Term Paper

Singapore's Smart Nations: A Case Study on IoT-enabled Contact Tracing

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Abstract

Amid the height of the COVID-19 pandemic, Singapore's "TraceTogether" app was introduced in late March 2020 as a pioneering initiative developed by the Ministry of Health, SG United, and GovTech Singapore by leveraging Bluetooth capabilities in mobile devices for proximity detection. When two devices are within 2 meters of each other, the app automatically establishes a "digital handshake" and stores the data to facilitate the government's "contact tracing" efforts through which they detect individuals who potentially came into close contact with the virus and apply quarantine measures. This paper provides an in-depth overview of the TraceTogether system by focusing on its technological framework, strengths, weaknesses, and opportunities for improvement. It investigates how current issues related to centralized data processing could be mitigated by adopting decentralized contact tracing models empowered by localized edge analytics for real-time data processing. By critiquing current solutions and offering actionable improvements, the paper presents a pathway for evolving TraceTogether and similar IoT-driven contact tracing systems into more enhanced tools for pandemic preparedness. The paper concludes with recommendations aimed to address critical concerns related to privacy, scalability, and responsiveness in managing future public health crises.

Keywords: TraceTogether, IoT, contact tracing, Bluetooth Low Energy, decentralized systems, edge computing, AI predictive analytics, privacy, scalability, pandemic preparedness

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I. Introduction

COVID-19 is the most significant pandemic which imposed a massive impact on humanity in the last century. Along with it came the world-scale disruptions that put nations' operations at risk and required a solution to somehow bring back a sense of control in response to the changes. Governments increasingly turned to IoT-driven digital contact tracing to minimize the spread of this highly infectious disease.

In Singapore, the highest numbers of confirmed cases surged drastically, with the Health Minister stating that during its peak, almost 4000 new cases of COVID-19 were confirmed in a day. The virus is transmitted primarily through close contact from one person to another.

Manual tracing poses high levels of risk for the operators as well as inefficiencies, particularly in this crisis, where manpower is a scarce resource that should be allocated efficiently. Not to mention the heavy reliance on health officials, who might be prone to errors, to provide accurate and timely data that we can refer to. Countries around the world have come up with their own innovative solutions to perform contact tracing, many of which were not compatible with one another.

Table 1. Technical information of COVID-19 response apps worldwide. [1]

App	**Country**	**Protocol**	**Tracing technology**	**GAEN**	**Interoperable**
Corona Warn App	Germany	DP-3T and TCN	Bluetooth	Yes	Yes
TousAntiCovid	France	ROBERT	Bluetooth	No	No
Immuni	Italy	DP-3T	Bluetooth	Yes	Yes
Radar COVID	Spain	DP-3T	Bluetooth	Yes	Yes
Koronavilkku	Finland	—	Bluetooth	Yes	Yes

NHS COVID-19	England and Wales	—	Bluetooth	Yes	Yes
Trace Together	Singapore	OpenTrace	Bluetooth	No	No
Self-Diagnosis app	South Korea	—	Reported data	No	No
Self-Quarantine app	South Korea	—	Reported data and GPS	No	No
Corona virus-SUS	Brazil	—	Bluetooth	Yes	No
Various integrated tracing functions in apps (eg, WeChat)	China	—	Quick response code, sensor data, and metadata	No	No

Hence, Singapore's government introduced TraceTogether, a solution that integrates technology in the contact tracing process. Among the initiatives, TraceTogether emerged as one of the first and most widely adapted Bluetooth Low Energy (BLE)-based contact tracing systems developed by the Ministry of Health, SG United, and GovTech Singapore [2]. This is in line with the Smart Nation Initiative introduced in 2014, making Singapore "A nation where people live meaningful and fulfilled lives, enabled seamlessly by technology, offering exciting opportunities for all." (Govtech, 2020)

While TraceTogether has proven effective, the system still faces notable challenges in its implementation overall, particularly concerning areas such as privacy, accessibility, and integration. These issues must be addressed to maximize the potential of such technologies and increase public acceptance.

This paper takes a closer look at TraceTogether by focusing on its technological framework, strengths, weaknesses, and areas for improvement. It will highlight how current issues related to centralized data processing can be overcome by shifting to decentralized contact tracing models and incorporating localized edge analytics to enable quicker and less invasive identification and intervention. Furthermore, the paper will consider the potential for AI-driven predictive analytics to anticipate and manage public health risks proactively.

In this context, the aim is not just to critique the existing TraceTogether model but also to offer practical recommendations for improving IoT-based contact tracing systems on a global scale.

II. IoT in Pandemic Response

With the sharp rise in confirmed cases and mortality rates, Internet of Things (IoT) became especially pivotal during the COVID-19 pandemic .

The rapid advancement of computational knowledge, driven by artificial intelligence (AI) and the Internet of Things (IoT) has revolutionized several sectors concerning human beings ranging from finance to healthcare to education and so on [3][4]. AI and IoT have evolved into indispensable tools particularly in the healthcare sector [5] to perform its day-to-day tasks. The fusion of machine learning (ML) and IoT in healthcare during the pandemic showcased the remarkable potential of these technologies in addressing global health crises.

Several machine learning techniques like Artificial Neural Networks, Convolutional Neural Networks, Linear models, Decision trees, and so on have been implemented. Machine learning models yielded fruitful results in healthcare sectors like dermatology, ophthalmology, cardiology, radiology, and genome interpretation [6]. These models improve the precision of medical predictions and at the same time increase accessibility to healthcare services by reducing the need for manual analysis and human intervention. Diagnostic tools driven by machine learning demonstrated remarkable effectiveness in identifying various conditions which often require sophisticated interpretation and expertise like skin cancer, retinal diseases, heart abnormalities, and genetic disorders.

In tandem with the rise of machine learning, IoT technologies have revolutionized patient care through continuous real-time monitoring of health parameters. The emergence of wearable devices makes it effortless to track metrics such as heart rate, blood oxygen levels, and temperature, transmitting data seamlessly to healthcare providers for ongoing analysis. IoT has become a central component in patient management systems and databases to provide healthcare professionals with timely information crucial for informed clinical decision-making and enhancing the quality of care provided to patients.

In the case of COVID-19, IoT plays a significant role in improving health services by adequately monitoring the patient in self-isolation or quarantine; infected victims are kept on track using the internet-based network [7][8]. Wearable technologies enabled health authorities and medical teams to remotely monitor the condition of infected individuals by tracking their vital signs and physiology without the need for direct physical interaction. This approach not only helped manage the overwhelming number of patients but also minimized the risk of further exposure among healthcare workers and patients alike [9]. Real-time alerts facilitate timely interventions by providing live updates when patients' conditions worsened. Medical professionals are then able to respond faster, subsequently preventing potential complications.

The role of IoT in managing COVID-19 extended beyond just individual patient care. Internet-based networks were used to track the movement and interactions of potentially infected individuals resulting in effective contact tracing. Systems like Singapore's TraceTogether used Bluetooth technology to log proximity interactions and provide authorities with crucial data for outbreak management. The integration of IoT in this context was essential for tracking exposure patterns and ultimately playing a pivotal role in controlling the spread of the virus.

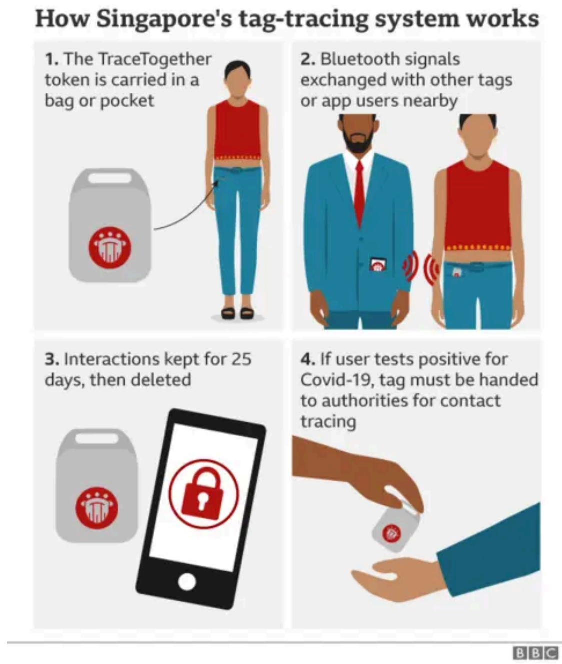
III. Singapore's TraceTogether System Infrastructure

Prior to the emergence of TraceTogether in March 2020, the Singapore Police Force, along with the Ministry of Health, performed contact tracing by collecting data from interviews, CCTV footage, ATM transactions, airline databases, ride-sharing companies, and cellphone records [10]. This app helped tremendously to bypass this labour heavy process and reached an audience of slightly more than 600,000 sign-ups within just three days after its release out of 5.7 million residents in Singapore [11].

TraceTogether operates using Bluetooth technology to automatically create a 'digital handshake' between app users who come into close contact with each other, creating a database that contact tracers can use to track down and alert potential cases [12], thereby preventing further transmission. Since its launch in March 2020, it has undergone multiple iterations and improvements. Initially, it was only available in the form of a mobile application, but in response to concerns of accessibility among individuals who did not own smartphones, the roll out wearable token version using the same Bluetooth technology was released in October 2020.

Fig 1. The First Batch of TraceTogether Tokens (Source: CNN)

Fig 2. How TraceTogether's Tag-Tracing System Works (Source: BBC)



The system has been integrated with the SafeEntry system of Singapore that logs entry and exit of public places and businesses. This integration allowed comprehensive tracking by merging location information with proximity information picked up through BLE. Although the system was initially praised for its ability to automate contact tracing, the system soon ran into challenges that stood in the way of its effectiveness, especially during the server congestion of user registration during peak crowds, as delays in notification of contact tracing would set in due to overloaded servers.

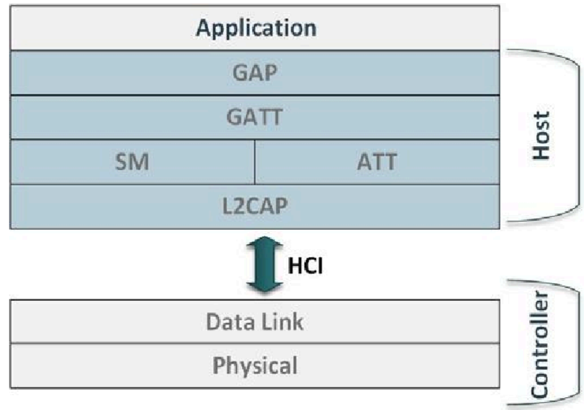
Such tokens extend the functions of the app and allow a greater share of the population to participate in contact tracing. The system was also integrated with other national services such as the national health records platform for better user experience. However, those resulted in additional issues of data synching and loads on the server. The more users TraceTogether attracted, the more complex it became to maintain and scale the system.

In one of the greatest technological challenges faced by TraceTogether in its infancy, it attempted to offer an unobtrusive user experience while juggling large amounts of incoming data. Centralized data storage meant that once a certain number of users were on-boarded to the system, more strain would be placed on the central servers. Hence, such were the bottlenecks formed around the time of peak load. Privacy also became a critical issue, and the government's ability to access personal data was heavily criticized. Although use of anonymous identifiers protects retrieval of user identity, concerns still remain with such centralized data reaching the wrong hands of a particular party, increased surveillance, or the misuse of sensitive health information.

IV. Strengths and Weaknesses of this BLE-Based Contact Tracing System

The TraceTogether system paved the way for Bluetooth Low Energy (BLE) technology implementation in contact tracing. Its integration of IoT into the public health domain provides several compelling strengths that have contributed to its success in Singapore, yet it is not without significant weaknesses. This section will critically evaluate the strengths and weaknesses of BLE-based contact tracing.

Fig 3. BLE Architecture



IV-I Strengths

BLE has been the backbone of many digital contact tracing applications.The key advantages lie in its low energy consumption and short-range communication, making it ideal for indoor environments [13]. BLE technology ensures that devices can run continuously in the background without significantly depleting battery life, which is crucial in a contact tracing app that needs to always be active. This reliability allows users to go about their day worry-free as there is no need for frequent charging. BLE also has a lower energy footprint than other wireless communication technologies and is overall cost-effective as it does not require additional hardware infrastructure to operate. Most modern smartphones are designed to be compatible with BLE technology, which allows for easy integration and makes it a highly adaptable solution for contact tracing across diverse user groups.

Bluetooth-based contact tracing is cost-effective, flexible, and efficient while supporting standard infrastructure [14]. Despite these advantages, there are still ongoing concerns about aspects such as privacy and security in its deployment.

IV-II Limitations

Despite the numerous benefits offered by BLE-based contact tracing systems, significant challenges remain, particularly regarding privacy and data security. While BLE enables efficient communication it generates sensitive data that raises concerns especially in the context of contact tracing. Some users may be apprehensive about the collection and storage of their interaction data, even when anonymized. This unease stems largely from the centralized architecture of many BLE systems where data is typically transferred to central servers for processing.

Although encryption and anonymization techniques are employed as an attempt to safeguard user privacy, the fundamental nature of contact tracing necessitates the collection of sensitive health-related information, which could be misused if not handled appropriately [15] This begs the need for a more robust privacy framework for BLE-based systems that ensures greater user autonomy and transparency over how their data is being used. A potential solution could involve developing a privacy model for Bluetooth-based tracing.

BLE typically operates within a range of 2-meters which may seem ideal for indoor environments but in reality, most places that we visit are obstructed by a myriad of physical barriers such as walls, buildings, or towers. These interferences may cause BLE signals to drop or fail to register, leading to missed interactions (or "handshakes") and detection failures.

The app may miss important interactions simply because individuals are not within the optimal range thereby diminishing the app's ability to detect potential exposure events. This issue is compounded in environments where individuals are spread across varying distances or where proximity is inconsistent. As a result the system's efficacy in capturing all potential contacts is reduced which could impair the overall effectiveness of the contact tracing effort.

While we have established the fact that BLE technology is generally more energy-efficient than other wireless alternatives, during prolonged usage, it still contributes to noticeable battery drain. The continuous operation of Bluetooth in the background especially during extended periods can significantly deplete a device's battery. This becomes a critical issue for users with older devices or those who already face limited battery capacity due to heavy app usage. The resulting battery drain may lead some users to deactivate the app to preserve power which in turn undermines the completeness of data collection and affects the system's overall utility [16]

V Proposed Improvements

TraceTogether has made strides in curtailing the spread of COVID-19, but has also revealed several challenges that confront its long-term effectiveness about contact tracing. These challenges call for radical rethinking of the design and implementation of IoT contact tracing systems. A very close analysis of systemic weaknesses within TraceTogether would ideally need to form the conceptual basis with which the nuanced approach towards resolution can be informed. This section will expound on key arguments against TraceTogether and suggest relevant, individualized improvements that centralization increases the efficacy of contact tracing.

V-I Centralized Processing and Privacy Concerns

At the core of the limitations of TraceTogether is the model of centralized storage of data. This testifies against the historical example of how intertwined privacy and security issues are concerning sensitive information. Singapore's government has put anonymization and encryption measures in place for these data, but the existing structure of centralized systems would create a *single point of vulnerability*. Sensitive health data, whether anonymized or not, would always be exposed to intentional and accidental risks. This begs significant questions in a world, particularly during a global health crisis, where concern about data misuse and surveillance has been more heightened. As data privacy has become an intense focal point of public discourse, worries surrounding TraceTogether mirror broader concerns on how such data might be misused, whether through unauthorized access or general misuse.

Under all these categories, individualized privacy issues blend into the bigger ones concerning public health management. Therefore, a consideration could be moving from a centralized system to a more decentralized one where processing of data takes place quickly and locally (i.e. on the user's own smartphone) rather than through a centralized server. The argument that centralised systems entail risks of breaches, while decentralised systems rule out such risks, has been influential in debates about digital contact tracing and was part of the reason that centralised apps have fallen out of favour in many places [17] . For instance, the European Parliament resolution on EU coordinated action to combat the COVID-19 pandemic and its consequences demands that "the generated data are not to be stored in centralised databases, which are prone to potential risk of abuse and loss of trust and may endanger uptake throughout the Union... all storage of data [must] be decentralised" (European Parliament, 2020)

Fig 4. The centralized architecture of Covid Tracing Apps [18]

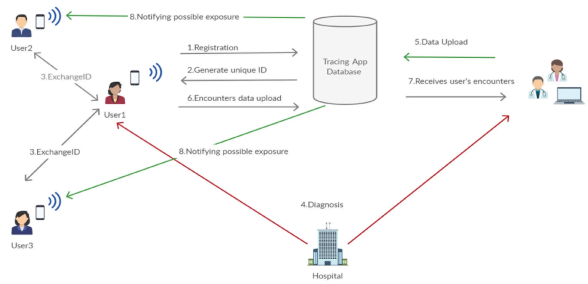
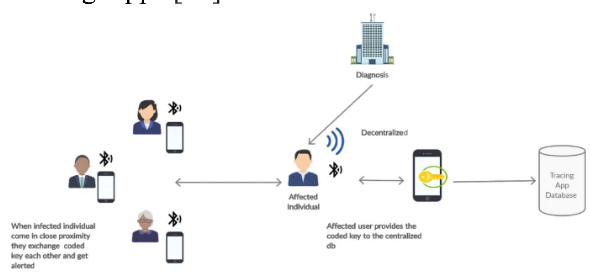


Fig 5. The decentralized architecture of Covid Tracing Apps [18]



A better approach would involve leveraging hybrid models that combine the benefits of edge computing with central servers for specific use cases. For instance, while basic proximity data could be processed locally on the device, critical health information (such as temperature or oxygen saturation levels) could be sent to centralized servers for deeper analysis. This hybrid model would balance the speed and privacy benefits of decentralized systems with the analytical power of centralized computing. An important aspect for decentralized models is that they should incorporate a fallback mechanism in case of device failures, ensuring that they still operate effectively in environments with limited connectivity.

Alongside, federated learning and blockchain technologies would develop a structure that maintained ownership of their data (user data could remain on their local devices) with users sharing only relevant anonymous information for contact tracing and analysis. Federated learning would use machine learning on individual devices to provide shared aggregated data; hence personal information would be kept private. Blockchain offers a transparent and immutable access ledger record that adds the benefit of securing interaction by greatly improving accountability and ensuring that no unauthorized changes are made to the data.

V-II Scalability and Access

While the transition to edge computing sounds promising, the current research does not fully address the scalability and real-world applicability of such systems in large-scale pandemics. As noted by several researchers, edge computing in the context of IoT health applications still faces challenges related to device capacity, data consistency across devices, and interoperability between edge devices and cloud infrastructure [19].

While it has succeeded to an extent in Singapore, a highly urbanized and technologically advanced nation, its applicability is put under scrutiny in many areas of the world where smartphone penetration is low or internet infrastructure is weak. Less developed regions would become even more demanding for a mobile-centric solution that could exclude major populations leaving behind especially the vulnerable (i.e., elderly, low-income individuals, and people in rural areas or underserved regions)

A possible solution here entails a hybrid one integrating mobile tracing with other low-cost, non-digital modalities such as wearables or tracing by SMS. Wearables, with Bluetooth technology, would be provided at little cost to people unable to afford smartphones, thereby ensuring an inclusive contact-tracing system. SMS tracing solutions could further ensure a wider reach, as in many parts of the world, mobile phones are more widespread than smartphones. It could operate as substitutes in rural or under-developed regions: giving people who otherwise would not have a method to receive critical exposure-risk notifications a cheap and accessible way to do so. Such solutions will, therefore, enable the scaling of the contact-tracing system beyond urban centers and improve its applicability on a global level.

V-III Real-Time Processing and Predictive Analytics

In terms of real-time effectiveness, TraceTogether is thus, like many IoT-driven health systems, limited by its reactive nature. The app only alerts users when he or she has been in contact with an infected individual; thus, it serves more as a post-exposure tool rather than as a proactive measure. It is valuable in aiding the identification of transmission cluster cases; however, it does not offer any anticipatory measures to hinder the virus from spreading before the exposure occurs.

For improving the predictability of its predictive enforcement, an aspect that could be considered is leveraging AI-based predictive analytics and machine-learning models that will ingest real-time data to forecast potential emergence sites or outbreaks. Mobility data pulled in from the phone of users, social distancing behavior, and regional infection rates could be utilized as variables for AI models to identify high-risk areas as well as people who are potentially elevated at risk even prior to any exposure to the virus. Such a predictive mechanism could prompt more proactive intervention, including early containment in areas classified as high-risk hotspots. A recent research done in 2020 by Magesh et al., [20] has shown that Machine learning models are very efficient in predicting diseases. In the proposed research work, besides the contribution of smart devices, Artificial Intelligence detectors were also deployed to reduce false alarms. Moreover, while machine learning algorithms could improve accuracy, they must be carefully designed to mitigate biases, particularly if they rely on personal health data.

VI Future of IoT in Pandemic Preparedness

The relevance of IoT technologies within the global community will only increase in the future as the world grapples with the many challenges posed by pandemics. This section aims at exploring the diverse trajectories that IoT can possibly create, highlighting emerging trends, potential innovations, and the broader implications for healthcare systems globally.

VI-I Integration with Wider Public Health Systems

One of the key lessons learned in the COVID-19 pandemic is the importance of public health systems that should function quickly, flexibly, and effectively. The reality is that wearables and actual time data analytics will be the basis of IoT in pandemic preparedness in the forthcoming phase. Next would be the needed extension of contact tracing with other public health systems as well as allowing connectivity with national health databases.

VI-II Predictive Analytics and Early Warning Systems

Predictive analytics would probably be the most thrilling frontier of IoTs for pandemic preparedness as it creates a possibility to predict and mitigate an outbreak before it spirals out of control. Predictive analytics could also be employed to recognize early signs of new outbreaks or mutations of pathogens, making it possible to take preemptive measures, such as increasing testing or social distancing in specific areas, before outbreaks become too widespread.

VI-III Decentralization of Data Models

The future of pandemic preparedness incorporates decentralized data models that offer privacy to the individual without compromising effective disease surveillance, as the privacy concerns linger atop the public debates regarding IoT-enabled public health systems.

VI-IV Global Interoperability and Cross Borders Collaboration

A crucial problem with regards to the world response to pandemics is the fact that contact tracing systems are not interoperable from different countries. Such was the case during the COVID-19 pandemic where each country developed its national system and which were not necessarily compatible with one another. Indeed, for the future of IoT in pandemic preparedness, there should be an increase in worldwide collaboration toward ensuring interoperability and the capability to exchange data across borders.

One possible answer would be through the establishment of international standards for IoT-based pandemic response systems. With such universally accepted protocols for data sharing, security, and privacy thus laid down, country systems would be able to work towards each other seamlessly. Cross-border contact tracing would be followed by much improvement in both speed and accuracy in identifying individuals at risk.

However, with the continuous evolution of IoT technologies, it would be imperative for policymakers, technologists, and public health experts to work in alliance in creating the systems that will work most effectively but ethically, inclusively, and with transparency.

VII Conclusion

The COVID-19 pandemic has brought about an unprecedented opportunity to observe how IoT technologies can be used in public health emergencies. For instance, Singapore's TraceTogether system has shown that IoT-driven solutions can indeed be deployed to combat the spread of infectious diseases, being one of the very first adopters of Bluetooth Low Energy (BLE) technology for contact tracing. The design and implementation of such a system, however, have demonstrated significant challenges as well, such as privacy concerns, scalability issues, and less efficient data processing. Such issues should indicate the constant need for innovation and adaptation of IoT systems to meet the growing demands that are placed on them with regard to the preparedness and response to pandemics.

This paper has explored the strengths and weaknesses introduced of the TraceTogether system, examining critically how IoT will be central to pandemic management, and outlines a few of the many practical changes that could be adopted. Some of them being decentralization, predictive analytics, and enhancing scalability. Decentralized models—such as federated learning or blockchain—are able to secure user privacy while meeting the performance standards for contact tracing. Predictive analytics can be integrated with real-time data processing at the edge, which will provide an automated decision-making process and reduce response times, thus bringing public health systems to be more agile and capable of preventing future outbreaks.

The future is promising for IoT in terms of pandemic preparedness. Through tying IoT to other broader healthcare infrastructures, expanding the application of IoT technologies beyond contact tracing, and ensuring interoperability across borders, the role of IoT systems in safeguarding health across countries will become even more pronounced. As IoT continues to evolve, however, it will be critical for policymakers, technologists, and public health experts to collaborate in creating systems that will be effective while being ethical, inclusive, and transparent.

In summation, while humanity struggles with public health challenges, systems endowed with IoT technology will pave the way for more resilient adaptive and responsive healthcare frameworks in effectively curbing emerging health crises.

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