Correlation of Returns in Non-Contemporaneous Markets*

Emel Kahya
Rutgers University,U.S.A.

This article investigates the effects of non-overlapping trading hours on the correlations and cross-serial correlations of returns in non-contemporaneous stock markets and develops a simple formula for calculating contemporaneous correlation measures. The presence of these effects is illustrated empirically using stock market returns data for the U.S., Japan, and the U.K. The results indicate that daily correlations of returns in these markets are biased downward while daily cross-serial correlations of returns are biased upwards. These findings have significant implications for studies investigating the transmission mechanism of stock price innovations across national stock markets and portfolio management (JEL G15).

Key words: mean spillovers, contemporaneous correlations of returns.

I. Introduction

Several articles examine the transmission mechanism of stock price innovations (mean spillovers) across international stock markets. Eun and Shim (1989) and Koch and Koch (1991) find that daily stock market innovations in the U.S. are rapidly transmitted to the rest of the world, whereas innovations in other national markets have a very low impact on daily stock prices in the U.S. Similar results for daily data are reported by Fischer and Palasvirta (1990), Becker, Finnerty, and Gupta (1989), and Von Furstenberg and Jeon (1989). These findings, however, are not supported for weekly data. Specifically, Theodossiou and Lee (1993) and Theodossiou et al. (1997) find that weekly market innovations in the U.S. and other major national stock markets have a

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very low or insignificant impact on weekly stock prices. Moreover, correlations of returns for daily data are consistently lower than those of weekly data.

The above irregularities may be attributed to the fact that trading hours in various national stock markets are not overlapping. As a result, a previous day's returns in one market are statistically related to the current returns in markets that close earlier, giving credence to the assertion of mean spillovers. Moreover, the correlations of daily returns for positively related markets are biased downwards and for negatively related markets are biased upwards. These biases are smaller and insignificant for weekly and monthly data.

To avoid the above problems, Hamao, Masulis, and Ng (1990) and Koutmos and Booth (1995) use intra-daily data. The use of intra-daily data resolves problems associated with the measurement of mean spillovers. Nevertheless, intra-daily data do not facilitate the calculation of contemporaneous correlations of returns. These correlations are very important for managing investment risk and, as such, they are closely monitored by major money market managers, e.g., Solnik 1991, p. 40.

This article develops a statistical framework to explain the effects of non-overlapping trading hours on the correlations and cross-serial correlations of returns in non-contemporaneous stock markets and presents a simple formula for calculating contemporaneous correlations measures. The presence of these effects is illustrated using stock market returns data for the New York Stock Exchange (NYSE), London Stock Exchange (LSE), and Tokyo Stock Exchange (TSE). Because these are the largest and most efficient markets in the world, the stochastic behavior of stock prices in these markets is expected to be in line with the underlying assumptions of the statistical framework presented in this article.

The article is organized as follows: Section II presents the statistical framework. Section III presents the empirical results. The article ends with a summary and concluding remarks in section IV.

II. Statistical Framework

A. Trading Hours and Stock Market Returns

Because of different time zones, trading hours and stock market returns on the NYSE, LSE, and TSE do not overlap. Specifically, the NYSE opens at 9:30 a.m. and closes at 4:00 p.m. The LSE opens at 9:00 a.m.

and closes at 4:00 p.m. local time or 11:00 a.m. New York time. The TSE opens at 9:00 a.m. and closes at 3:00 p.m. local time or 1:00 a.m. (the same day) New York time. Thus, the LSE closes five hours earlier than the NYSE and the TSE closes ten hours earlier than the LSE and fifteen hours earlier than the NYSE.

The time diagram below represents two successive equal-length periods for the NYSE. The length of a period can be a day, a week, or a month.

$$
\begin{array}{c}
t_{-n} \rightarrow t_{-n+1} \rightarrow \cdots \rightarrow t_{-1} \rightarrow t_0 \rightarrow t_1 \rightarrow \cdots \rightarrow t_{n-1} \rightarrow t_n \\
t-1 \xrightarrow{\hspace{4cm}} t \xrightarrow{\hspace{4cm}} t+1
\end{array}
$$

Each period is divided into n subperiods of equal time length, denoted by t_{s-1} to t_s, where $s = 0, \pm 1, \pm 2, \pm 3, \cdots \pm n$. For convenience, the time length of each subperiod, denoted by Δt, is taken to be an hour. Each time point t_s can be expressed in terms Δt as $t_s = t + s\,\Delta t$. Note that the number of subperiods n depends on the period's length. Specifically, for daily length periods $n = 24$, for weekly length periods $n = 168$, and for monthly length periods $n = 720$. By construction, $n\,\Delta t = 1$ period.

For practical purposes, periods for the NYSE, LSE, and TSE extend from one closing to the next closing of the exchanges. Thus, for period t to $t + 1$, the time point $t + 1$ represents the closing time for the NYSE. The corresponding period for the LSE is t_{-k} to $t_{-k} + 1$, where $t_{-k} + 1 = t - k\,\Delta t + 1 = t + (n - k)\,\Delta t$ is the closing time for the LSE. Note that $k = 5$, because the LSE closes 5 hours earlier than the NYSE. Similarly, the corresponding period for Japan is t_{-p} to $t_{-p} + 1$, where $t_{-p} + 1 = t + (n - p)\,\Delta t$ and $p = 15$ (TSE closes 15 hours earlier than the NYSE). Clearly, periods on the three exchanges are not overlapping.

Let $P_{us}(t + 1)$ be the value of a stock market price index in the U.S. at time $t + 1$; henceforth called the close price. Furthermore, let $P_{uk}(t_{-k}+1)$ and $P_{jp}(t_{-p} + 1)$ be the respective close prices for the U.K. and Japan. The log-return for the U.S. during period t to $t + 1$ is

$$
\begin{aligned}
R_{us}(t+1) &= \ln P_{us}(t+1) - \ln P_{us}(t) \\
&= \sum_{s=1}^{n} (\ln P_{us}(t_s) - \ln P_{us}(t_{s-1})) = \sum_{s=1}^{n} r_{us}(t_s),
\end{aligned}
\tag{1a}
$$

where $r_{us} = \ln P_{us}(t_s) - \ln P_{us}(t_{s-1})$ is the log-returns for the subperiod t_{s-1} to t_s. The corresponding log-returns for the U.K. and Japan are

$$R_{uk}(t_{-k}+1) = \ln P_{uk}(t_{-k}+1) - \ln P_{uk}(t_{-k}) \tag{1b}$$

$$= \sum_{s=-k+1}^{n-k} \left(\ln P_{uk}(t_s) - \ln P_{uk}(t_{s-1})\right) = \sum_{s=-1+k}^{n-k} r_{uk}(t_s),$$

and

$$R_{jp}(t_{-p}+1) = \ln P_{jp}(t_{-p}+1) - \ln P_{jp}(t_{-p})$$

$$= \sum_{s=-p+1}^{n-p} \left(\ln P_{jp}(t_s) - \ln P_{jp}(t_{s-1})\right) = \sum_{s=-1+p}^{n-p} r_{jp}(t_s), \tag{1c}$$

where $r_{uk}(t_s)$ and $r_{jp}(t_s)$ are the log-returns for the U.K. and Japan during the same subperiod t_{s-1} to t_s.

Define

$$\sigma_i^2 = \text{var}(r_i(t_s)), \tag{2}$$

$$\sigma_{i,j} = \text{cov}\left(r_i(t_s), r_j(t_s)\right), \tag{3}$$

and

$$\rho_{i,j} = \sigma_{i,j} / (\sigma_i \sigma_j), \tag{4}$$

for $s = 0, \pm 1, \pm 2, \ldots$ and i, j = *us*, *uk* and *jp*, to be respectively the variance, covariance, and correlation of returns in the three markets for the subperiod t_{s-1} to t_s. These measures are contemporaneous and reflect the *true* stochastic relationship of returns in the three markets. Note that because trading in the three markets does not take place twenty-four hours per day, the above measures cannot be estimated in the standard way. Nevertheless, they provide the foundation for understanding the effect of non-overlapping trading hours on the calculation of covariances and correlations of returns in such markets.

B. Variance, Covariance, and Correlation of Returns

Under the assumption that stock prices in each market are random walk processes, the returns for each period and subperiod are identically and independently distributed across time with the same mean and variance. Consequently, the variance of observable returns in each period is equal to the sum of the variances of the returns for its respective sub-periods.[2] That is,

$$\operatorname{var}\left(R_i(t_{-l}+1)\right) = \sum_{s=-l+1}^{n-l} \operatorname{var}\left(r_i(t_s)\right) = n\,\sigma_i^2\,, \tag{5}$$

for i = *us*, *uk* and *jp*, and l = 0, k and p (U.S., U.K. and Japan). Moreover, the covariance of observable returns for the three markets is

$$\begin{aligned} \operatorname{cov}\left(R_i(t_{-l}+1), R(t_{-m}+1)\right) &= \operatorname{cov}\left(\sum_{s=-l+1}^{n-l} r_i(t_s), \sum_{s=-m+1}^{n-m} r_j(t_s)\right) \\ &= \operatorname{cov}\left(\sum_{s=-l+1}^{n-m} r_i(t_s), \sum_{s=-l+1}^{n-m} r_j(t_s)\right) = (n-m+l)\,\sigma_{i,j}\,, \end{aligned} \tag{6}$$

for i, j = *us*, *jp* and *uk*, and $l < m$ = 0, k and p. It follows easily from (5) and (6) that the correlations of observable returns are

$$corr\left(R_i(t_{-l}+1), R_j(t_{-m}+1)\right) = \frac{(n-m+l)}{n}\rho_{i,j}\,, \tag{7}$$

for i, j = *us*, *jp* and *uk*, and $l < m$ = 0, k and p. Equation 7 implies that the correlation of observable returns in markets i and j, that close l and m ($l < m$) hours prior to the U.S. market, is biased downward by a factor of $(n – m + l)/n$. This is because $0 < (n – m + l)/n < 1$. Note that in the trivial case where $m = l$ (i.e., the markets close the same time), the bias in the correlation coefficient is zero. Note that in moving from higher (daily) to lower frequency data (weekly), n gets larger, but m and l stay the same, and the ratio $(n – m + l)/n$ gets closer to one, thus the bias decreases. It follows easily from the above equation that the correlation of observable returns for the U.S. and the U.K. is

$$corr\left(R_{us}(t+1), R_{uk}(t_{-k}+1)\right) = \frac{n-k}{n}\rho_{us,uk}\,, \tag{7a}$$

2. The term observable returns refers to the returns extending from closing to closing.

with $k = 5$, between the U.S. and Japan is

$$corr\left(R_{us}(t+1), R_{jp}(t_{-p}+1)\right) = \frac{n-p}{n}\rho_{us,jp}, \tag{7b}$$

with $p = 15$, and between the U.K. and Japan is

$$corr\left(R_{uk}(t_{-k}+1), R_{jp}(t_{-p}+1)\right) = \frac{n-p+k}{n}\rho_{uk,jp}. \tag{7c}$$

with $p - k = 10$.

C. Cross-Serial Correlations of Returns

Under the hypothesis of random walk behavior for stock prices, past returns in one market do not correlate with current returns in another market, provided that trading hours in these markets overlap. Consequently, the cross-serial correlations of returns in these markets are expected to be zero. The analysis below shows that this condition does not hold for markets with non-overlapping trading hours.

Let $R_i(t_{-l})$ be the return in market i for the period $t_{-l} - 1$ to t_{-l}, and $R_j(t_{-m} + 1)$ the return in market j for the period t_{-m} to t_{-m} +1,where $l < m$ are as defined previously. Note that the overlapping between the two periods is $t_{-m} - t_{-l} = (m - l)\,\Delta t$ sub-periods. Thus, the above returns will have $(m - l)$ contemporaneous sub-period returns.

The covariance of the two returns is

$$\begin{aligned} \mathrm{cov}\left(R_i(t_{-l}), R_j(t_{-m}+1)\right) &= \mathrm{cov}\left(\sum_{s=-n-l+1}^{-l} r_i(t_s), \sum_{s=-m+1}^{n-m} r_j(t_s)\right) \\ &= \mathrm{cov}\left(\sum_{s=-m+1}^{-l} r_i(t_s), \sum_{s=-m+1}^{-l} r_j(t_s),\right) \qquad (8) \\ &= (m-l)\,\mathrm{cov}\left(r_i(t_s), r_j(t_s)\right) = (m-l)\,\sigma_{i,j}, \end{aligned}$$

for $i, j = us, uk,$ and jp and $l < m$. In case of perfect overlapping of trading hours in markets i and j, $m = l$, and the above covariance is equal to zero. This is a byproduct of the assumption that returns in each subperiod are i.i.d. random variables. Equation 8 can also be zero in case the covariance of contemporaneous returns in the two markets is zero, i.e., $\sigma_{i,j} = 0$, regardless of whether $l = m$. The variances for the aforementioned returns is the same as that given by (5). Thus the (cross) correlation of the returns is

$$corr\left(R_i(t_{-l}), R_j(t_{-m}+1)\right) = \frac{m-l}{n}\rho_{i,j} \, . \tag{9}$$

It easily follows from (9) that the pair-wise correlations between the U.S., U.K., and Japan are

$$corr(R_{us}(t), R_{uk}(t_{-k}+1) = \frac{k}{n}\rho_{us,uk} \, , \tag{9a}$$

$$corr\left(R_{us}(t), R_{jp}(t_{-p}+1)\right) = \frac{p}{n}\rho_{us,jp} \, , \tag{9b}$$

and

$$corr\left(R_{uk}(t_{-k}), R_{jp}(t_{-p}+1)\right) = \frac{p-k}{n}\rho_{uk,jp} \, . \tag{9c}$$

Equation (9) indicates that in markets with non-zero contemporaneous correlations ($\rho_{i,j} \neq 0$) and no price spillovers, the correlation of past observable returns in market *i* and current observable returns in market *j* (market *i* closes earlier than market *j*) will be non-zero, indicating the presence of price spillovers from market *i* to market *j*. The cross-serial correlation, expressed as a percentage of the contemporaneous correlation, is larger the larger the extent of non-overlapping between market *i* and market *j*, measured by the ratio $(m - l)/n$. As *n* increases, the latter ratio approaches zero.

D. Contemporaneous Correlations of Returns

Interestingly, the sum of (7) and (9) is equal to the contemporaneous correlation of returns in markets *i* and *j*. That is,

$$\begin{aligned}\rho_{i,j} &= \mathrm{cov}\left(R_i(t_{-l}+1), R_j(t_{-m}+1)\right) \\ &\qquad + \mathrm{cov}\left(R_i(t_{-l}), R_j(t_{-m}+1)\right).\end{aligned} \tag{10}$$

Thus, the correlations among the three markets are

$$\rho_{us,uk} = \text{cov}(R_{us}(t+1), R_{uk}(t_{-k}+1)) + \text{cov}(R_{us}(t), R_{uk}(t_{-k}+1)). \tag{10a}$$

$$\rho_{us,jp} = \text{cov}\big(R_{us}(t+1), R_{jp}(t_{-p}+1)\big) + \text{cov}\big(R_{us}(t), R_{jp}(t_{-p}+1)\big). \tag{10b}$$

$$\rho_{uk,jp} = \text{cov}\big(R_{uk}(t_{-k}+1), R_{jp}(t_{-p}+1)\big) + \text{cov}\big(R_{uk}(t_{-k}), R_{jp}(t_{-p}+1)\big). \tag{10c}$$

The above equations provide a means of obtaining contemporaneous correlations for markets with non-overlapping trading hours.

III. Empirical Results

The data include daily, weekly, and monthly stock market returns for the U.S., Japan, and the U.K. and span the period of May 4, 1984, to October 25, 1994. The data include 2,477 daily observations, 544 weekly observations, and 124 monthly observations. The returns for each market are computed using the formula $R_{i,t} = \ln(P_{i,t}) - \ln(P_{i,t-1})$, where $P_{i,t}$ is the level of the stock price index in market i at time t, for $i = us, jp$, and uk. The indices used are the S&P500 for the U.S., the Topix for Japan, and the FT100 for the U.K.

Table 1 presents various statistics on the correlations of daily, weekly, and monthly stock market returns in the U.S., U.K., and Japan. The correlation coefficients of returns are calculated using the standard correlation formula. The first number in each set gives the correlation of returns. The second and third number give the standard deviation and 95% confidence interval for each correlation. The standard deviations and confidence intervals are computed using the Bootstrap method with 1,000 replications, e.g., Efron (1982).[3]

3. Let $\rho_{x,y}$ be the correlation between the variables X_t and Y_t. Consider the regression model $Y_t = \alpha + \beta X_t + u_t$, where α and $\beta = \rho_{x,y}(\sigma_y/\sigma_x)$ are the OLS estimates, u_t, for $t = 1, 2, ..., T$, are the regression residuals, and T is the sample size. During each bootstrap replication, the sequence of Y_t's is artificially constructed using the model $Y_t^R = \alpha + \beta X_t + u_t^R$, where u_t^R

TABLE 1. Correlations of Observable Returns

Frequency of Data	$corr(R_{us}(t+1), R_{uk}(t_{-k}+1))$	$corr(R_{us}(t+1), R_{jp}(t_{-p}+1))$	$corr(R_{uk}(t_{-k}+1), R_{jp}(t_{-p}+1))$
Daily Correlations	.3995	.1779	.2356
Standard Deviations	.0242	.0188	.0200
95% Conf. Interval	$.3520 < \rho < .4440$	$.1406 < \rho < .2159$	$.1972 < \rho < .2741$
Weekly Correlations	.5268	.3534	.3264
Standard Deviations	.0329	.0369	.447
95% Conf. Intervals	$.4617 < \rho < .5924$	$.2801 < \rho < .4242$	$.2418 < \rho < .4155$
Monthly Correlations	.7840	.3565	.3439
Standard Deviations	.0295	.0783	.0833
95% Conf. Intervals	$.7229 < \rho < .8394$	$.2086 < \rho < .5030$	$.1843 < \rho < .4989$

Note: $R_{us}(t+1)$, $R_{uk}(t_{-k}+1)$, and $R_{jp}(t_{-p}+1)$ are the respective stock market log-returns for the U.S., U.K., and Japan during period t to $t+1$. The subscripts k and p indicate that the stock market in the U.K. closes k (= 5) hours prior to the U.S. market and in Japan it closes p (=15) hours prior to the U.S. market, thus returns in the three markets are not contemporaneous. The correlations are calculated using the standard formula for the correlation. The standard deviations and the 95% confidence interval for each correlation are obtained using the Bootstrap method with 1,000 replications.

The results of table 1 are in line with the theoretical relationships for the daily, weekly, and monthly correlations in non-contemporaneous markets, as established in the previous section. As expected, the correlations get larger as we move from daily to weekly and from weekly to monthly data, e.g., equation 7. The daily correlations lie below the 95% confidence interval for the weekly and monthly correlations, providing strong (statistical) support to the assertion that daily correlations are biased downward. As expected, the weekly and monthly correlations are close to each other. The only exception is the monthly correlation for the U.S. and U.K. The latter irregularity may be the result of significant spillovers from the U.S. to the U.K., or simply a statistical artifact attributed to a small monthly sample size.

Table 2 presents various statistics for the cross-serial correlations of returns. That is, the simple correlations of one-lag returns in the U.S. with current returns in Japan and the U.K. and one-lag returns in the U.K. with current returns in Japan.

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is a residual selected randomly with replacement from the sequence of residuals u_t, for $t = 1, 2, ..., T$. For each bootstrap sample, the correlation $\rho_{x,y}$ is computed using the standard formula for the correlation between X_t and Y_t^R. The set of correlations from each bootstrap sample provides the empirical distribution of the correlation. This distribution can be used to test various hypothesis regarding the correlation coefficient.

TABLE 2. Cross-Serial Correlation of Observable Returns

Frequency of Data	$corr(R_{us}(t), R_{uk}(t_{-k}+1))$	$corr(R_{us}(t), R_{jp}(t_{-p}+1))$	$corr(R_{uk}(t_{-k}), R_{jp}(t_{-p}+1))$
Daily Correlations	.2908	.2225	.1678
Standard Deviations	.0198	.0200	.0206
95% Conf. Interval	$.2513 < \rho < .3289$	$.1845 < \rho < .2627$	$.1250 < \rho < .2085$
Weekly Correlations	.1509	.0816	.0527
Standard Deviations	.0437	.0417	.0422
95% Conf. Intervals	$.0642 < \rho < .2374$	$-.0022 < \rho < .1587$	$-.0310 < \rho < .1368$
Monthly Correlations	.0493	.1916	.0879
Standard Deviations	.0890	.0919	.0910
95% Conf. Intervals	$-.1289 < \rho < .2156$	$-.0011 < \rho < .3653$	$-.0821 < \rho < .2646$

Note: $R_{us}(t)$ and $R_{uk}(t_{-k})$ are returns for period $t-1$ to t. $R_{uk}(t_{-k}+1)$ and $R_{jp}(t_{-p}+1)$ are returns for period t to $t+1$. The subscripts k and p indicate that the markets in the U.K. and Japan close k (=5) and p (=15) hours prior the market in the U.S. The correlations are computed using the standard formulas for the correlations. The standard errors and 95% percent confidence intervals for these correlations are calculated using the Bootstrap method with 1,000 replications.

The standard deviations and 95% percent confidence intervals for these correlations are also obtained using the Bootstrap method with 1,000 replications. All daily cross-serial correlations are positive and statistically significant. The correlations get smaller and statistically insignificant as we move from weekly to monthly data. This is easily verified by the fact that the 95% confidence intervals for the correlations include the zero value.

Table 3 provides estimates for the contemporaneous correlations of returns calculated using equations 10a–10c.[4] Standard deviations and 95% confidence intervals for these correlations are obtained using the Bootstrap method with 1,000 replications.[5] Interestingly, the daily, weekly, and monthly correlations are close to each other and fall within their 95% confidence intervals. The only exception is the monthly correlation for the U.S. and the U.K. that falls slightly outside the confidence intervals for the daily and weekly correlations. As previously mentioned, the latter irregularity may be a statistical artifact or the result of significant spillovers from the U.S. to the U.K.

4. These are also obtained by summing the respective correlation from tables 1 and 2.

5. The empirical distribution of each contemporaneous correlation is obtained by summing up the correlations and cross-serial correlations of observable returns at each bootstrap replication.

TABLE 3. Contemporaneous Correlations of Returns

Frequency of Data	$\rho_{us,uk}$	$\rho_{us,jp}$	$\rho_{uk,jp}$
Daily Correlations	.6902	.4004	.4034
Standard Deviations	.0312	.0275	.0289
95% Conf. Interval	$.6311 < \rho < .7511$	$.3478 < \rho < .4549$	$.3453 < \rho < .4612$
Weekly Correlations	.6777	.4350	.3791
Standard Deviations	.0548	.0556	.0605
95% Conf. Intervals	$.5743 < \rho < .7907$	$.3255 < \rho < .5409$	$.2607 < \rho < .4938$
Monthly Correlations	.8333	.5482	.4318
Standard Deviations	.0939	.1210	.1213
95% Conf. Intervals	$.6417 < \rho < 1$	$.2899 < \rho < .7753$	$.1957 < \rho < .6736$

Note: This table provides the estimates of the contemporaneous correlations of returns, $\rho_{i,j}$, for i, j = *us*, *jp*, and *uk*. These are calculated using equations 10a–10c. Standard errors and 95% confidence intervals for these estimates are obtained using the Bootstrap method with 1,000 replications.

IV. Summary and Concluding Remarks

This article develops a statistical framework to explain the effects of non-overlapping trading hours on the correlations and cross-serial correlations of returns in non-contemporaneous stock markets and presents simple formulas for calculating contemporaneous correlations measures. The presence of these effects is illustrated using stock market returns data for the U.S., Japan, and the U.K. The results indicate that daily correlations of returns in positively related non-contemporaneous markets are generally biased downward while cross-serial correlations of returns are generally biased upwards. The opposite is true for negatively related markets. These biases are smaller and statistically insignificant for weekly and monthly data. The simple formulas presented in this paper appear to provide a good means to correct for the effect of non-overlapping trading hours on the contemporaneous correlations of returns.

Accurate measurement of contemporaneous correlations of returns in international markets is a topic of great importance and interest to portfolio managers and international investors. This is because the argument in favor of international investments is based on the assumption that prices of financial assets in international capital markets have lower correlation than prices of financial assets in domestic markets. Consequently, the inclusion of foreign financial assets in domestic portfolios results in lower portfolio risk without sacrificing expected return. The understatement of correlations among the domestic and foreign capital markets may induce portfolio managers to invest a larger percentage of funds in foreign securities, resulting in non-optimal portfolios.

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