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What Determines the Future Value of an Icon Wine? Evidence from Australia

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CIES DISCUSSION PAPER 0233

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Abstract

The Australian wine auction market is characterised by large variations in price between different vintages of the same wine. Yet the release prices of those wines exhibit considerably less volatility. This paper addresses the question: to what extent can we anticipate the future price of such icon wines from information available at the time of release? Specifically, it looks at the importance of the weather conditions during the grape-growing season. A hedonic model is estimated to explain the variation in price between different vintages using several weather variables plus dummy variables for capturing changes in winemaking and grape growing techniques. The model is estimated using auction price data for four South Australian icon red wines: three by Penfolds (Grange, St Henri and Bin 707), and one by Henschke's (Hill of Grace). We show that weather variables and changes in production techniques, along with the age of the wine, have significant power in explaining the secondary market price variation across different vintages of each wine. The results have implications for winemakers in determining the prices they pay for grapes and charge for their wines, and for consumers/wine investors as a guide to the quality of immature icon wines.

Key words: wine quality, investment under uncertainty, hedonic pricing model

JEL codes: C23, D12, D44, D80, G12

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What determines the future value of an icon wine? Evidence from Australia

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The Australian wine auction market is characterised by large variations in price between different vintages of the same wine. Yet the release prices of these wines exhibit considerably less volatility. Thus, there exists the potential for buyers to improve their investment returns by choosing to purchase those vintages that are under-priced at the time of release, relative to their future secondary market value. Similarly, wine producers could improve profits either by charging higher prices for the better vintages (reflective of the price they will receive later in the secondary market), or by holding back some of the better vintages to sell later as the wine's future quality becomes more obvious.

An important question for both these producers and buyers is: to what extent can we anticipate the future prices of such icon wines from information available at the time of purchase? Tasting the young wine, even by professionals, is unreliable because the high tannin content makes them astringent to the palate in their early years.

Weather conditions during the grape-growing season, long recognised by vignerons as a determinant of the quality of a vintage, may provide an objective and easily quantifiable guide (Gladstones 1992). Econometricians have tested that hypothesis for Bordeaux wines and found it is strongly supported (Ashenfelter, Ashmore and Lalonde 1995). A more-limited test on just one Australian wine (Grange) using only three years of auction data gave promising results as well (Byron and Ashenfelter 1995). The purpose of the present paper is to make use of the much larger database now available to test this hypothesis for a broader range of icon wines using up to 13 years of auction prices.

Specifically, a hedonic model is estimated to explain the variation in the secondary (auction) market price between different vintages of particular wines, using several weather variables plus dummy variables for capturing changes in winemaking and grape growing techniques over time (based on interviews with the chief winemakers of the relevant wineries). The model is estimated using auction price data for four South Australian icon red wines: three by Penfolds (Grange, St Henri and Bin 707), and one by Henschke's (Hill of Grace).[1] This attempt to explain the variation in price between different vintages of the same wine label is in contrast to numerous studies that seek to explain the variation in price between the same vintages of different wineries (see Oczkowski (2001), Schamel and Anderson (2001) and the references therein).

The paper is structured as follow. We first review previous studies that attempt to quantify the relationship between weather conditions during the growing season and wine prices. We then discuss our choice of variables for explaining the relationship between quality and weather, production techniques and wine age. The next section presents the empirical results, while the final section draws out conclusions, offers some implications for winemakers and consumers/investors, and suggests areas for future research.

Previous Literature

Ashenfelter, Ashmore and Lalonde (1995) were the first to attempt an empirical explanation of the variation in price between different vintages of the same wine. They consider the variation in price between different vintages of a representative sample of thirteen Bordeaux wines (used to create a vintage price index). The paper uses weather conditions during the growing season that produced the wine, widely recognised in the viticulture literature as a determinant of wine quality. Ashenfelter et al. also include age as an explanatory variable to capture the effect of increasing scarcity and the opportunity cost of holding wine. They find that age alone can explain 21% of the variation in the price index between vintages. However, the inclusion of three weather variables in the model increases the model's explanatory power (as measured by R^2), to 83%. The 'Bordeaux Equation' as it is termed, constitutes a hedonic price equation. The coefficients estimate the implicit marginal price of the 'attributes', in this case the weather conditions that produced the vintage and the age of the wine decision.

That model was modified for a single wine by Byron and Ashenfelter (1995) in a study of Penfolds icon wine, Grange, and by Fogarty (2000) in a study of the West Australian wine, Moss Wood. These studies found a number of weather variables and age to be significant explanators of variation in price of these wines (with $\overline{R}^2$ of 0.83 and 0.88, respectively). In addition, the models were demonstrated to have strong out-of-sample predictive power. The findings of these studies support the Ashenfelter et al. hypothesis that the secondary market price of a given vintage depends on the weather conditions that produce the vintage.

1 Some information on these classic wines is provided in Appendix 1. For more details see Halliday (1998) and Read and Caillard (2000).

Jones and Storchmann (1999) more clearly articulate the relationship between weather and wine quality. They adopt a two-step approach to modelling the price variation of Bordeaux wines, both between different wines and across vintages. Firstly, they estimate a model to explain variation in sugar and acid content at harvest by climatic variables. Secondly, they use these two endogenously determined variables as explanatory variables in the price regression, thus highlighting the channel through which weather influences quality and hence price. Another contribution made by this paper is recognition of the contribution of winemaking techniques to quality variation.

Our model

It is possible to explain the existence of secondary market price variation between different vintages of the same wine by adapting the hedonic price methodology proposed by Rosen (1974). Rosen's model explains price variation between a differentiated set of commodities via evaluation of an implicit or 'hedonic' price associated with each characteristic.

Rosen (1994) states that a particular class of commodities can be described by a vector of n objectively measured characteristics as

(1) $$z = (z_1, z_2, ..., z_n)$$

where z_i is the amount of the i th characteristic contained in each good.

In the context of this paper the 'class of commodities' refers to the set of vintages under consideration for a particular icon wine. The n characteristics which differ between the vintages include the age of the wine and the qualities of the wine once mature, which we include indirectly via objectively measured weather and technological change variables that impart these qualities.

The market price of a particular vintage reflects the 'price' of each of the characteristics embodied in that vintage. That is,

(2) $$p(z) = p(z_1, z_2, ..., z_n)$$

where p is an increasing function of all the characteristics.[2]

[2] Detailed properties of this model are laid out in Appendix 2.

The aim in this paper is to estimate this hedonic price function in order to relate the price of a given vintage to its quality, as indicated by the objectively measured characteristics of weather, grape growing and winemaking techniques, and age.

Explanatory variables

What factors explain the variation in quality (and hence price) between different vintages of the four icon wines in this study? The potential quality of a wine is a product of the quality of the inputs (particularly grapes) and the winemaking technique used to transform these inputs into the final product. The quality of grapes in turn is determined by the interaction of soil, topography, climate and grape growing techniques. Given that we are attempting to explain variation in price of different vintages of the same wine label, it is reasonable to treat soil quality, aspect, slope and altitude as constant between vintages. Thus, this study focuses on variations in weather and changes in grape growing and winemaking techniques as explanators of potential quality differentials. However, the actual quality of the wine at any point in time depends on whether it has yet reached or has passed its potential, and thus we also discuss the importance of age in explaining quality variation across vintages at any point in time.

Weather

The influence of weather conditions during the growing period on grape quality has been well established. In recognition of the importance of climate, winemakers develop grape growing techniques to maximise the beneficial aspects of climate while reducing weather-based fluctuations in quality. Smart (2001) argues that while all climate parameters can be important in influencing grape quality, temperature is undoubtedly the most important. Gladstones (1999) suggests an average daily temperature during the growing season (mid-September to March in southern Australia) of 20-22ºC is optimal for the formation of colour, flavour and aroma compounds in red table wines. Thus, we assume that grapes grown under these optimal conditions will be of the best quality, and vintages produced from these grapes will receive the highest prices. Ashenfelter, Ashmore and Lalonde (1995) report a positive linear relationship between average temperature during the growing season and price for Bordeaux red wines. However, when considering the warmer Barossa region of South Australia where the average growing season temperature regularly exceeds the suggested optimum, Byron and Ashenfelter (1995) find a quadratic function to be the most appropriate way to model the effect of temperature on wine prices. The quadratic function they estimate is concave with a turning point of 19.05 degrees, just slightly below the temperature range Gladstones puts forward as optimal.

Temperature also has the potential to affect quality and yields through its variation. Gladstones points out that the biochemical processes of grape development are favoured by a low diurnal temperature range (ie. the difference between the daily maximum and the nightly minimum temperatures). His argument is supported by Byron and Ashenfelter, who find a significant negative relationship between the price of Grange and the average temperature differential during its growing season.

The fact that diurnal temperature variability has the potential to affect grape quality suggests that average daily temperature (the average of the daily maximum and minimum temperatures) may not be the most appropriate index to test the affect of temperature on grape quality. For example, even though one vintage year may have a lower average temperature than another, this may simply be because the minimum temperatures are lower (and hence the diurnal temperature range larger). The average maximum temperature during the growing season therefore would seem to be a more reliable index than simply the average temperature to quantify the affect of temperature on a particular grape vintage.

This is supported by Happ (1999), who develops a 'heat work index' which measures the thermal character of a particular day based on 20-minute temperature observations. He shows that, as a less data intensive approximation, the average maximum temperature provides a superior measure of the temperature conditions affecting wine grapes to the average temperature. Happ's (1999) index is based on the numbers of hours of the day with temperatures between 16ºC and 22ºC (a favourable zone for development of grape flavour compounds). While a simple daily maximum does not provide such an accurate measure of optimal conditions, Happ shows it provides a reasonable indicator of a site's tendency to experience temperatures above 22ºC.

The number of hours of sunshine is another variable important to grape quality, both directly and for its interaction with temperature. Gladstones (1992) suggests that sunshine hours during the growing season, particularly in early spring, have a positive influence on quality. However, previous statistical analyses (Ashenfelter et al. 1995, Byron and Ashenfelter 1995, and Fogarty 2000) fail to identify any statistically significant relationship between hours of sunshine and icon wine prices. This failure is likely to be linked to the correlation between sunshine hours and temperature, which makes isolating their separate effects difficult.

After temperature, Smart (2001) ranks rainfall as the next most important climatic determinant of grape quality. As Gladstones (1992) points out, it is the seasonal distribution of rainfall which is important. Rainfall during winter and early spring aids grape development, particularly since the four wines considered come from vineyards that rely wholly or mostly on precipitation. On the other hand, rainfall in the period prior to harvest can waterlog the soil and thus prove detrimental to both grape yield and quality. These effects find statistical support in the study by Ashenfelter et al. (1995), who report evidence of a negative relationship between rainfall prior to harvest and Bordeaux wine prices, and a positive relationship between rainfall during the winter preceding the vintage and price. While the study of Grange prices by Byron and Ashenfelter (1995) also finds statistical evidence of the detrimental effect of rainfall prior to harvest, they do not find any statistically significant relationship between winter rainfall and price.

Gladstones (1992) also suggests there is a positive relationship between wine quality and relative humidity in February, the last month of the growing season. This relationship is particularly important in the relatively warm wine regions in Australia where afternoon humidity is necessary to encourage ripening when February temperatures are high.

The final climatic variable listed by both Gladstones (1992) and Smart (2001) as important to grape quality is windiness. Wind can have both a positive and negative influence on quality. On the positive side, wind can help prevent frosts and provides air circulation to the vines (which lowers humidity). However, strong winds have the potential to harm grape quality (Hamilton 1988). In South Australia, added dangers arise from hot, dry summer winds because they can cause imperfect ripening.

Vineyard management techniques

In addition to these weather influences, changes in vineyard management techniques can explain quality differences between the grapes used to produce different vintages. Gladstone (1992) details a range of practices important to both grape yield and quality. The spacing of vines determines the exposure of vines to sunlight, water and soil nutrients and therefore affects both yield and quality. Also affecting sunlight exposure is the orientation of rows. The height of vines is also important, because it determines the amount of heat the vine is exposed to via radiation from the soil. Further improvement of the efficiency of light use can come from the adoption of a suitable trellising system and canopy management. Irrigation, fertilisation, artificial drainage and windbreaks are other vineyard management techniques that may be important influences on grape yield and quality.

Winemaking techniques

High-quality grapes are an essential but not sufficient condition for producing high-quality wines. It is only when quality grapes are combined with superior winemaking techniques that excellent wines are produced. The first important facet of winemaking is the selection of the grapes, followed by any blending. For the three Penfold wines considered in this study, the blends change with each vintage along with changes in grape quality from different sites. For Henschke's Hill of Grace, a single-vineyard wine, the absence of the option to blend to offset quality variation means that the choice of grapes is of utmost importance.

Another important aspect of making icon wines is the oak in which the wine is matured. Changes in the type of oak and the length of maturation can alter the distinctive quality of the wine and thus its market price, as can whether the barrels are new or used.

Age of the wine

A characteristic of icon wine of the sort considered in this study is their ability to develop and improve with age. These wines are characterised by a high content of tannins in their youth, making them unpleasant for early drinking. Then as the tannin content recedes, the quality gradually improves until the maximum quality is reached. This state can persist for a number of years or even decades before the quality begins to decline. Although previous studies model the relationship between quality and age linearly (Ashenfelter et al., Byron and Ashenfelter, and Fogarty), it seems reasonable, given the nature of the maturation process, to model age as a quadratic.

Age is also related to price because the scarcity of a given vintage is non-decreasing with time. As a wine ages, more of the given vintage stock is consumed so that scarcity, and hence price, increases.

The data

Price data

Wine auctions are the principal secondary market for icon wines in Australia, aided by the fact that the liquor licensing laws in many states prohibit private sales of wine. Auction prices provide a comparatively high degree of price transparency, and therefore provide the best indication of the equilibrium value of a particular vintage of wine at any point in time. In addition, these auctions are of the 'silent bid-written tender' kind and thus circumvent many of the problems of auctions as a price determination mechanism. Langtons represent over 70% of the wine auction market in Australia,[3] and they have kindly provided the price data for this study.

The data provided are the high and low sale price and the date for every occasion on which each of the four icon wines was traded over the period 1988-2000. From this, the unweighted average of the sale price for each vintage in each auction year is calculated for each of the four wines. The prices are unweighted because data on the volume of wine traded at each date are, unfortunately, not available. However, in so far as differences in volumes traded are not large and are randomly distributed for a given vintage, this should not unduly affect the analysis.

Because the wine auction market in Australia only really developed in the last decade, many of the vintages were not traded every year, particularly in the first few years. Thus, only the auction years which provide a sufficient number of observations are considered for each wine. They are 1988-2000 for Grange, 1994-2000 for St Henri and Bin 707, and 1995-2000 for Hill of Grace.

In addition, some of the earlier vintages of each wine are excluded from the analysis either because they were too infrequently traded or because their price reflects collector value rather than quality. These older vintages belong in a different market, where price is driven purely by scarcity rather than quality. The vintages that are included are: 1960-1995 for Grange, 1965-1995 for St Henri, 1971-1994 for Hill of Grace, and 1976-1995 for Bin 707. Despite, narrowing the data sets there still remains a number of 'missing' observations, when a particular vintage is not traded in an auction year within the sample range.

The unweighted average nominal price in each auction year is converted into real terms using the Consumer Price Index with base year 2000.

Weather data

The weather data are sourced from the Australian Bureau of Meteorology's Nuriootpa and Coonawarra Climate Stations. A major issue is determining the weather conditions during the growing season for Penfolds grapes, becausethey are sourced from various regions but in different proportions each vintage. Because the exact percentages of grapes used from each region to produce a given vintage are not publicly available, it is not possible to create a weighted average weather index for each vintage. Mike Farmilo, the Chief Winemaker at Penfolds, suggested the Nurioopta Climate Station would be the most representative site for Grange, and indeed Byron and Ashenfelter (1995) found that the data from this station provided

3 Details are given in the annual report of Langton's *Australian Fine Wine Investment Guide,* Sydney.

the best fit. Hence this study will also use Nurioopta as a representative Climate Station for Grange. St Henri, like Grange, also uses grapes primarily sourced from the Barossa region and so Nurioopta will be used as the representative station for this wine also. For Bin 707, the majority of grapes are sourced from the Coonawarra region and so Coonawarra is chosen as the representative climate station. However, data from Coonawarra are not available for all the variables of interest and thus Nurioopta data are used for the variables not collected at Coonawarra. For Hill of Grace, a single site wine, Nurioopta is the closest Climate Station with sufficient data available.

Technological change data

Data on the major changes in viticultural management and winemaking techniques were collected by interviewing the Chief Winemakers at Southcorp (the producer of Penfolds) and Henschke. In the interviews John Duval from Penfolds and Stephen Henschke discussed what they considered to be the major changes in their grape growing and winemaking techniques over the sample period.

In recognition of the importance of grape quality to all its blended wines, Penfolds introduced the star quality system in 1983. This system helps overcome the possible principal-agent problem, by offering substantial bonuses to grape growers in line with the number of stars (a measure of quality) that their grapes achieve. Penfolds management adopted this system to maintain the integrity of their top wines, by introducing a minimum star requirement for the grapes used to produce each wine. However, while it is likely the plan has improved quality (and reduced quality risks) since its introduction, the fact that it was phased in over a number of years makes it less likely to show up as significant than if it was introduced overnight.

Another innovation introduced across all three Penfolds wines was a change in grape-pressing techniques in 1990, again aimed at improving the quality of the wine produced.

For Bin 707, a subtle change in style was introduced in 1985, from which vintage the wines became more ‘focused’. Thus, we also test for this change in style using a dummy variable to see if it is positively recognised in the secondary market price.

Langtons 1998 *Fine Wine Investment Guide* suggests that early vintages of Hill of Grace (1971-1977) are not considered as distinguished as vintages produced from 1978 when Stephen and Pru Henschke took over the family winery. Thus, we include a dummy variable with a break at 1978 to determine whether this is indeed the case.

In addition, Stephen Henschke detailed a number of changes introduced during his period of managing the winery that may have improved the quality and hence the demand for the wines. In 1983, refrigeration was introduced into the winery. In the same year, the wine was matured in new French Oak barrels for the first time. And in a further attempt to improve grape quality, a new trellising system was introduced in 1990.

Estimation methodology

The price data set for this study is more extensive (in the number of both vintages and auction years) than considered in the previous studies of single wines by Byron and Ashenfelter (1995) and Fogarty (2000). Both those analyses use only three years of auction data, and both studies estimate separate hedonic price functions for each year for just one wine. However, given that we have a number of years of auction data for each wine, panel data analysis is a more appropriate methodology to adopt.

Panel data analysis utilises longitudinal data sets, examining a set of the same individuals at various points in time. The data set for this study is unique in that both the cross sectional (auction year) and time series (vintage year) components of the data set have a time dimension. However, this by no means limits the application of the normal panel estimation techniques. The advantage of employing the panel data methodology in this context is that we have a greater number of observations for a given number of estimable parameters, and therefore we achieve more efficient estimates of these parameters.

A key consideration in panel data analysis is differentiating between homogeneous (same for each cross section) and heterogeneous (cross section specific) parameters. It is necessary to provide a theoretical basis for the choice in each case. We would expect to see variation in price between auction years, reflecting underlying macroeconomic influences, changes in tastes or prices of substitutes or complements that are not included in the model. Thus, we conclude that the pooled OLS technique (which simply pools data across cross-sectional units) is inappropriate. However, theoretical considerations suggest that the coefficients of the explanatory variables would be constant across auction years. That is, we expect implicit prices associated with the weather and technique variable to be independent of factors such as macroeconomic conditions. Thus, we only need to estimate one parameter for each explanatory variable. These theoretical considerations suggest that fixed or random effects models would most appropriately capture the heterogeneity in the data. The fixed effects approach includes an auction year specific constant term to capture the heterogeneity, whereas the random effects model includes an independently and identically distributed auction year specific disturbance. Given the likely systematic nature of the auction year specific effects, it is more appropriate to employ the fixed effect estimation methodology here.

Given all the above, we evaluate the implicit prices associated with the characteristics imparted through each of the explanatory variables by specifying the following hedonic price function:

$$P_{it} = F(A_{it}, W_t, I_t)$$

where P_{it} = the auction price of vintage 't' in auction year 'i',
A_{it} = the age of vintage 't' in auction year 'i',
W_t = the weather conditions during the growing season of vintage 't',
I_t = the techniques used by winemakers to produce vintage 't',

More specifically, the explanatory variables, as discussed above, are:

Age_{it}: Age of vintage 't' in auction year 'i';

$RainH_t$: Total rainfall in January, February and March, (the period just prior to harvest) in the year that produced vintage 't';

$\text{Max}Temp_t$: Average daily maximum growing season temperature, calculated by averaging the daily maximum temperatures over the months October-March;

$\text{Max}TempS_t$: MaxTemp squared,

$TempD_t$: Average daily growing season temperature variation, calculated as (average monthly max – average monthly min) then averaged over the months October- March,

$Humid_t$: Average daily 3p.m. relative humidity in March,

$Wind_t$: Average daily wind speed in November and December,

$WindS_t$: Wind Squared,

Sun_t: Total hours of bright sunshine during spring (September, October, November).

$Press_t$: A dummy variable for Penfolds wines with break at 1990, the year in which Penfolds changed their pressing technique,

$Style_t$: A dummy variable for Bin 707 with a break at 1985, the year Penfolds changed the style to create a more 'focused' wine,

SP_t: A dummy variable for Hill of Grace with a break at 1978, the year Stephen and Prue Henschke took over the family winery,

$Fridge_t$: A dummy variable for Hill of Grace with break at 1983, the year refrigeration was introduced in the winery,

Oak_t : A dummy variable for Hill of Grace with break at 1990, the year a new trellising system was introduced and also the year from which the wine was matured in new French Oak.

Estimation Results

The estimates of the hedonic price functions for each of the four wines are presented in Tables 1 and 2. It is evident that for each wine there is a statistically significant relationship between the age, weather and technological change variables and the secondary market price of the wines. Each variable is considered in turn.

Age of the wine

The effect of age on price is not directly comparable across all four wines in the study because of the different functional forms adopted. For Grange and St Henri, age is estimated to effect the secondary market price in a linear fashion. For both wines, the coefficient on age is positive and significant as expected. However, the magnitude of the coefficients differ markedly. The coefficient for Grange, 0.025, suggests that an extra year of aging corresponds to an average 2.5% increase in the real price, ceteris paribus. This is in line with previous studies (Ashenfelter et al., Byron and Ashenfelter, and Fogarty) which report estimated coefficients (based on nominal prices) of 0.035, 0.041 and 0.03, respectively. St Henri's coefficient on age, 0.003, is significantly different from zero but much lower. We suggested two factors that would determine the coefficient on age: quality improvement and increasing scarcity over time. In this case the difference in the estimated coefficients may be due to the difference in the aging potential of the two wines, with Grange exhibiting a much longer term cellaring potential than St Henri. According to Read and Caillard (1994), all but four of the vintages of Grange in our sample were still at their peak or were yet to reach their peak in the auction years considered. For St Henri, by contrast, many of the earlier vintages were considered past their peak, in which cases an additional year of aging would not be valued for St Henri. Also, like many of the first growths from Bordeaux that achieved a similar coefficient on age in the Ashenfelter et al. study, Grange has collector value well beyond its potential for drinking. That is, the vintages of Grange still in circulation but possibly past their prime for drinking are mainly in the market as antiques, rather than as part of the market for fine wine, withconsumers implicitly valuing highly their scarcity.

For Hill of Grace and Bin 707, age produces the best fit when modelled as a quadratic. For both wines the function is concave and significant. The turning points of the functions are approximately 13 years for Bin 707 and 24 years for Hill of

Grace. These are estimates of the average peak drinking times for these wines. (Drinking recommendations in Read and Caillard (1994) have 13 years as the lower end of the average cellaring recommendations for Bin 707.) For both these wines, their price is estimated to decline at a slow rate after the peak quality is reached, consistent with the idea that the quality of well-cellared icon wines plateau and then decline only slowly after reaching their peak. This adds support to the hypothesis that the relationship between price and age for these two wines is primarily driven by quality.

Temperature

Temperature is found to have a significant effect on the secondary market price variation of the vintages for the icon wines considered. For the three Penfold's wines, the average maximum temperature during the growing season was shown to be significant in explaining the secondary market price variation between the vintages. For Grange, and St Henri, this relationship is found to be best modelled as a linear one, with coefficients of 0.094 for Grange and 0.024 for St Henri. This suggests that a one degree increase in the average maximum growing temperature, leads to a 9.4% increase in the price of Grange but only a 2.4% increase in the price of St Henri. For Bin 707, the relationship between secondary market price and average maximum growing season temperature is found to be best approximated by a quadratic. That is, higher average maximum temperatures lead to higher secondary market prices up to the 24.5˚C optimal level, but for temperatures higher than 24.5˚C, the opposite is true. These results cannot be directly compared to the previous studies, because we consider the average maximum temperature rather than average temperature.

The diurnal temperature range is also found to be significant in explaining the variation in price between vintages for all of the wines considered. Consistent with the viticulture literature, the estimated relationship in each case is negative, suggesting a large temperature range has a negative affect on the quality of the grapes in a particular vintage year.

Rainfall

The estimated effect of total rainfall in the period prior to harvest was remarkably consistent across all four icon wines. In line with viticultural expectations, higher rainfall during this period has a negative effect on grape quality and thereby on secondary market prices. We estimate a one-millilitre increase in the total rainfall prior to harvest leads to an average 0.4% decrease in the secondary market price of

Grange, 0.5% for St Henri and 0.2% for both Hill of Grace and Bin 707. These estimates are also remarkably similar to those estimated in other studies (0.4% for Ashenfelter et al. and 0.3% for Byron and Ashenfelter).

On the other hand we find winter rainfall, estimated in the Ashenfelter et al. study to be significantly positively related to the secondary market price of Bordeaux wines, to be positive but insignificant for all four Australian icon wines. Interestingly, neither of the two previous hedonic price studies of Australian wine detected a significant winter rainfall effect. Presumably this is because of the greater use of irrigation in Australia, which can compensate for below-average winter rain.

Other weather variables

Humidity, windiness and sunlight were all discussed above as potentially important to wine quality. Although they were not found to be so in previous statistical studies, in this study they are all found to be significant for at least one of the wines considered. Humidity in the last month of the growing season is significant and of the expected sign and magnitude for both Grange and Bin 707. Windiness in November and December, estimated to be significant in explaining the price variation of all of the wines considered, is in each case best modelled as a quadratic, consistent with viticulture theory. The optimal wind speeds were estimated to be 11.3 kmph for Bin 707, 12.0 for Hill of Grace and slightly higher at 16.7 and 18.2 for Grange and St Henri, respectively. The model suggests that there are negative implicit prices associated with higher winds once these optimal speeds are reached. The difference in the optimal levels is likely to be related to the interaction of wind with the other weather variables and the underlying style of the wine.

While sunshine during spring is only found to be significant in explaining price variation for Hill of Grace, it is estimated to have a large affect for this wine: one additional hour of bright sunlight during spring is estimated to increase the secondary market price of the vintage by 2.7%. However, correlation between hours of sunlight and average temperature may explain the absence of a significant sunlight relationship for the other wines. Presumably this is why these two variables are never both significant in explaining price variation for the same wine.

Technological change

Changes introduced by the viticulturists and oenologists are shown to have a positive effect on the secondary market prices of their wines wherever they show up as being statistically significant. The introduction of a new pressing technique for Penfolds wines in 1990 has had a positive effect on the price of Grange. The change in style by winemakers to produce a more ‘focused’ Bin 707 in 1985 is also well received by consumers, who increased their willingness to pay by an average of 17.5% for the new style vintages. For Hill of Grace, consumers are increasingly willing to pay for vintages produced since the time that Stephen and Prue Henschke took over their family winery in 1978. Although it is not possible to separate out the effects of the introduction of refrigeration and the switch to new French Oak in 1983, jointly these changes are shown to have further increased the secondary market prices of that wine. Furthermore, the improvement in grape quality as a result of a new trellising system in 1990 also isreflected in the secondary market prices of vintages produced from that year onwards.

Auction price dummies

The estimated auction year specific constant term for each wine is presented in Table 2. Although these constants have limited interpretation, we note that for each wine the constants tend to increase in each successive auction year. These constants are designed to capture the effects of exogenous influences on prices across auction years. Therefore, the increase over time in the auction year dummies may be a reflection of income growth or shifts in preferences towards consumption of Australian icon wines in the sample period (e.g. greater awareness of these wines in Asia as a consequence of publicity via wine writers such as Robert Parker), causing prices to rise independent of quality over the periods of auction years considered. This trend reversed slightly in 1999 or 2000 for all of the wines, perhaps reflecting the influence on consumer and investor confidence of the Asian financial crisis of the late 1990s.

Goodness of fit

The signs of all the coefficients in our model are in line with viticultural expectations. In addition, there are other indications that our model is explaining well the price variation between different vintages of the same wine. Firstly, the unweighted adjusted R^2 for every model is high, at 0.77, 0.59, 0.70 and 0.78 for Grange, St Henri, Bin 707 and Hill of Grace, respectively. This indicates that the weather and changes in production techniques, along with the age of the wine, explain around 60% of the price variation between vintages for St Henri, and 70-78% for the other wines. In addition, the models in each case demonstrate significantly superior explanatory power compared to models estimated with age as the only explanatory variable. The unweighted adjusted R^2 for the models with weather and technological change variables excluded are just 0.62, 0.45, 0.45 and 0.67 for Grange, St Henri, Bin 707 and Hill of Grace, respectively.

Furthermore, the model is found to be particularly robust to alternative specifications in each case. For each wine the regression was re-estimated, systematically dropping one of the vintage observations each time. The coefficients in each of the models exhibited minimal variation, and there was shown to be no statistically significant change in the models' explanatory power (as measured by adjusted R^2) any of the times that each model was re-estimated. The coefficient values attributable to each of the explanatory variables were also shown to be remarkably robust to the inclusion of insignificant explanatory variables in each model. Thus, given the theoretical plausibility of our models, along with their evident statistical robustness, we conclude that there is support for our hypothesis that the variation in consumer's willingness to pay for different vintages is related to quality differentials across the vintages brought about by variation in age, weather and production techniques.

Summary and conclusions

This study adds to the existing empirical literature on wine pricing by considering the determinants of secondary market price variation between different vintages of the same wine. We assume that the price of a given vintage on the auction market is determined by the quality of the wine. Therefore, the price variation between vintages can be explained by differences in quality, which affects the consumers' willingness to pay (and sellers to sell). In particular, extending the framework of Ashenfelter, Ashmore and Lalonde (1995), we are able to explain these quality differences on the basis of weather conditions during the growing season and improvements in grape growing and winemaking techniques, in addition to age of the wine, via estimation of a hedonic price function using panel data techniques.

The theoretical plausibility of our model is supported by the fact that our estimates of the implicit prices imparted through superior weather conditions and winemaking techniques are in line with viticultural expectations. Our model is further validated by its robustness to alternative specifications, and by its high values for R^2.

The findings of this study have possible implications for viticulturists, wine makers, wine consumers and investors. For viticulturists, the study provides an indication of the most appropriate climatic regions for growing ultra premium wine grapes. In the past, this decision has been based mainly on the understanding of the relationship between terroir (physical and hydrological aspects of soil, macro- and meso-climates, topography, etc.) and quality. However, by quantifying the relationship between climate and price, our study may allow a more detailed cost-benefit analysis of the decision to plant in different areas, given their climatic history.[4] For

[4] See Ashenfelter (1997) on how this hedonic approach can be applied to vineyard site selection.

winemakers buying grapes from independent growers, the price paid could be set in part on the basis of the weather variables using the equations presented in this study, pending the development of more-reliable quantitative indicators of grape quality such as grape colour, baume, pH using NIRS technology.[5]

For the wine consumer, our study provides an objective guide to quality of immature icon wines. While the consumer has a number of avenues for establishing the quality of the wine once mature, such as expert tasters' opinions (see, for example, Schamel and Anderson 2001), less information is available the further away are the peak drinking years of the wine. Since weather variables evidently provide a reliable indicator of future quality, our model provides a useful guide to the wine investor/consumer.

Although not explored in this study, due to difficulty in obtaining the release price data, wine investors and/or producers may be able to benefit from a study of the efficiency of the primary (release) markets for icon wines. If the release price of a wine does not fully reflect all the weather features of its vintage, then wine investors could exploit the publicly available weather information and make economic profits by choosing only to invest in those vintages that are under-priced at the time of their release. Alternatively winemakers could use that same information not only in setting their grape purchase price but also the wine release prices and/or quantities. For example, if the winemaker knows the weather conditions were exceptionally good for her/his grapes relative to others' grapes in the same region in a particular year, s/he would benefit from withholding some of that vintage for later sale once consumers realize how exceptional is that vintage.

We have yet to go back through critics' ratings books to see the extent to which their ratings when these wines were first released provided better or worse guidance to consumers than the weather variables identified in the equations estimated in this study. This may provide an interesting avenue for future research. So too would backcasting, to show the extent to which our model can track past price movements. Does the actual price approach the price predicted by our model (from below in good vintages and from above in poor vintages) as the wine ages? Is the pace of that convergence increasing over time as investors/consumers/producers learn more about the weather and other determinants of quality (and in particular as viticulturalists find more-precise ways to compensate for adverse weather conditions)? And why do producers vary the release price of their icon wines so much less from one vintage to the next relative to the fluctuations in weather conditions from year to year?

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5 See Golan and Shalit (1993). For details of the progress being made in Near Infra Red Spectroscopy (NIRS) in Australia, see GWRDC (2001).

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Appendix 1: The four icon wines

Penfolds Grange

Penfolds Grange is Australia's most-recognised icon wine. The first vintage of Grange was released in 1951 by the late Max Schubert. Grange is made predominately from ultra-premium Shiraz grapes (85-100%), but may also include a proportion of Cabernet Sauvignon (up to 15%). It is a multi-district blend, with three source regions: Barossa, Clare Valley and McLaren Vale. The percentage of grapes sourced from each region varies according to vintage conditions. Since its inception, Grange has been matured in new American oak (with the exception of the 1957, 1958 and 1959 vintages which were produced in secret and matured in used barrels). Although Grange is released four years after it is bottled, it only begins to reach its peak after 12-15 years. However, Grange has much longer term cellaring potential, with the best vintages still at their peak after forty years.

Penfolds St Henri

John Davoren produced the first vintage of Penfolds St Henri in 1956. Like Grange, it is primarily made from Shiraz (85-100%), but can include up to 15% Cabernet Sauvignon. The Shiraz grapes are sourced predominately from Barossa Valley, with smaller contributions from McLaren Vale, Clare Valley and Eden Valley. The Cabernet Sauvignon, when included, is sourced from Coonawarra and Barossa Valley. The wine is matured mostly in 2000 litre old oak vats called ovals. St Henri is a medium term cellaring wine (generally peaking at around 12-15 years), although exceptional vintages exhibit longer cellaring potential.

Penfolds Bin 707

Although first released in 1964, Bin 707 was discontinued in 1969 but then reintroduced in 1976 and released on an annual basis (with the exception of 1981,) since then. It is produced from Cabernet Sauvignon grapes, the majority of which are sourced from Coonawarra but the Barossa contributes up to one-third. The wine is matured in new American oak, and exhibits medium to long-term cellaring potential.

Henschke's Hill of Grace

The Henschke's most influential icon wine, Hill of Grace, was pioneered by Cyril Henschke in 1958. Hill of Grace is produced from Shiraz grapes, from a single Keynton vineyard in the Eden Hills Region, from vines 70-130 years old. The wine is matured in new oak and has long-term cellaring potential.

Appendix 2: A modified Rosen model

Rosen (1994) states that a particular class of commodities can be described by a vector of n objectively measured characteristics as

(1) $z = (z_1, z_2, ..., z_n)$

where z_i is the amount of the ith characteristic contained in each good.

In the context of this paper the 'class of commodities' refers to the set of vintages under consideration for a particular icon wine. The n characteristics which differ between the vintages include the age of the wine and the qualities of the wine once mature, which we include via objectively measured weather and technological change variables that impart these qualities.

The market price of a particular vintage reflects the 'price' of each of the characteristics embodied in that vintage. That is,

(2) $p(z) = p(z_1, z_2, ..., z_n)$

where p is an increasing function of all the characteristics.

The consumption decision

Rosen outlines the strictly concave utility function as

(3) $U(x, z_1, z_2, ..., z_n)$

where x is all other goods consumed. The utility function demonstrates how a consumer's utility changes as they consume an additional unit of one of the attributes, holding the level of consumption of each of the other attributes constant. We assume each of the attributes of the wine of a particular vintage is considered a 'good' i.e. they provide positive marginal utility.

Consumers in the model maximise their utility subject to their budget constraint. Rosen defines the non-linear budget constraint as

(4) $y = x + p(\underline{z})$

where the price of x is set equal to unity and y is measured in units of x.

The budget constraint demonstrates the total income available, y, to spend on all other goods, x, and the utility bearing characteristics of wine, given their implicit price.

The Lagrangean for this model is

(5) $L = U(x, z_1, z_2, \ldots\ldots\ldots, z_n) + \lambda[y - (x + p(\underline{z}))]$

with the following First Order Conditions:

(6) $\frac{\partial L}{\partial x} = U_x - \lambda = 0$

(7) $\frac{\partial L}{\partial z_i} = U_i - \lambda p_i(\underline{z}) = 0$

(8) $\frac{\partial L}{\partial \lambda} = y - [x + p(\underline{z})] = 0$

Solving (6) for λ yields

(9) $\lambda = U_x$

Substitute (9) into (7) to get

$U_i - p_i(\underline{z})U_x = 0$

$U_i = p_i(\underline{z})U_x$

(10) $p_i(\underline{z}) = \frac{U_i}{U_x} \quad i = 1, \ldots\ldots\ldots, n$

where $p_i(\underline{z})$ is the marginal rate of transformation of characteristic i for x. The marginal rate of transformation is the market trade-off between goods, in this case the amount of all other goods, x, the consumer must give up to gain one more unit of characteristic *i*.

U_i is the consumer's marginal utility from characteristic i. This measures the amount of extra utility a consumer derives from consuming an additional unit of characteristic i, holding constant the consumption of all other goods x, and all of the other n-1 characteristics. U_x is the marginal utility from good *x*. The ratio of these two marginal utilities, $\left(\frac{U_x}{U_i}\right)$, is the marginal rate of substitution of i for x. That is, the maximum amount of x a consumer is willing to give up to get one more unit of characteristic i.

According to (10), the consumer will maximise utility by setting his/her personal trade-off (the marginal rate of substitution) equal to the market trade-off (the marginal rate of transformation).

As Rosen demonstrates, the model is easily expanded to include several quantities (i.e. the consumer purchasing multiple bottles), but we require the additional assumption that the consumer purchases the bottles of only one particular vintage. The utility function becomes:

(11) $U(x, z_1, ..., z_n, m)$

where m is the number of units of a vintage with characteristic vector $\underline{z}$. The budget constraint becomes

(12) $y = x + mp(\underline{z})$

for which the Lagrangean is

(13) $L = U(x, z_1, ..., z_n, m) + \lambda[y - (x + mp(\underline{z})]$

with the following First Order Conditions:

(14) $\frac{\partial L}{\partial x} = U_x - \lambda = 0$

(15) $\frac{\partial L}{\partial m} = U_m - \lambda p(\underline{z}) = 0$

(16) $\frac{\partial L}{\partial z_i} = U_i - \lambda m p_i(\underline{z}) = 0$

(17) $\frac{\partial L}{\partial \lambda} = y - x - mp(\underline{z}) = 0$

From (14) it follows that

(18) $U_x = \lambda$

Substitute (18) into (15) to get

$$U_m - U_x p(\underline{z}) = 0$$

(19) $p(\underline{z}) = \frac{U_m}{U_x}$

Then substitute (18) into (16) to get

$$U_i - U_x m p_i(\underline{z}) = 0$$

(20) $$p_i(\underline{z}) = \frac{1}{m}\frac{U_i}{U_x}$$

From (11), the consumer maximises utility by setting his/her personal trade off proportional to the market trade off. That is, even as we introduce multiple quantities into the model the consumer's reservation price for an additional unit of characteristic z_i is proportional to the ratio of his/her marginal utility from characteristic i to his/her marginal utility from x. Thus, allowing consumers to purchase multiple quantities does not affect the underlying pattern of consumer preferences and behaviour. Therefore, we can constrain m to be equal to one without affecting the interpretation of the regression coefficients.

Following Rosen, we can allow parameterisation of tastes. The taste parameter α is assumed to differ between consumers. Incorporating this parameter, the utility function can be written as

(21) $$U(x, z_1, \ldots\ldots, z_n; \alpha)$$

The equilibrium value function is shown by Rosen to depend on both α and consumer income, y. Therefore, for the population at large there exists a joint distribution function $F(y, \alpha)$, which determines the implicit price function.

The production decision

Rosen considers the supply of the differentiated product in terms of the production decision. That is, he considers a firm's profit maximising behaviour, given the costs and revenues associated with incorporating different amounts of the n characteristics in their products. He defines the total costs of a firm producing in the commodity class as

(21) $$C(M, \underline{z}, \beta)$$

where $M(\underline{z})$ is the number of units produced with attribute bundle $\underline{z}$, and β is a shift parameter which differs between firms and represents variables in the cost minimisation problem such as factor prices and technologies. However, given that our 'class of commodities' is the output from the same firm over different periods, the analysis must be approached differently.

The total cost function for the winery in a given vintage year is

(21) $$C(M, \underline{z}, \beta)$$

where $M(\underline{z})$ is the number of bottles of a vintage produced with attribute bundle $\underline{z}$,

β is a shift parameter, which differs over time for the winery, representing changes in technology, and

$$\underline{z} : \begin{cases} \underline{z}_x = z_1, \ldots\ldots\ldots, z_j \\ \underline{z}_n = z_{j+1}, \ldots\ldots, z_n \end{cases}$$

where $\underline{z}_x$ are the attributes that are exogenous to the winemaker's production decision for a given vintage, including weather conditions, and

$\underline{z}_n$ is the attributes that are endogenous to the winemakers production decision for a given vintage, including winemaking and grape growing techniques

Assumptions

- C is convex;
- $C_M > 0$ i.e. the marginal cost of producing more bottles of a given vintage is positive;
- $C_{z_{ix}} = 0$ i.e. the marginal cost of increasing an exogenous attribute is zero (since outside the winemakers control); and
- $C_{z_{in}} > 0$ i.e. the marginal cost of increasing an endogenously determined attribute (e.g. improving winemaking technique) is positive.

For each vintage the winemaker maximises profit:

(22) $$\pi = MR(\underline{z}) - C(M, z_{j+1}, \ldots\ldots, z_n)$$

where the First Order Conditions are:

(23) $$\frac{\partial \pi}{\partial z_{ix}} = R_{ix}(\underline{z})M = 0$$

(24) $$\frac{\partial \pi}{\partial z_{in}} = R_{in}(\underline{z})M - C_{z_{in}}(M, z_{j+1}, \ldots\ldots\ldots, z_n) = 0$$

(25) $$\frac{\partial \pi}{\partial M} = R(\underline{z}) - C_M(M, z_{j+1}, \ldots\ldots\ldots, z_n) = 0$$

From (23) there exists no solution. The winemaker's profit is a continually increasing function of z_{ix}, since increases in z_{ix} increase marginal revenue without increasing marginal cost. But given that z_{ix} is outside the winemaker's control, we expect to observe fluctuations in profit as growing season weather conditions fluctuate. From (24)

$$R_{in}(\underline{z})M = C_{z_{in}}(M, z_{j+1}, \ldots\ldots\ldots, z_n)$$

(26) $$R_{in}(\underline{z}) = \frac{1}{M} C_{z_{in}}(M, z_{j+1}, \ldots\ldots\ldots, z_n)$$

The profit maximising winery will produce up until the point where marginal revenue from changing technologies is equal to the marginal cost of introducing these qualities, per bottle sold. From (25)

$$R(\underline{z}) = C_M(M, z_{j+1}, \ldots\ldots\ldots, z_n)$$

The firm will produce bottles of wine up until the point where marginal revenue (release price) is equal to the marginal production cost, evaluated at the optimal bundle of characteristics.

We further assume that the new release market is efficient, that is, the influence of the $\underline{z}$ vector of weather conditions and techniques on the quality and hence price when mature are fully factored into the wine at the time of release. Therefore

(27) $$p(\underline{z}) = R(\underline{z})(1+r)^t$$

where r is the opportunity cost of holding and storing wine. That is, we assume that the secondary market sellers earn zero economic profit and earn a rate of return commensurate to the opportunity cost of holding and storing wine.

Market equilibrium

In determining market equilibrium, Rosen states that it is necessary to consider both the demand and supply for each characteristic. That is, it is necessary to find the function $p(\underline{z})$ such that $Q^d = Q^s$ for all $\underline{z}$. Thus, market prices are fundamentally determined by the distribution of consumer tastes, α and producer costs, β. This creates an identification problem, making it impossible to separate out the effect of consumer preferences and production technologies in generating the observed set of hedonic prices. In an empirical framework,

(28) $$p_i(\underline{z}) = F^i(z_1, \ldots., z_n, Y_1) \qquad \text{(demand)}$$

(29) $$p_i(\underline{z}) = G^i(z_1, \ldots.., z_n, Y_2) \qquad \text{(supply)}$$

where Y_1 is the empirical counterpart of the taste parameter, α, in the theoretical model

and Y_2 is the empirical counterpart of the technology parameter, β, in the theoretical model. For $i = 1,........, j$, $z_{1,},........, z_j$ are exogenous to the supply, therefore, $p_i(z)$ is also exogenous to the supply decision. This is sufficient to identify the hedonic demand function for these characteristics (Schamel 2000). Thus, we estimate the model using the hedonic price method (by regressing the vintage prices on their associated weather conditions). The estimated implicit prices of weather conditions, the $\hat{p}_i(z)$, reveal consumer preferences for each of the j exogenous attributes. Since $i = j+1,......., n$, $z_{j+1},.........., z_n$ are endogenous to both the supply and demand functions, thus these characteristics along with their implicit marginal prices, $p_i(z)$, are simultaneously determined. Thus, if we estimate the model using the hedonic price method we cannot interpret the coefficients in the desired manner. However, as Rosen outlines, if we have data over different time periods then it becomes possible to determine the changes in the marginal prices and qualities brought about by technology and thus to reveal consumer preferences for each of the $j+1,......, n$ endogenous attributes.

Table 1: Regression estimates

(a) Penfold's Grange Regression Estimates

	Age	RainH	Maxtemp	TempD	Humid	Wind	WindS	Press
p_{it}	0.025	-0.004	0.094	-0.210	0.007	0.261	-0.008	0.561
$\lvert tstatistic \rvert$	9.92**	9.17**	4.99**	5.80**	3.12**	7.38**	-7.63**	8.08**

(b) Penfold's St Henri Regression Estimates

	Age	RainH	Maxtemp	TempD	Wind	WindS
p_{it}	0.003	-0.001	0.024	-0.031	0.073	-0.002
$\lvert tstatistic \rvert$	2.36*	6.71**	2.74**	1.68	4.56**	4.25**

(c) Penfold's Bin 707 Regression Estimates

	Age	AgeS	RainH#	Maxemp#	MaxtempS#	TempD#	Humid#	Wind	WindS	Style
p_{it}	0.072	-0.003	0.005	3.33	-0.068	-0.143	0.008	1.220	-0.054	0.175
$\lvert tstatistic \rvert$	3.86**	4.10**	5.23**	2.28*	2.27*	5.16**	2.52**	5.22**	5.05**	2.51**

(d) Henschke's Hill of Grace Regression Estimates

	Age	AgeS	RainH	SunS	TempD	Wind	WindS	SP	Fridge	Oak
p_{it}	0.043	-0.001	-0.002	0.027	-0.109	0.184	-0.008	0.086	0.113	0.077
$\lvert tstatistic \rvert$	3.96**	3.71**	6.17**	5.41**	4.39**	4.05**	4.02**	2.63**	3.06*	2.32**

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Table 2: Auction price dummies

(a) Penfold's Grange

	88	89	90	91	92	93	94	95	96	97	98	99	00
Coefficient	2.83	2.74	2.62	2.61	2.71	2.82	2.96	3.03	3.24	3.37	3.39	3.34	3.36

(b) Penfold's St Henri

	94	95	96	97	98	99	00
Coefficient	0.69	0.75	0.81	0.90	0.94	0.96	0.92

(c) Penfold's Bin 707

	96	97	98	99	00
Coefficient	-42.36	-42.09	-41.93	-41.95	-41.92

(d) Henschke's Hill of Grace

	95	96	97	98	99	00
Coefficient	1.22	1.33	1.41	1.46	1.46	1.44

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