

PCS and RF Components

The new “wireless” is different from the decades of radio communications between fixed locations. Mobile and personal communications have brought portable radio communication to the consumer, affecting system design and manufacture.

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Almost overnight, everyone in the electronics business is making products for “wireless” applications. Those who had been in the RF component business have always made products for wireless applications and might assume that the rest of the world has finally come to their door. But this is not so. Today’s wireless market, as described in almost every publication, is far different from the wireless market we had known before. It is now described by two most important words, *portable* and *consumer*.

Portable wireless has its roots in mobile radio. Radio’s first applications were fixed *services* within which both receivers and transmitters were more or less fixed in location. But the advantage of two-way communications with moving vehicles was soon realized as radio moved to ships and then to planes, trucks and cars. With the move from fixed service, equipment had to be not only smaller but more efficient and rugged. Semiconductor technology found a home as size and weight reduction became more important.

Advances were also being made in capacity utilization. Channelization based on narrow-band FM modulation became the norm. This system, while inefficient by today's standards, was adequate for dispatch services and public safety communications. Not until the idea of combining telephone service with two-way mobile radio was implemented did the demand expand beyond the capacity of the two-way radio system.

The potential of telephone service from a moving vehicle ignited a whole new market with business people in sales and service. Two-way radio capacity was soon used up. A better system of frequency reuse was needed. The answer was cellular radio. In the cellular system, frequencies can be reused by dividing a geographic area into overlapping circular regions, cells, wherein the transmit range is limited to the confines of the cell. Frequencies are not reused in adjacent cells thereby reducing co-channel (same frequency) interference.

When a user moves from one cell to another, the system hands the user off to the next cell, and a new frequency. As an example of the efficacy of spatial frequency reuse, imagine an analog FM system with 70 channels and a square service area 100 miles on a side. The maximum number of calls which can be handled by the system is, of course, the number of available separate frequencies, in this case 70. On the other hand, using a cellular approach with a seven cell reuse scheme (the same as used by North American analog and TDMA digital) and 10 mile on a side square cells, the number of cells would be 100 with each cell having 10 channels available channels. The same 70 frequency channels can now handle 1000 calls (100 cells with 10 channels per cell). If the cell diameters are reduced to one mile, the same 70 channels can service 100,000 calls with the same reuse pattern. Actually, cells are hexagonal to better approximate circles of constant radius, but the effect is the same.

Cellular was conceived and implemented as a mobile radio system. System specifications are designed for high-speed handoff of calls as a vehicle passes from one cell to another. Being designed for vehicles, subscribers were forecast in the early 1980's to number 4 to 5 million in the U.S. by the mid 1990's. But this estimate proved far too low and the actual number exceeded 20 million subscribers in the U.S. and nearly 50 million worldwide by 1994. That shift was caused by the portable cellular phone. No longer was the mobile telephone confined to vehicles. Consumers were already becoming used to *tetherless* phone service through the use of cordless

telephone equipment. Portable cellular phones became the equivalent of super cordless telephones and the wireless revolution was underway.

Personal Communications Services, PCS

The important innovation in PCS is for a telephone number to be a means to access a person rather than a piece of equipment. The wireless aspect of the PCS is only one constituent of the concept. In fact, a limited form of PCS could be implemented in a completely wire-based system. If the system has knowledge of the location of the subscriber, the communication services, which are really what is being offered, can be forwarded from station to station as the subscriber migrates among locations.

These services include basic two-way voice and data transmission, and notification that someone desires to reach the subscriber (paging or ringing). Other services, such as voice mail for when the subscriber is unavailable, conferencing, and so forth., can also be included. What is important is that these services be available to the subscriber *anywhere, anytime*. Wireless communications thus becomes a key component of the PCS concept. PCS, then, is the making available of an array of high-quality voice and data services to customers, wherever they might be, at costs which the user finds acceptable.

Don Cox of Bellcore in his 1987 paper "Universal Digital Portable Communications" gives an excellent analysis of the technical aspects of making the PCS vision a reality[1]. The communicator of the future will be a hybrid of a pager, a personal computer, a cellular phone and a cordless phone (Figure 1).

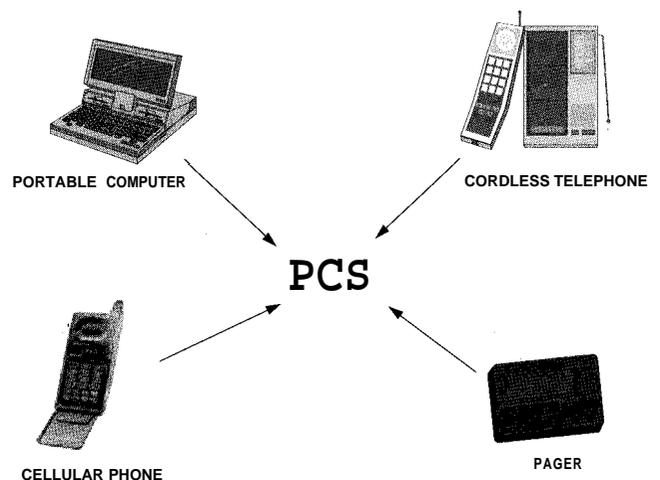


Figure 1. PCS include communications via personal computers, cordless and cellular phones, and pagers. Ultimately, a single portable hybrid device may combine all of their functions.

Presently, the pager meets the cost and mobility objectives of PCS and notifies the subscriber of someone desiring to communicate and how they can be reached. It does not, however, allow two-way or voice communications. The personal computer allows conversion of data into information and high-speed data transfer but is large, heavy and expensive. A cellular phone allows voice communication over a wide area but voice quality is often poor and even when furnished without charge for the subscriber equipment, has a high service cost when compared with wireline service. The cordless phone meets cost objectives but is limited in range and security.

The explosive growth of the cellular and cordless phone markets has not gone unnoticed by the telecommunications community. Obviously, the more accessible telecommunications services are, the more frequently those services are used. The radio spectrum -once the purview of broadcasters, fixed services and the military-- has been invaded by the telecommunications giants. At the last World Administrative Radio Conference (WARC), personal communications proponents won significant victories (frequency allocations) at the expense of fixed service operators.

Cellular radio was given new allocations at 1.5GHz. The 1.7 to 2.2GHz segment was designated specifically for development of wireless PCS systems under the definitions of Future Public Land Mobile Telecommunications System (FPLMTS). Western European, Japanese and North American governments were quick to allocate bands for new services. Emerging PCS candidate systems are shown in Tables 1 and 2. With the allocation of spectrum and the setting of system specifications, the stage is set for the development of the personal communicators themselves.

	IS-54 NORTH AMERICA	IS-95 NORTH AMERICA	GSM EUROPE +	PDC JAPAN
FREQUENCY	RX: 869-894MHz TX: 824-849MHz	RX: 869-894MHz TX: 824-849MHz	RX: 935-960MHz TX: 890-915MHz	RX: 940-956MHz TX: 810-826MHz RX: 1477-1501MHz TX: 1429-1453MHz
ACCESS METHOD	TDMA/FDM	CDMA/FDM	TDMA/FDM	TDMA/FDM
DUPLEX METHOD	FDD	FDD	FDD	FDD
CHANNEL SPACING	30kHz	125kHz	200kHz	25kHz
NUMBER OF CHANNELS	832	10	124	1600
USERS PER CHANNEL	3	118	8	3
BIT RATE	48.6kb/s	1.2288Mb/s	270.833kb/s	42kb/s
MODULATION	$\pi/4$ DQPSK	BPSK/OQPSK	GMSK (0.3 GAUSSIAN)	$\pi/4$ DQPSK

Table 1. Emerging digital wireless standards for macro-cellular.

	CT2 EUR/ASIA/NA	DECT EUROPE	DCS1800 EUROPE	PHS JAPAN
FREQUENCY	EUR: 864-868MHz CAN: 944-952MHz	1880-1990MHz	RX: 1895-1907MHz TX: 1710-1785MHz	1895-1907MHz
ACCESS METHOD	TDMA/FDM	TDMA/FDM	TDMA/FDM	TDMA/FDM
DUPLEX METHOD	TDD	FDD	TDD	TDD
CHANNEL SPACING	100kHz	1728kHz	200kHz	300kHz
NUMBER OF CHANNELS	40	10	750	300
USERS PER CHANNEL	1	12	16	4
BIT RATE	72kb/s	1.152Mb/s	270.833kb/s	384kb/s
MODULATION	GFSK (0.3 GAUSSIAN)	GFSK (0.5 GAUSSIAN)	GMSK (0.3 GAUSSIAN)	$\pi/4$ DQPSK

Table 2. Emerging digital wireless standards for micro-cellular & telepoint.

Wireless System Characteristics

While the vision of PCS exists, its implementation is yet undefined. A review of available wireless systems is useful in understanding how PCS may be implemented.

An established wide area system is the land mobile FM system. Developed in the late 1930's for police and other public services, its finds use in dispatch systems for taxicabs and other fleet services. It features high transmit power levels ranging from five to twenty-five watts, a simplex communication format wherein the same frequency is used both for transmit and receive, and analog frequency modulation.

Useful as it is there are drawbacks with the land mobile FM system if applied for PCS. First, the high transmit power levels require powerful, heavy batteries to afford acceptably long talk time. The high power, wide area coverage would limit frequency reuse, and with it system capacity. Market demand for full duplex communications (simultaneous transmission and reception) would not be satisfied with the simplex communication mode (alternate transmission and reception on the same frequency) of the land mobile FM system. Finally, the analog FM transmission cannot provide a high quality and secure (private) voice channel.

A limited range system that is widely used is the analog cordless telephone (CTO). Developed in the mid 1970's for the consumer residential market, the cordless telephone is a low cost FM system that provides full duplex communications. Only transmitting 10 milliwatts, the average phone has a range of a few hundred feet and a battery life between recharges of over a week. The use of analog FM is the main limitation of this system for PCS. Similar to the land mobile system, the voice quality and security are poor. The *second generation cordless telephone* addressed these problems.

Developed in the mid 1980's in Europe, the second generation cordless telephones (CT2) digitally encoded and compressed the voice. They also used digital frequency modulation for increased voice quality and security. In addition, the CT2 was one of the first widely available systems using *time division multiple access* (TDMA) for increased system capacity. The CT2 phones provide a digital communication link with high quality voice and security in a low power, low cost system. Though it has many features of a PCS system, the limited range of the CT2 system would have to be overcome with a smart infrastructure to permit *roaming* beyond the immediate vicinity of the local basestation.

The fastest growing two-way system today is the analog cellular system. Introduced in the early 1980's for the business market, it provides mobile wide area coverage. It features full duplex FM communications in the 900 MHz frequency band with a transmit power level as low as 0.6 watts. Though a strong contender as a PCS system, the large cell size limits the system capacity in densely populated area. In addition, voice quality and security are too limited due to the use of analog FM. As with the cordless telephone system, digital cellular systems solve many of these problems.

Digital signal processing technology is being employed not only to improve capacity but also voice quality. Current wireline telephone systems have been converted from primarily analog voice to digital data transmission systems for these reasons. Superficially, digitizing voice would seem inefficient, since the Nyquist theory demands a factor of two increase in digital signal bandwidth over the analog counterpart. Actually, however, the digital signal can be coded and processed, yielding not only greater bandwidth efficiency but excellent voice quality as well, due to the fact that the signal can be easily reconstructed in nearly its original form. As an example of the power of digital coding, the same telephone lines which struggled to pass data at a 1200 or 2400 bits per second rate 10 years ago can now handle 14400 bits per second with fewer errors.

Two leading TDMA digital cellular systems are the North America Digital Cellular (NADC) and the Global System for Mobile Communications (GSM). Both systems increase capacity by digitally encoding and compressing the voice channel and time sharing frequencies among multiple users. The main interest for an RF component manufacturer is the modulation format. NADC uses a non-constant envelope DQPSK (differential quadrature phase shift keying) modulation which requires linear amplification.

In comparison, the GSM system uses near constant envelope GMSK modulation that uses highly efficient nonlinear amplifications for increased talk time and reduced battery size.

A competing digital cellular system is the CDMA (code division multiple access) IS-95 format in North America. Like the other digital systems, the voice channel is digitally encoded and compressed for increased capacity, voice quality, and security. However, instead of increasing capacity by time sharing the frequency, the signal is spread across a shared band[2, 3]. The major system challenge is the required power level control. CDMA signals are automatically conducted at the lowest usable transmitter power in order that their interference with other users (which appears as an increase in the noise floor) be minimized. However, this gain control throughout the transmitter increases system complexity and cost.

	FREQ BAND (MHz)	TRANSMIT POWER (W)	MODULATION	ACCESS METHOD	DUPLEX METHOD	AMPLIFICATION
2-Way Mobile	50, 150, 450	>5	FM	FDMA	Simplex	Non-Linear
CT0 Cordless	50	0.01	FM	FDMA	FDD	Non-Linear
CT2 Cordless	866	0.01	GFSK	TDMA	TDD	Non-Linear
Analog Cellular	900	>0.6	FM	FDMA	FDD	Non-Linear
TDMA Cellular	900	>0.8	GMSK π/4DQPSK	TDMA	FDD	Non-Linear Linear
CDMA Cellular	900	>0.8	BPSK OQPSK	CDMA	FDD	Linear

Table 3. Comparison of Wireless Systems.

PCS Communicator Characteristics

PCS requirements can be mapped into the specifications of the personal communicator to be used by the subscriber. As already noted, the key words describing subscriber equipment for the new PCS services are portable and consumer. Portability is served by the wireless aspect of the new equipment, but the equipment must also be lightweight, rugged and have long battery life. On the consumer side are cost and quality consistent with current high-end cordless phones and wireline phone service. Telecommunications quality is being addressed by the new digital techniques already described. The challenge to phone manufacturers and the component suppliers on their teams is to supply complex pieces of communications gear at the prices currently paid for much simpler cordless phones.

A simplified block diagram of the radio portion of a typical digital wireless personal communicator is shown in Figure 2. The signals received at the antenna are switched to the receive section by the transmit/receive (T/R) switch, amplified by the low-noise amplifier (LNA) and downconverted to an intermediate frequency (IF). The low noise amplifier is critical to setting the sensitivity of the receiver. This heterodyne approach, as opposed to direct demodulation of the RF signal into data, is preferred for reasons of selectivity and dynamic range. The IF subsystem converts the IF signal to baseband and will include quadrature demodulation for I and Q coded signal of the QPSK modulation format. The baseband processor does the final decoding into either data or reconstructed voice.

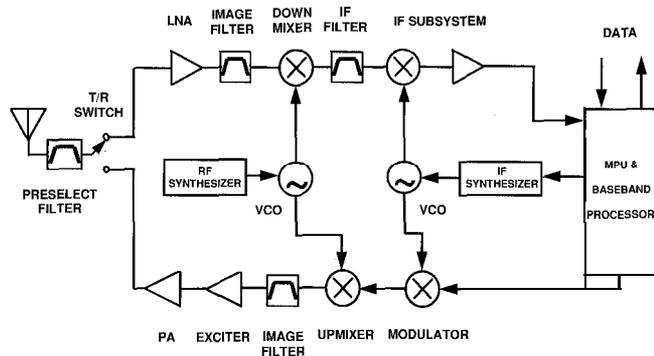


Figure 2. Simplified radio block diagram of the PCS communicator.

On the transmit side, the coded signal from the baseband processor is applied to the modulator, which imparts the modulation to the same IF used in the receiver. This IF is upconverted to the transmit frequency, amplified in the power amplifier chain, and routed to the antenna through the T/R switch. Some FDD systems still use a duplex filter in place of the T/R switch, but this can generally be eliminated, since transmitting and receiving do not occur simultaneously. If the modulator is capable of operation at the transmit frequency, the IF portion of the transmitter can be eliminated along with the image filter, for reduced cost. The IF is still required for the receive chain. In GFSK systems, the baseband signal is applied to either the IF or RF synthesizer. While the "direct launch" approach of modulating the RF VCO (voltage controlled oscillator) simplifies the block diagram, the performance required of the VCO and synthesizer may make this approach more costly.

This basic block diagram has undergone a tremendous increase in the level of integration as the communicator has been shrunk from handbag size, assembled mostly from discrete RF components, to shirt pocket size. RF component manufacturers have responded to the request for higher levels of integration with new RF integrated circuits. But, as opposed to digital circuitry, for which high scales of integration have been the norm for years, the RFICs are just now emerging from the high cost military environment. Even in digital radios the RF circuitry is still analog in nature and so must operate over wide dynamic range. Integrating digital designs where only state changes are important is by far an easier task.

Receiver/transmitter design remains a means of performance differentiation for phone manufacturers. The proliferation of proposed radio systems with their variety of output power requirements, frequencies and modulation schemes runs counter to the standardization which could result in the high volume discounts for standardized chipsets. The *single chip radio* awaits for its birth a more standardized approach to radio design. Meanwhile, component manufacturers must work closely with phone manufacturers to negotiate levels of integration for RF components around the equivalent of small and medium scale integration (SSI and MSI) in digital integrated circuits.

Packaging and test also enter into the integration equation. High quality RF packages have, in the past, been constructed of multilayer ceramics, facilitating the inclusion of transmission line structures. But the cost of such packages is prohibitive in consumer electronics. SSI circuits are generally packaged in modified discrete SOT style plastic packages. MSI circuits are packaged in SOIC and SSOP style packages. The need for multiple ground leads and the increased parasitics associated with wirebonds and lead lengths have limited RF components to packages with about 20 leads. This pin count limits the number of functions which can be included in the package. Typical partitioning for ICs being offered include LNA/downmixers, power amplifiers, quadrature modulator/upmixers, and upconverter/exciter. Integration of converter functions with IF subsystems is also an option.

High-speed testing of RFICs is still in its infancy. Fixture maintenance and correlation are constant problems. Hand testing of certain parameters is common. Wafer probing has not yet allowed 100% RF testing on wafer due to high probe costs and short probe lifetime. In general, RFIC design capability far outstrips packaging and test capability.

Efficiency is a performance characteristic of subscriber equipment that is crucial to the success of PCS. Long talk time is required to fulfill the wireless promise. Battery voltages, nominally 5 volts, will drop to three volts or less. Therefore, high efficiency operation at low voltages is crucial to RF component manufacturers. RF component manufacturers are responding with not only high efficiency ICs, but circuit control logic which can place the device in a low current standby or sleep mode when ordered to do so by the controlling microprocessor. In TDMA applications, the receive rather than the transmit current actually may be the more critical specification due to the duty cycle difference of eight or more between receive and transmit operation.

Selection of modulation, while a systems design consideration, can have pronounced influence on the efficiency of RF power amplifiers. Systems which have nearly constant envelope modulation such as the GMSK used in GSM can utilize amplifiers operated close to saturation, enjoying high efficiency. DQPSK derivative modulations such as used in NADC and Japan's PHS require amplifiers to be operated "backed off" from saturation, where efficiency is much lower.

The choice of semiconductor platform is important in the cost/performance trade-off Tables 4 through 6 compare the various semiconductor technologies applicable to RFICs in terms of characteristics, passive component capability and applicability to system building blocks.

	BJT	BICMOS	GaAs MMIC	HFET MMIC	HBTMMIC
SEMICONDUCTOR MATERIAL	Si	Si	GaAs	GaAs	Si/GaAs
ACTIVE DEVICE	NP/NPN	NP/NPN BJT MOSFET N&P ENDEPL	N. MESFET (E, D, F)	HEMT	HBT
F_T	> 12 GHz	> 15 GHz	> 20 GHz	> 20 GHz	> 20 GHz
BREAKDOWN VOLTAGE	>15 v	>10 V	>10 V	>10 v	>15 v
REACTIVE ELEMENTS	POOR	POOR	GOOD	GOOD	GOOD (GaAs) POOR (Si)
MIN SUPPLY VOLTAGE PA (1 TO 4 W)	5 V	N/A	3 V	3 V	3 V
PROCESS COMPLEXITY	MEDIUM	VERY HIGH	LOW	HIGH (EPI)	HIGH (EPI)
COST	LOW	MEDIUM TO HIGH	MEDIUM TO HIGH	VERY HIGH	VERY HIGH
INTEGRATION CAPABILITY	MEDIUM - HIGH	VERY HIGH	MEDIUM	MEDIUM (1BD)	MEDIUM (TBD)

Table 4. RFIC semiconductor technologies comparison.

	PARAMETERS	GaAs	SILICON	PCB
INDUCTORS	Q	MEDIUM	LOW	HIGH
	RESONANT FREQUENCY	HIGH	MEDIUM	MEDIUM
	PARASITICS	LOW	HIGH	LOW
	COST/SIZE	HIGH	MEDIUM	VERY LOW
RESISTORS	TYPE	FILM/IMPLANT	FILM/IMPLANT	CHIP
CAPACITORS	Q	MEDIUM	MEDIUM	(chip) MEDIUM/HIGH
	RESONANT FREQUENCY	MEDIUM/HIGH	MEDIUM	MEDIUM
	PARASITICS	VERY LOW	HIGH	LOW
	COST/SIZE	HIGH	MEDIUM	VERY LOW

Table .5 RFIC passive components comparison.

	HI SPEED BJT	BICMOS	GaAs MMIC	HFET MMIC	HBTMMIC
LNA	GOOD	FAIR	VERY GOOD	VERY GOOD	VERY GOOD
MIXERS	VERY GOOD	VERY GOOD	GOOD	GOOD	GOOD (PROCESS CONTROL?)
P.A.	N.A.	N.A.	GOOD	GOOD	VERY GOOD
RF SWITCH	N.A.	N.A.	GOOD	GOOD	N.A.
VCO	GOOD	GOOD	FAIR	FAIR	GOOD
PRESCALERS	VERY GOOD	GOOD	GOOD	GOOD	VERY GOOD
ANALOG FUNCTIONS	GOOD	VERY GOOD	FAIR	FAIR	GOOD
DIGITAL FUNCTIONS	POOR	VERY GOOD	FAIR	FAIR	GOOD

Table 6. RFIC semiconductor technology functionality for wireless applications.

GaAs would seem to be the ideal medium for RFICs due to its semi-insulating properties and high electron mobility. It is particularly attractive for amplifiers because of high efficiency and gain and for RF switches due to its low loss. Despite high material costs, GaAs IC processing requires much fewer mask layers than comparable silicon processes. Still, GaAs is the highest cost technology commonly in use, with a cost per wafer of about \$1500. This makes the inclusion of matching circuitry and logic functions on-chip costly. Additional, MESFETs, being square-law devices and having wide parameter variation even on a single chip, are not well suited to the differential circuits common in multiplier and scaling circuits.

High-speed bipolar processing can rival GaAs in speed at the frequencies where the new PCS systems are being implemented and is the lowest cost approach now. The technology is particularly useful in mixer functions wherein the differential amplifier Gilbert Cell is favored. Nevertheless, for high-efficiency amplifiers and RF switches, GaAs is preferable. BiCMOS, long the technology of choice for digital application, has advanced to the point at which RF performance is quite good. The ability to integrate low-current logic is a definite advantage and common bipolar logic can be included in the chip design.

The versions of BiCMOS which are useful for RF can have 30 or more mask layers, making BiCMOS almost as costly as GaAs. Heterojunction processes in both GaAs and silicon are being applied to the power amplifier function. These technologies give the highest device efficiencies possible with production processing. Low-throughput of the epitaxial processing required to make these devices makes these technologies very expensive. As these processes move from the aerospace environment to commercial volumes, cost should come down making HFET and HBT RFIC viable candidates for RF power amplifiers. HBTs may hold promise for frequency converter applications if cost can be reduced sufficiently. The lower cost of silicon bipolar and BiCMOS will probably make these, at least for the near future, the technologies of choice for all but the RF amplifier and switch functions.

Future Trends

By the beginning of the 21st century, it can be expected that the PCS concept will be implemented using a number of system designs. Wireline will compete with micro-cellular systems and CATV for the local loop, that last link from the telecommunications system to the subscriber. The subscriber equipment undoubtedly will be realized as wireless pica-cellular and will be compatible with one or more roaming systems. These micro and macro-cellular based roaming systems will compete with and complement and satellite systems. The standards issues eventually will be resolved promoting standardized chipsets, including RFICs. One can envision a two-chip RF section comprised of a GaAs LNA, PA and switch chip and a bipolar or BiCMOS transconverter and synthesizer chip. The entire digital portion of the radio will probably be on one chip.

As wireless systems emerge, RFIC technology is being called upon to meet the demands of reduced size and weight at low cost. Manufacturers are responding with SSI and MSI functions at costs which would have been unthinkable a few years ago. The combination of technologies required include packaging and test as well as selection of appropriate semiconductor platform. As systems mature and stabilize, integration and standardization will advance. The PCS vision gives RF component manufacturers their first true high-volume opportunity since the beginnings of two-way radio.

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