting its function.

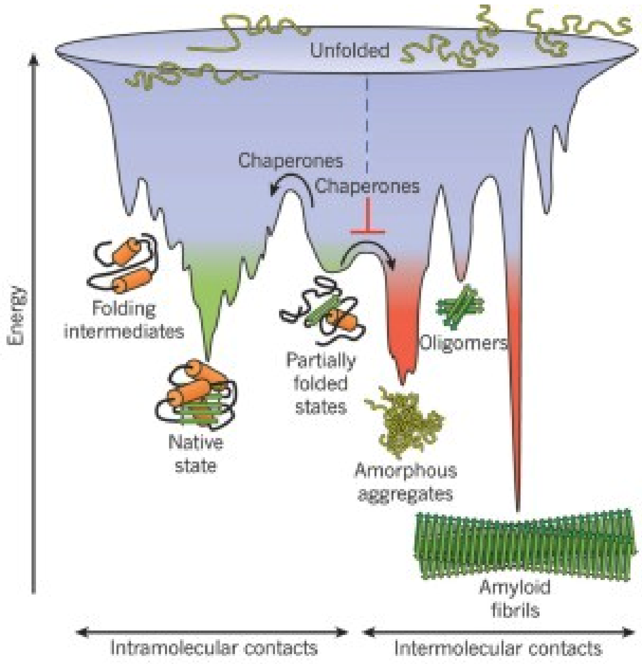


Image courtesy: https://doi.org/10.1038/nature10317

**Figure 1:** Competing reactions of protein folding and aggregation

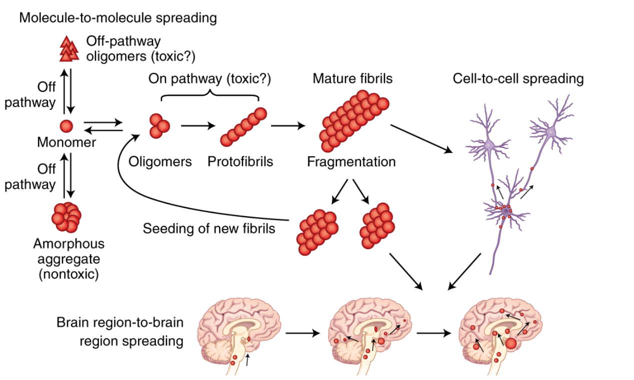


**Figure 2:** Protein aggregation and its affecting mechanisms from molecule to molecule.

## 1.5 Mechanisms by Which Protein Aggregates Disrupt Cellular Function

Toxicity to neurons: Aggregates interfere with cellular processes, causing oxidative stress, mitochondrial dysfunction, and inflammation, ultimately leading to cell death.

Impaired protein clearance: Dysfunction of cellular quality control systems, such as the ubiquitin-proteasome system and autophagy-lysosomal pathway, contributes to the accumulation of aggregates. The aggregated proteins can further impair these clearance pathways, creating a vicious cycle.

Seeding and spreading: Aggregates can propagate by inducing misfolding of normal proteins in neighbouring cells, contributing to disease progression.

The causes of aggregation are multifactorial, including genetic mutations, environmental stressors, ageing, and failure of molecular chaperones and quality control machinery. Deficiencies in protein homeostasis (proteostasis) exacerbate the accumulation of toxic aggregates, which are pathogenic in these diseases.

Understanding these aggregates is critical, as their formation marks the onset and progression of neurodegeneration and is a primary target for therapeutic intervention.

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**About the Author**

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## About airis4D

Artificial Intelligence Research and Intelligent Systems (airis4D) is an AI and Bio-sciences Research Centre. The Centre aims to create new knowledge in the field of Space Science, Astronomy, Robotics, Agri Science, Industry, and Biodiversity to bring Progress and Plenitude to the People and the Planet.

## Vision

Humanity is in the 4th Industrial Revolution era, which operates on a cyber-physical production system. Cutting-edge research and development in science and technology to create new knowledge and skills become the key to the new world economy. Most of the resources for this goal can be harnessed by integrating biological systems with intelligent computing systems offered by AI. The future survival of humans, animals, and the ecosystem depends on how efficiently the realities and resources are responsibly used for abundance and wellness. Artificial intelligence Research and Intelligent Systems pursue this vision and look for the best actions that ensure an abundant environment and ecosystem for the planet and the people.

## Mission Statement

The 4D in airis4D represents the mission to Dream, Design, Develop, and Deploy Knowledge with the fire of commitment and dedication towards humanity and the ecosystem.

**Dream**

To promote the unlimited human potential to dream the impossible.

**Design**

To nurture the human capacity to articulate a dream and logically realise it.

**Develop**

To assist the talents to materialise a design into a product, a service, a knowledge that benefits the community and the planet.

**Deploy**

To realise and educate humanity that a knowledge that is not deployed makes no difference by its absence.

## Campus

Situated in a lush green village campus in Thelliyoor, Kerala, India, airis4D was established under the auspicious of SEED Foundation (Susthiratha, Environment, Education Development Foundation) a not-for-profit company for promoting Education, Research. Engineering, Biology, Development, etc.

The whole campus is powered by Solar power and has a rain harvesting facility to provide sufficient water supply for up to three months of drought. The computing facility in the campus is accessible from anywhere through a dedicated optical fibre internet connectivity 24×7.

There is a freshwater stream that originates from the nearby hills and flows through the middle of the campus. The campus is a noted habitat for the biodiversity of tropical Fauna and Flora. airis4D carry out periodic and systematic water quality and species diversity surveys in the region to ensure its richness. It is our pride that the site has consistently been environment-friendly and rich in biodiversity. airis4D is also growing fruit plants that can feed birds and provide water bodies to survive the drought.